The Development of A Low Cost Non-destructive Inspection System for Plating Quality Assessment of Plated-through Holes in Printed Circuit Boards

A Thesis Presented in Partial Fulfilment of the Requirements for the
Degree of Master of Technology
in the
Department of Production Technology
at
Massey University

KAM CHIU MAK

1995

ABSTRACT

The status of printed circuit board inspection is reviewed with special focus placed on the existing techniques of assessing plated-through hole quality. The need for developing a non-destructive method for plated-through hole inspection has been identified and is the major objective of this research.

The results of the investigation into various methods that could lead to this objective are presented. This investigation has been concerned with the application of image processing techniques and the leakage light detection method. The hardware and software requirements for automatic visual inspection of stuffed board components are established initially using available equipment from the Department of Production Technology.

Image processing techniques are found to be capable of discriminating copper-plated and unplated surfaces using the difference in reflectance between the surfaces. This suggests the possibility of applying such techniques to assess the quality of through-hole plating.

The leakage light detection method can be implemented to assess the plating coverage of plated-through holes. A low cost inspection system demonstrating the principle of leakage light detection has been constructed. This system is particularly relevant to the small batch manufacturers in the printed circuit board industry.

The performance of the demonstration system has illustrated the simplicity and reliability of the design. It is concluded that the leakage light detection technology offers a practical low cost solution for non-destructive plated-through hole inspection.

ACKNOWLEDGEMENTS

I wish to thank my supervisors, Professor Bob Hodgson and Dr Roger Browne, for all the guidance, the support, and the time they generously provided during the course of the work. I am also indebted to Dr Ross Nilson for his valuable comments and suggestions at various stages of this research.

Messrs Dexter Muir, Ken Mercer, Farshad Nourozi, Gary Allen and Peter Haw are thanked for their helpful technical support.

I also wish to thank my sister-in-law, Marlene, and her husband, Shaoquan (Dr Liu), for proof-reading this text. Finally, I shall always be grateful to my wife, Yvonne, for her understanding and tolerance to my frequent staying up late during the preparation of this thesis.

CONTENTS

APPENDICES

LIST OF FIGURES AND TABLES

LIST OF ABBREVIATIONS

ANSI	American National Standard Institute
CAD	Computer aided design
CCD	Charge coupled device
DIP	Dual in line packaging
DPI	Dots per inch
IPC	Institute for Interconnecting and Packaging Electronic Circuits
IC	Integrated circuit
IR	Infrared
LLD	Leakage light detection
PCB	Printed circuit board
PWB	Printed wiring board
PTH	Plated-through hole
ROI	Region of interest
SNR	Signal-to-noise ratio
UV	Ultra violet

CHAPTER ONE

INTRODUCTION

Printed circuit boards (PCBs) are the building blocks of almost all modern electronic systems. They provide a convenient way of mounting and interconnecting electronic components to form circuits and systems. The primary functions of the PCB are component support and circuit interconnection.

1.1   BACKGROUND

According to [THE62] the concept of the printed circuits has earlier origins than it is commonly supposed. A US patent dated 1903 describes ribbon cables formed *in situ* by electro-deposition. Between 1923-1929, a number of US patents were granted covering some of the techniques now still in use for printed circuit manufacture [THE62]. In 1936, P. Eisler was granted a British patent under the title "Printed Circuits" [EIS85]. Although Eisler's idea of etched foil circuits eventually became the most widely used method of producing circuits, the idea was not immediately successful [POL84]. Some of the early printed circuit patents granted to Eisler can be found in appendix 1-1.

During the Second World War the heavy demand for electronic devices stimulated the investigation into methods of producing circuits quickly and cheaply [POL84]. The first major application of the printed circuit concept occurred in 1945 when mass production of a United States military proximity fuse began at 5000 units a day. The circuit pattern was screen printed on a ceramic wafer using a conducting ink. The ink consisted of a binding agent, a solvent and fine silver powder. The printed ceramic plate was then heated to 500-800 °C, driving off the solvent and leaving the silver fused to the ceramic surface. The silver thus formed an excellent solid conductor and was well adhered to the ceramic base plate [THE62].

The success of the proximity fuse stimulated the launch of the printed circuit industry after the war. By the middle of the 1950s, printed circuits were being used in consumer products as well as military and industrial equipment [POL84]. Since then, the basic elements making up a PCB have remained unchanged. These are the base and the conductors. The base is a thin insulating material supporting all the conductors and electronic components. The conductors are customised patterns of thin metal strips, usually copper, firmly bonded to the base to form a laminate.

A PCB provides the necessary interconnections for the mounted components, it is also referred to as a printed wiring board (PWB) [LEO81]. By shaping the conductor patterns appropriately, it is possible to incorporate passive components such as small

inductors, small capacitors and resistors directly on the board. In this case it is always called a printed circuit board because the functional circuitry is also printed [HAI91]. To avoid confusion, this thesis uses only the term Printed Circuit Board (PCB) and PWB is treated as a synonym of PCB.

1.2 PRINTED CIRCUIT BOARD MANUFACTURERS

According to [TYL94], up to 60 percent of the PCB manufacturers world wide are in the prototype and small batch sector. They provide services "where price is less of an issue and customers are prepared to pay for things in a hurry" and that these small companies generally "enjoy much higher profit margins than their large competitors". It has been estimated that the small batch sector represents 10 percent of the entire PCB market. On the contrary, 50 percent of the total PCB output is produced by only 7 percent of the manufacturers [TYL94].

In a case study report prepared for the Ministry of Research, Science and Technology, McNaughton [MNA92] suggests that the main problem faced by the New Zealand electronics industry is a matter of scale when adapting overseas technology to New Zealand needs. In coping with New Zealand's small production runs, specialised technology has to be developed to counter the scale problems.

1.2.1 Example of a Small Batch Production Facility

The Department of Production Technology at Massey University has established a manufacturing pilot plant (MPP) for electronic products. The plant is capable of PCB design, bare board production and component assembly. As stated in [NIL91], one of the many aims of the MPP is "to focus on the technology and management of a strategic New Zealand industry". To be of New Zealand relevance, the MPP "is a low cost process capable of short runs and rapid response".

The level of technology involved is a double-sided PTH capability. Output volume has been designed at up to fifty panels (each 305 x 406 mm or 12 x 16 inches) a day. Various features of the MPP are described in [NIL91].

1.2.2 Competition Strategy of Small Batch Manufacturers

Tyler [TYL94] identifies four key investment targets that are becoming essential for contemporary PCB manufacturers to survive in competition. These are:

- Yield improvement
- Reduction of labour cost
- Fine line and small hole technology
- Guaranteeing product quality in the field.

It has been estimated that typical investment in response to such demands would require US $0.3-0.5 million. Drilling and visual inspection systems are the two top areas of spending [TYL94].

Unlike major PCB manufacturers that can afford to stay ahead in technology and equipment, the small batch manufacturers' competitive strategy is to remain profitable on a low capital base. For example, commercial machine vision systems are designed for high volume inspections and require heavy capital investments (minimum US $ 0.3 million) [TYL94]. The small batch manufacturers will find this level of spending prohibitive. Most importantly, such systems fail to match the needs of small scale production. This is a "matter of scale" problem no different to that as described in the McNaughton report (section 1.2). This helps to explain why in small scale production human visual inspection dominates.

1.2.3 Meeting the Needs of the Small Batch Manufacturers

Installation of suitable low cost PCB inspection systems could help the small batch competitors to achieve three goals:

- improved yield
- reduced labour cost
- better quality of the product.

A higher customer confidence and higher yield will combine to create a potential of increased profits. Here, low cost inspection systems constitute a significant investment advantage for the small manufacturers. This is due to:

- A low level of injected capital generates relatively high return
- Minimal increase in sales is required to adequately cover the injected capital
- Overall capital level remains low to retain profitability.

Such an investment strategy therefore falls in line with the low capital base strategy of the small batch manufacturers. It can be anticipated that low cost inspection systems, though less sophisticated than their expensive counterparts, would meet the needs of most small batch PCB competitors.

1.3   OBJECTIVE, SCOPE AND RELEVANCE OF THIS RESEARCH

1.3.1 Main Objective

The main objective of this research was to explore and develop non-destructive methods for PTH inspection. These methods are relevant to small batch PCB production such as the facility in the Department of Production Technology at Massey University.

1.3.2 Scope

This research covers only double-sided PCBs with PTHs. Work has been focused on low cost solutions only. The PCB manufacturing process described in this thesis is based on the pilot plant facilities in the Department of Production Technology at Massey University. Although some of the work involved may be extended to cover certain categories of multilayer boards, such tests have not been conducted.

1.3.3 Relevance

The low cost approach towards non-destructive PTH inspection is targeted at providing technology support to the prototype and small batch sector of PCB manufacturers. Such a strong orientation towards serving the small business sector is relevant to the New Zealand industry.

1.4 LIST OF CONFERENCE PAPERS PUBLISHED

The following conference papers have been published in connection with the work described in this thesis:

1. K.C.Mak, R.M.Hodgson, R.F.Browne, R.R.Nilson, 'Image processing techniques for non-destructive testing of printed circuit boards'. *Proc. 2nd New Zealand Conference on Image Vision & Computing*, Palmerston North, August 1994, pp.2.5.1-2.5.5.

2. K.C.Mak, R.M.Hodgson, R.F.Browne, R.R.Nilson, 'Image analysis of copper plated surface - towards non-destructive inspection of plated through holes in printed circuit boards'. *Proc. Inaugural New Zealand Postgraduate Conference for Engineering & Technology Students*, Palmerston North, August 1994, pp.277-281.

3. K.C.Mak, 'Identifying defective through-hole plating in printed circuit boards using the leakage light detection method'. *Proc. 2nd New Zealand Postgraduate Conference for Engineering & Technology Students*, Auckland, August & September 1995, pp.195-200.

1.5 ORGANISATION OF THIS THESIS

A literature review on PCB manufacture and inspection is presented in chapters 2 and 3. Chapter 2 starts with a description of double-sided bare board manufacturing. The

key processes of PTH production are then examined. Chapter 3 describes the status of PCB inspection, focussing on the conventional method of testing PTHs. The need to develop non-destructive inspection methods for PTHs is identified.

The use of image processing techniques to discriminate between copper-plated and unplated surfaces is reported in chapter 4. The potential requirements and implications of applying these techniques to assess the through-hole plating quality are then discussed.

Chapter 5 examines alternative schemes for non-destructive inspection of PTHs and highlights the potential use of visible light as a penetrant for surface flaw detection.

Following the development in the previous chapter, chapter 6 focuses on the leakage light detection method and describes the development and performance of a low cost leakage light detection system for PTH inspection.

Chapter 7 presents the preliminary results on establishing the hardware and software requirements for a stuffed board component inspection system.

The important issues identified during this research are summarised in chapter 8. This chapter also discusses the inspection strategy and then examines the possible impact of a low cost inspection system on PCB manufacturers in the prototype and small batch sector. Chapter 9 concludes this thesis and recommends some directions for future work.

PRINTED CIRCUIT BOARD MANUFACTURING

This chapter describes the major steps in bare board manufacturing by focusing on the production process of double-sided PCB with PTHs. This is the level of technology used in the Manufacturing Pilot Plant in the Department of Production Technology at Massey University. The production of PTHs will be described in more detail since it is the key step in bare board manufacture.

2.1 INTRODUCTION

Earlier PCB constructions were single-sided, so named due to the presence of conductors on only one side of the board. These PCBs are still a cost-effective method for constructing simple low density circuit designs. Single-sided boards are the simplest variety of PCBs and are the least costly to manufacture [FLA92]. In the late sixties, processes were developed for plating copper on the walls of drilled holes in PCBs. This technique allowed PCBs to have conductors on both surfaces, interconnected by PTHs. These double-sided PTH PCBs allowed for the interconnection of medium density circuit designs and quickly became the industry standard [FLA92].

Subsequent technological development has brought many improvements to the design and manufacture of PCBs and alternative technologies and materials have been introduced. This can be illustrated by the move to multilayer technology, the reduction of conductor width and the use of epoxy-glass and more advanced base materials.

Multilayer technology allows higher interconnection density than double-sided boards by bonding more than two conductive layers together. The multilayer boards are used when very dense and complex circuits are required in a limited space [MAT90]. Boards of up to 42 layers were manufactured in 1990 and the layer count is reported to have increased to 48 in the 1994 literature [HAI91,OST91,ANG94].

Conductor line width has been reduced from 0.3 mm in the mid 1960's to less than 0.1 mm in the mid 1980's [WEI89]. This trend combines with the move to multilayer boards to realise a significant size reduction in PCBs having complicated interconnections. For example, Fujitsu's M-780 computer uses a 42-layer board with 3 Km of signal wiring at 60 μm width. The CRAY-3 "supercomputer" has 40 μm wide conductors on its main board [NAK92].

The replacement of phenolic-paper by epoxy-glass base materials gives better mechanical, electrical and chemical properties at lower costs [KEA87]. Table 2.1 gives a comparison of some properties of a typical phenolic-paper substrate, FR-2, with an

epoxy-glass substrate, FR-4. Phenolic-paper materials usually suffer from brittleness and high moisture absorption - a serious drawback in a humid operating environment.

Table 2.1   Selected properties of two substrate materials

Laminate	*Water absorbency %*	*Flexural strength psi*	*Dielectric breakdown kV*	*Electric arc resistance*	*Alkali resistance*
FR-2 (Phenolic-paper)	0.75	11250	60	poor	poor
FR-4 (Epoxy-glass)	0.25	55000	45	good	excellent

Source: [BOS83,KEA87]

Depending on the end-product application, the characteristics and dimensions of modem PCBs vary considerably [ANG94]. Table 2.2 provides an overview of such variations:

Table 2.2   Characteristics and dimensions of PCBs

Feature	*Typical value or material*	*Remarks*
Board size	10 x 10 to 610 x 910 mm	
Board thickness	0.3 to 6 mm	includes multilayer boards and flexible circuits
Layer count	1 to 48	single-sided to multilayer boards
Conductor width/spacing	0.3 to 0.04 mm	
Laminates	various resins	depends on the thermal/dielectric requirements
PTH diameter	0.7 to 1.2 mm	for mounting components
Via hole diameter	0.15 to 0.7 mm	for interconnection only
Electroless plating	copper, nickel	thickness from 3 to 30 μm
Coating materials	Sn, SnPb, NiSn, NiAu, solder masks, organics	optional

Source: [ANG94]

Driven mainly by growing demands for very dense and complicated interconnections within limited space, production of multilayer boards and surface mount PCBs are the expanding sector of the PCB industry [TYL94]. Nevertheless, the high accuracy double-sided PCB with PTHs is still one of the major categories of modern PCBs

manufactured world wide each year [FLA92,TYL94]. Compared with multilayer boards and surface mount boards, the double-sided PTH PCBs can be manufactured in a lower cost process using less sophisticated equipment. A double-sided board costs approximately one-fifth as much as a multilayer board [MAT90]. This advantage is highly significant for many inexpensive electronic products where the cost of production is the major consideration for manufacturers and customers.

2.2 STANDARDS AND SPECIFICATIONS

Printed circuit board specifications set to establish uniform quality for the finished products. Government organisations and professional institutions such as the US Department of Defense and the Institute for Interconnecting and Packaging Electronic Circuits (IPC) are recognised as the primary sources of initiation, implementation and control of PCB specifications [FLA92]. These specifications cover every sector of PCB manufacture: materials, design, workmanship standards, acceptability and methods of testing.

2.2.1 Documentation

The following are some documents often referred to by manufacturers and customers and so are regarded as industry-wide standards for bare board production:

- **Material**

    This set of specifications defines the electrical, mechanical, and chemical properties of the material involved in PCB manufacturing such as laminate and solder. Examples are:

IPC-AM-361	Specification for rigid substrates for additive process in printed boards
MIL-P-13949	Military specification, plastic sheet, laminated, copper clad, for printed wiring
IPC-SP-819	General requirements for electronic grade solder paste

- **Design Criteria**

  These specifications set the guidelines for the PCB designer:

ANSI / IPC-D-275	Design standard for rigid printed boards and rigid printed board assemblies
MIL-STD-275	Military specification, printed wiring for electronic equipment

- **Workmanship/ Quality assessment**

  These specifications quantify all the finished board attributes and set the acceptance guidelines:

ANSI / IPC-RB-276	Qualification and performance specification for rigid printed boards
MIL-P-55110	Military specification, printed wiring boards
IPC-A-600	Acceptability of printed boards

- **Methods of Testing**

  A collection of specific test methods and procedures including environmental conditioning on all forms of printed circuits. Individual test methods are updated separately. The collection is intended to achieve uniformity and reproducibility for the testing of PCBs:

IPC-TM-650	Test methods manual

The customers often set additional specifications that reflect their dedicated service requirements in a particular product and their policy on quality and reliability.

2.2.2 Performance Classification of Printed Circuit Boards

Different performance requirements are set depending on the end-use of the products. According to the IPC specifications three general end-product classes have been established to reflect progressive increases in sophistication, functional performance requirements and inspection frequency. The definitions of this performance

classification can be found in all IPC specifications document under the section "scope". The following is a summary of the classification.

Class 1 - General electronic products

The major requirement is function of the product and cosmetic defects are not important. These include:

- Consumer products
- Some computer and computer peripherals
- General military hardware.

Class 2 - Dedicated Service Electronic Products

High performance and extended life of the product is required. Uninterrupted service is desirable but not critical. Certain cosmetic defects are allowed. Examples are:

- Communications equipment
- Sophisticated business machines and instruments
- Certain military equipment.

Class 3 - High Reliability Electronic Products

Continued performance or performance on demand is vital. These include critical equipment such as:

- Life support systems
- Flight control systems
- Special military equipment.

Performance requirements as specified in the IPC documentation are separated so that PCBs may be tested to any one of the three classes.

2.3 DOUBLE-SIDED PLATED-THROUGH HOLE PRINTED CIRCUIT BOARDS

A double-sided PTH PCB has electrical conductors bonded on each side of the board interconnected by plated-through holes. These holes provide electrical interconnections

between each surface of the PCB or are designated for mounting and soldering the component leads. The term "via hole" is reserved for a PTH intended for interconnection only.

2.3.1 Material

Material used for this type of PCB manufacture is usually copper cladded laminates. These laminate sheets have copper foil on both surfaces and are therefore referred to as double-clad. Laminates are available in various standard thicknesses. Non-standard thickness materials can also be obtained but are more costly [LEO81]. Table 2.3 is a list of standard laminate thickness based on the military specification MIL-P-13949.

Table 2.3   Standard laminate thickness for PCB manufacture

Laminate Thickness (based on MIL-P-13949 specification)					
mm	0.8	1.2	1.6	2.0	2.4	3.2
inch	1/32	3/64	1/16	5/64	3/32	1/8

Source: [MAT 90]

Base materials for the laminate are mainly epoxy glass and polyimide glass. Polyimide glass is the usual material for flexible printed circuits. Table 2.4 shows the laminate designators and description for some of the most common base materials for rigid PCBs.

Table 2.4   Common printed circuit base materials

Laminate	Description
FR-2	Phenolic/paper
FR-4	Epoxy/glass fabric, flame-retardant
G-10	Epoxy/glass fabric, general purpose
G-11	Epoxy/glass fabric, heat-resistant version of G-10
FR-5	Epoxy/glass fabric, flame-retardant version of G-11

Source: [KEA87]

The selection of a laminate type is based on costs and the specifications of the product [ARA89]. Hostile operating conditions such as extreme temperatures, humidity, corrosion, shock and vibrations must be taken into consideration in the selection process.

2.3.2 Manufacturing Process

The process starts from large sheets of laminate material being cut into panels of the required size. Panels are used to standardise the working dimensions of all equipment, clamps and fixtures in the manufacturing process [ARA89] but the ideal panel size mainly depends upon the plating equipment and for many manufacturers it is about 305 x 406 mm or 12 x 16 inches [LEO81]. Appendix 2-1 shows the maximum panel size allowed with different manufacturing operations. A panel may contain one or more PCBs. The number of boards in a panel is determined by the following factors [ARA89]:

- Physical dimensions of the PCBs
- Optimal geometrical placement of boards on a panel
- Physical process equipment constraints
- Economics of the process within panel yield.

A panel goes through all the manufacturing steps until finally being cut up into individual circuit boards and the remaining part of the panel is scrapped. A typical manufacturing process for double-sided bare boards with PTHs involves up to fifty steps. Appendix 2-2 gives the sequence of operations involved. The following is a simplified description of the principal steps:

- **Panel drilling**

  This is a mechanical process in which tooling holes and functional holes are drilled. Tooling holes are larger holes placed on the panel for subsequent alignment purposes. A common drilling practice is to stack several panels to minimise handling costs [LEO81,KEA87]. Entry and backup materials are utilised to sandwich the stacked panels. These are usually aluminium or phenolic sheets and the purpose is to

reduce hole burrs. Block [BLO89] provides a discussion on how these sheets are essential for successfully drilling PCBs.

- **Electroless copper plating**

    Electroless plating is also known as chemical plating. It is a method that deposits a thin layer of copper, typically 5 to 7 μm over the entire panel surface as well as on the hole walls. This process can produce very even plating thickness [NAK92]. Prior to plating, it is essential that the panels are deburred (see section 2.4.2.2) to remove traces of contaminants and burrs generated during the drilling operation. Otherwise, the success of the electroless plating will be severely affected [LEO81,BLO89]. The copper coating enables the through-holes to conduct electricity, hence connecting the conductors on both surfaces of the board. Since electroless plating is a slow process, usually a very thin layer of copper is deposited. Then the panels are transferred to an electrolytic bath to build up a further 3 to 7 μm of copper (flash plating). This is to condition the panel surface for the next manufacturing step [LEO81]. Details of electroless copper plating will be further described in section 2.4.2.3.

- **Application of photoresist and expose**

    This is an imaging process in which the circuit layout is transferred to surface of the panel. Photoresist is an organic compound that changes its solubility to certain solvents when it is exposed to UV light [HAI91]. Image transfer is initiated by applying photoresist to the panel surface and then it is exposed to UV with a mask carrying the circuit pattern. Unexposed photoresist is washed away using a suitable solvent, leaving behind the required circuit pattern on the copper surfaces. The function of the photoresist is to protect specific areas of copper from subsequent processing. All copper areas including the PTH walls that will remain on the finished PCB are unprotected by the resist.

- **Electroplating**

    The panel is electroplated with the specified thickness of copper, usually 20 to 25 μm is required (see section 2.4.1.2) on the uncoated circuit pattern and hole walls.

This is followed by overplating with tin-lead (or solder). The solder will protect the circuit pattern and the hole walls from the subsequent etching actions. The deposited solder must be at least 8 μm thick to be an effective etch resist [LEO81].

- **Strip and Etch**

  The photoresist is then removed from the panel using solvents, sometimes augmented by mechanical scrubbing [ARA89]. This is often referred to as resist stripping. After this, the redundant copper is no longer protected and can be removed by a chemical etchant. The etchant does not attack solder hence leaving the circuit pattern intact. Leonida [LEO81] provides a detailed account of the process.

- **Application of solder mask and legends**

  The solder mask (or solder resist) is generally an epoxy-based resin that seals off the entire PCB surfaces except for those areas that require to be soldered or to make electrical connection externally. The solder mask serves as a barrier to solder, thus safeguarding a PCB against unwanted solder bridgings or short circuits during component soldering [ARA89]. This is essential for high specification contemporary PCBs as conductor widths and spacings have been decreased due to miniaturisation. Another function of the solder mask is to protect the condition of the PCB from degrading over its life span. For example, oxidation and dendritic growth of copper crystals are greatly reduced under the protection of solder masks.

  Legends are markings on a PCB to aid component assembly or to provide other information as required. Both the solder mask and legends can be applied by screen printing. Wall [WAL86] gives an account of screen printing covering the types of product used, the areas of application and suggests methods for obtaining best results. It has been reported that positioning tolerances of 250 μm can be achieved on modern screen printing equipment [WEI89].

Figure 2.1 (a) to (g) illustrates the process of bare board manufacturing from drilling to finish.

copper

epoxy-glass

(a) copper cladded laminate
FR-4

drilled
hole
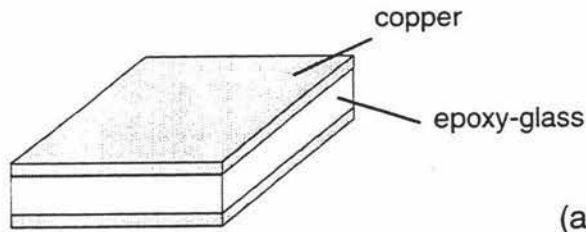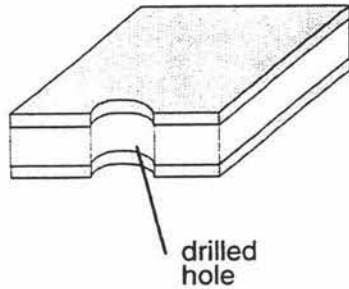
(b) panel drilling
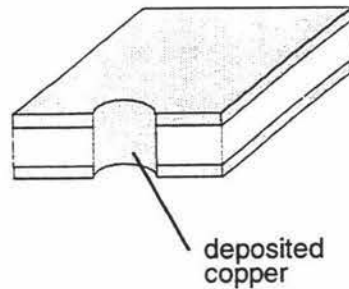
deposited
copper

(c) electroless copper plating

*A very thin layer of copper
is deposited on the panel
surface including the hole
walls.*
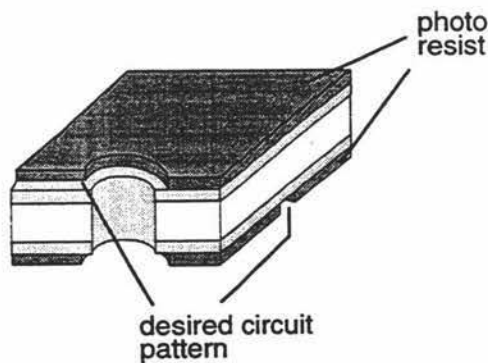
photo
resist

(d) apply photo resist

*The desired circuit pattern
is exposed.*

desired circuit
pattern

Figure 2.1 (a)-(d)   Steps of a typical bare board manufacturing process
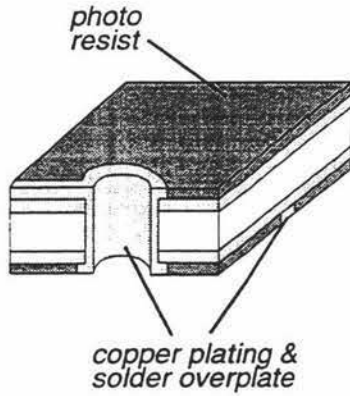
photo
resist

(e) electroplating

Deposite copper to specified thickness and overplate with solder

copper plating &
solder overplate

substrate
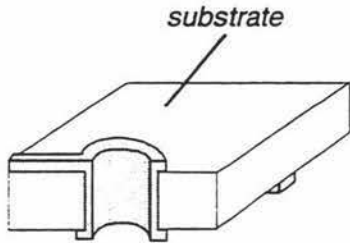
(f) strip and etch

Photo resist & unwanted copper are removed
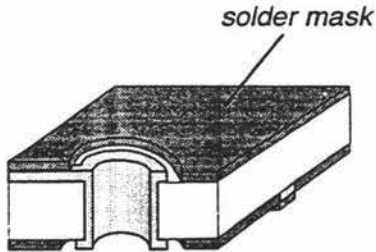
solder mask

(g) apply solder mask

All surfaces covered except areas to be soldered

Figure 2.1 (e)-(g)   Steps of a typical bare board manufacturing process

2.4   PRODUCTION OF PLATED-THROUGH HOLES

Plated-through holes are found in many types of PCBs. These include single-sided, double-sided and multilayer boards. Single-sided PCBs with PTHs are uncommon, this

particular type of board provides better soldering of component leads than ordinary single-sided boards [LEO81].

2.4.1 Design Requirements

The design requirements for PTHs can be found in PCB design specifications such as the IPC-D-275, "Design standard for rigid printed boards and rigid printed board assemblies". Figure 2.2 is a cross-sectional view of PCB that depicts the definitions of the more frequently used terms in PCB manufacturing and inspection.

A: PTH diameter
B: Conductor width
C: Conductor spacing
D: PTH plating thickness

E: Annular ring
F: Board thickness
G: Conductor thickness
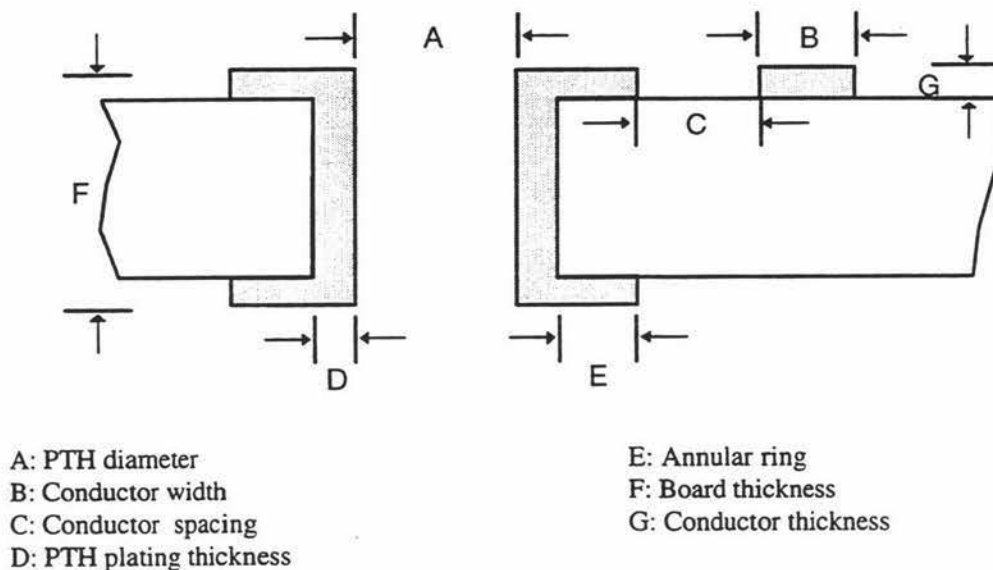
Figure 2.2   Definition of terms

2.4.1.1   Hole Size

PTHs intended for insertion of component leads will have diameters dependent on the size of component leads. Automatic insertion of components requires larger PTH sizes than manual insertion [MAT90]. All the dimensions are referred to the finished product and hence the design must make allowance for the plating thickness of hole walls.

2.4.1.2 Plating Thickness

According to the IPC-RB-276 specification, the thickness of through-hole copper plating should be an average minimum of 20 μm for class 1 products and 25 μm for class 2 and 3. Figure 2.3 depicts the plating criteria for the commonly used 1.6 mm thick substrate.

Dimension of features:

1.6 mm substrate

35 μm base copper

20-25μm through-hole plating

(drawing not to scale)

plated copper

base copper

substrate

> 125 μm
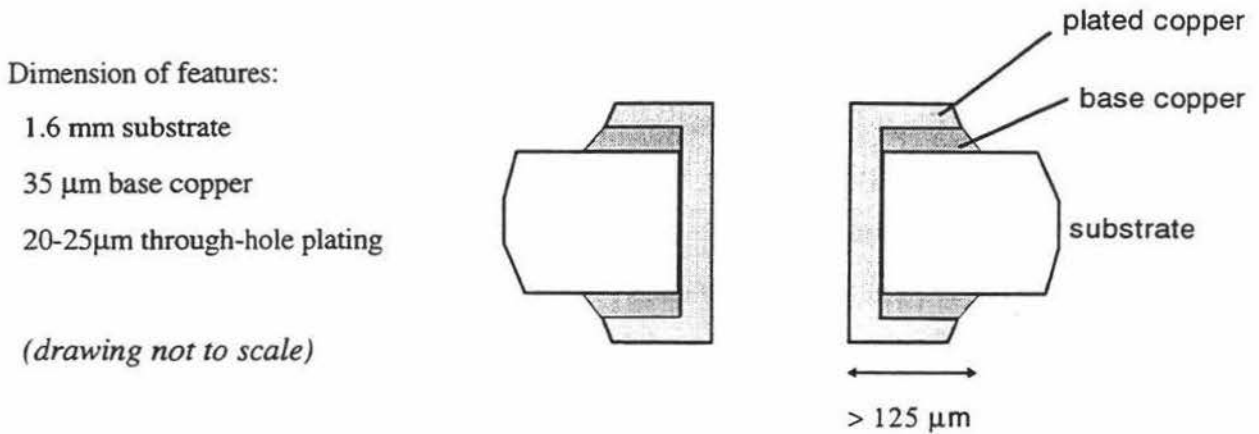
Figure 2.3 Example of through-hole plating thickness

2.4.1.3 Acceptability Criteria

The following table shows the requirements for acceptable through-hole plating according to the IPC-RB-276 specification:

Table 2.5   Acceptability of through-hole plating

Property	*Class 1*	*Class 2*	*Class 3*
Copper plating voids	3 voids allowed per hole. No circumferential voids over 90° allowed	None allowed	None allowed
Final coating	3 voids not exceeding 5% of hole wall area per void	3 voids not exceeding 5% of hole wall area per void	1 void not exceeding 1% of hole wall area

In addition, there shall be no separation of plating layers and no plating cracks. Definitions for class 1 to 3 products have been described in section 2.2.2.

2.4.2 Key Processes of Plated-through Hole Production

The production of PTHs has been briefly outlined in section 2.3.2 on the manufacturing process of bare boards. The following is an account focusing on the key processes of PTH production.

2.4.2.1 Drilling

The majority of substrate materials used for this type of PCBs is epoxy-glass. Holes can be produced by drilling, punching or more recently plasma etching and laser ablation. Punching epoxy-glass laminate does not leave the clean and smooth hole required for plating [LEO81,HED87]. As a result, drilling is the preferred method in PTH technology although it is a more expensive process than punching [ANG94]. Given the tight tolerances allowed for PTH locations and the presence of large amount of PTHs in the modern day PCBs, highly specialised NC drilling machines have been developed [KEA87]. Kea [KEA87], Block [BLO89] and Angstenberger [ANG94] discuss how vital the drilling process is towards the production of reliable PTHs.

A detailed description of panel drilling can be found in [KEA87] and [LEO81]. Vandervelde [VAN88] identifies the key variables that need to be controlled in the hole drilling process as:

- Choice of drilling machine
- Stacking and pinning of panels
- Drilling parameters, eg. feeds and speeds
- Drill bits
- Entry and backup materials

When properly controlled and maintained, hole drilling can be accomplished with consistent and acceptable quality. Methods to optimise key parameters have been discussed in [BER84,SEN86,TSU88,VAN88]. A list of criteria for assessing the drilled hole quality is given in [TSU88]. These are:

- Epoxy smear (see next section)

- Burring at entry and exit points
- Hole wall roughness
- Hole positional accuracy

Inspection is usually carried out immediately after drilling to extract relevant information about the drilled hole quality. If done properly, this would remove most of the sub-standard holes from being plated in the electroless copper stage.

2.4.2.2   Deburring / Desmearing

Burrs often occur near the drilled hole edges. A burr will eventually lead to cracked plating and will cause a large concentration of current locally during the electroplating process. Burrs can be removed using mechanical methods or an abrasive liquid or both.

Smear refers to thin layers of substrate material generated by overheated drill bits due to excessive friction during the downstroke. The resin first softens, then distorts and smears. If left unremoved, resin smear will contaminate the plating baths and once metallised, lead to large reduction in the finished PTH diameter [LEO81]. Angstenberger [ANG94] describes methods of desmearing and examines the selection of the optimal desmear method with respect to the substrate material. Smearing is usually considered as a problem with multilayer boards but some manufacturers also run double-sided boards through a desmear process to improve the adhesion of plating to the hole walls [LEA86c].

2.4.2.3   Electroless Copper Plating

This is typically a 15-step chemical plating process. The sequence of steps is given in appendix 2-3. The primary purpose of the process is to make the drilled hole walls conductive. Electroless copper plating makes use of special activators to sensitise the hole walls. A panel is dipped into a solution containing stannous and palladium ions. Stannous ions are first deposited on the surfaces to be catalysed. Immediately following

that, palladium ions are deposited, creating metallic sites for copper deposition to take place. Such a panel is referred to as being activated [HAI91].

After activation, the panel is transferred to a copper bath where copper ions are reduced to the metallic form with the palladium acting as a catalyst. Common plating rates are several micro-inches per minute or equivalent to a few μm per hour [HAI91] and the rate of deposition tends to decrease as the thickness of copper increases [LEO81]. Due to this slow rate, copper deposition is stopped when the thickness of the coating is sufficient for electroplating, or 5 to 7 μm [LEO81,NAK92]. The chemistry involved in electroless plating can be found in appendix 2-4.

Electroless plating is sometimes immediately followed by a flash plating of electrolytic copper, usually 3 to 7 μm [LEO81]. This is the thickness required to protect the electroless copper if the panels are to be cleaned by a mild etch before full electroplating (refer to the sequence in appendix 2-2 on bare board manufacture). Flash plating also allows storage of the panels for some time before further processing [HED87].

2.4.2.4   Electroplating

After the circuit pattern has been transferred on to the panels, electroplating of copper follows. This process is necessary to add thickness to the plated hole walls to meet a required standard. A minimum of 20 to 25 μm of copper is required (section 2.4.1.2). The overall metal thickness will determine the thermal and current-carrying capabilities of the finished PTHs [HAI91].

The deposition rate of electroplated metal is a function of current density and current distribution. Current density is greatest at the corners, edges and isolated holes but is lowest in recessed areas [BID87]. Rough hole walls are therefore undesirable as non-uniform current density affects the plating thickness. The presence of organic contaminants affects the current distribution. All these factors contribute to the variation of plating thickness across a panel [LEO81].

2.4.3 Summary

Electroplating of copper is followed by the plating of tin/lead or etch resist. The subsequent steps are common to the production of PCBs either with or without PTHs. These steps have already been outlined in section 2.3.2.

It can be seen that the production of PTHs involves a complicated multi-step process which is highly susceptible to drifts. Thus the inspection of PTHs plays an important role in assuring the quality of PCBs. This will be discussed in the next chapter on PCB inspection.

CHAPTER THREE

PRINTED CIRCUIT BOARD INSPECTION

This chapter is a description of PCB inspection concerning bare board surface conductors, PTHs and stuffed board component placement. Focus will be on the destructive and non-destructive methods of PTH inspection. A wide range of other inspection issues such as board warpage, hole pattern accuracy, annular rings, solderbility and solder joints are not covered.

3.1 INTRODUCTION

The main objective to inspect any product is to ensure that its quality meets the specifications. A secondary but equally significant objective is to extract information associated with the production process for the benefit of improving the process. Also trends are monitored to allow process control and so the key parameters can be kept within specification.

Inspection is costly since considerable time and labour are consumed in the process. Therefore the choice of features to inspect, the way in which samples are taken and the way in which inspections are conducted all need to be considered carefully. For example, trying to inspect every board of an inexpensive product may not be cost-effective. Kear [KEA87] lists four factors that influence the degree and the extent of the inspection to be used. These are:

- Cost of the circuit board.
- Function of the circuit board.
- Design of the circuit board.
- Statistical quality history.

3.1.1 In-process Inspection

As described in chapter 2, the production of bare PCBs is a multi-step process. Each step has its variability and so contributes to the overall product reject rate. Apart from the final inspection that qualifies a certain product as acceptable, in-process inspection must also be conducted. This is a sequence of inspection tasks at various stages of the production cycle. Any defects identified could help to determine whether a panel should be scrapped or reworked at that stage. Otherwise the final reject rate could be very high. As Tyler [TYL94] puts it: "boards rejected at the end of the production process contain the maximum added value of a company's profit and loss account". The information extracted from in-process inspection also helps to monitor any drifts in the manufacturing process. Thus, in-process inspection is an important means to reduce scrap losses and to minimise the cost of rework.

3.1.2 Bare Board Testing and Inspection

To verify for product acceptability, the finished bare boards are normally subjected to both electrical testing and visual inspection. Acceptability is established by meeting the various requirements defined by the customer specifications, or any such standards recommended by government and industrial organisations. One of these, for example, is IPC-B-276, "Qualification and Performance Specification for Rigid Printed Boards". This specification will be frequently referred to in this chapter.

Another important role of end-product inspection is to feed back information to the personnel in charge of production. In this way, corrective measures can be implemented as soon as possible should products fail to meet the specifications.

Electrical testing is particularly efficient in detecting open or short circuits. The testing facility can be automated to enhance the testing effectiveness for high density interconnections. This usually involves a fixed array of probing pins (so called "bed-of-nails") each connected to the automatic test station. Resistances at different points of the finished product can be measured according to a testing sequence [HAI91].

The commonly used "bed-of-nails" systems are criticised as having major drawbacks in [ANG87]. These are:

- Testing component patterns in small grids may become difficult.
- With low voltage equipment, any line width violation may not be reported; running the assembly in its final designation with higher voltages may cause interrupts of the affected interconnections.
- There is no possibility of 100% testing of closely toleranced line widths.

It follows that relying on electrical testing alone to verify the product quality is not sufficient. Currently, visual inspection is the major means to identify both existing and potential defects in a PCB. Pau [PAU90] points out that up to 80 percent of PCB inspections are visually based. Naturally human vision, as a well-developed and sophisticated system, can be employed to accomplish the task.

3.1.3 The Move towards Automatic Visual Inspection

With growing interconnection density and miniaturisation of modern day electronic circuits, human visual inspection has become increasingly inefficient and error prone [DOY84]. Double-sided and multilayer PCBs with line widths less than 150 μm and PTHs smaller than 0.6 mm in diameter are already manufactured in large quantities [WEI89]. Regardless of whatever magnifying devices are used, the human visual system is subject to fatigue. According to [ANG87], the limits of human visual inspections related to fatigue of human inspectors are as follows:

- The capability of finding any defects decreases exponentially with time.
- Depending on the complexity of a given PCB, after one hour of intensive inspection as many as 70% of the existing defects will be missed.

Another factor that discourages employing manual inspection is merely the huge volume of PCBs produced each year. In 1994, the world wide output was valued around US $26 billion [CUS94]. In coping with large scale automatic production, the only workable solution would be to also automate PCB inspection [AND88]. Tyler [TYL94] points out that the US PCB industry is currently spending 1.4 percent of its annual turnover on automatic optical inspection equipment and the installation of this equipment is growing by 14 percent each year. Such demand to perform visual inspection efficiently and reliably has already brought the application of digital image processing techniques into the subject of printed circuit board inspections. As will be seen in section 3.4, a number of machine vision systems have been designed for such applications.

3.1.4 Standard Test Patterns and Test Coupons

Test patterns are special conductor patterns used to define test coupons or test boards. They are intended as a reference in evaluating a PCB manufacturer's material and processes. A test coupon is defined as "a sample or test pattern usually made as an integral part of the printed board, on which electrical, environmental and microsectioning tests may be made to evaluate board design or process control without

destroying the basic board" [COO88]. The use of test coupons and their significance towards PCB quality control are highlighted in [MCO92]. The coupon results are taken as a "true" indication of the board quality although this may not always be the case. Appendix 3-1 shows a standardised test pattern for PTHs and illustrates how test coupons can be located on a production panel. Table 3.1 summarises the range of parameters that can be checked with the use of test coupons.

Table 3.1   Some test coupon testable parameters

Manufacturing Process	Example Parameters
Drilling Quality	Hole Location Drill Smear Burring Drill Wear out
Electroless Copper	Plating Thickness Adhesion Bath Decomposition
Imaging	Registration Accuracy Exposure/ Print Quality
Etching	Bath Activity Degree of Etching Definition
Desmearing	Hole Cleanliness Etchback Quality
Plating	Bath Chemical Balance Cracking Adhesion
Solder Fusion	Wetting Quality Solderability
Solder Resist	Registration Accuracy Adhesion Definition
Legend	Registration Character Definition

Source:[MCO92]

Many manufacturers always include test coupons in the design and production of circuit boards. Test coupons are selectively removed from panels for inspection at convenient stages of the production process. As described in [MCO92], "the test coupon is taken as a 'true' indication of the board quality and thus is inspected thoroughly while the main board is briefly checked". However, whether a coupon may be taken as a "true" indication of the board quality is a subject to investigate. A "major US corporation" has carried out an investigation on its PCB manufacturing facility and revealed that "the extent of agreement (of PTH quality) between the various test coupons and corresponding intelligent board areas was not satisfactory within or across boards" [HAY89]. The results of the investigation suggest that the coupon-to-board correlation has to be established using statistical process control.

3.2   SURFACE CONDUCTOR DEFECTS AND INSPECTION

For a double-sided PCB, the surface conductors appear on both surfaces of the board that form the circuit interconnection. Any surface conductor defects will likely affect the circuit reliability by introducing unexpected open or short circuits. Common occurring surface conductor defects are well documented [KEA87,PAU90]. These features have been made a requirement for bare board inspection in most specifications such as the IPC-RB-276.

3.2.1 Common Surface Conductor Defects

The defects found in bare PCBs can be grouped into the following three types:

1.   Dimensional

These may occur anywhere on a board as unacceptable variations of board or conductive feature geometries. Examples are warped board, wrong board thickness, improper conductor width and wrong hole size. The dimensional defects violate the PCB design specifications.

2. Cosmetic

Such defects affect the appearance but not the function of the circuit board. Examples are discoloured or scratched base material and smeared markings [KEA87]. Normally, cosmetic defects only need some touch-up work.

3. Functional

These are often more difficult to evaluate than the other types of defects [KEA87]. In defining functional defects, many PCB customers specify their own requirements along with the usual industry-wide specifications. Different forms of functional defects exist but they all affect the integrity of the circuit interconnection. Figure 3.1 illustrates some common defective features: (a) protrusion; (b) nick; (c) dent; (d) improper edge definition; (e) unetched copper; (f) short circuit; (g) open circuit; (h) intrusion; (i) pinhole; (j) void; (k) conductor peeling.
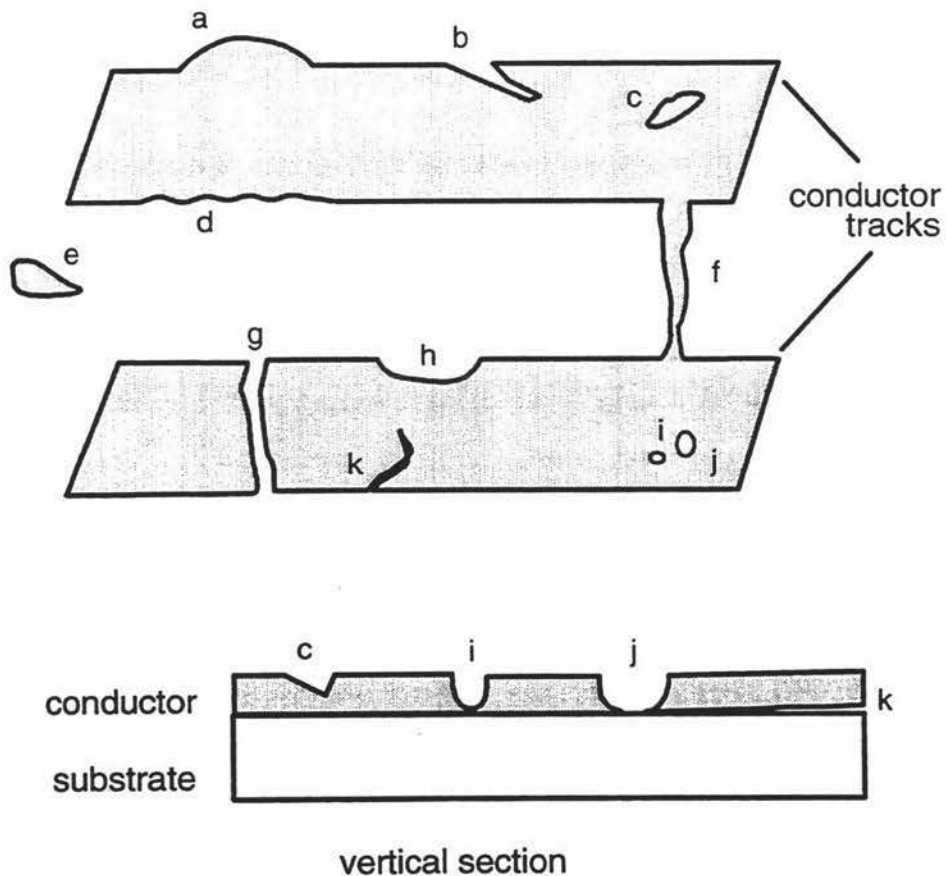
Figure 3.1 Common PCB surface conductor defects

3.2.2 Inspecting Surface Conductors

According to the IPC-RB-276 regarding test methods, visual inspections are carried out at a minimum of 1.75x magnifications. Conventional PCB surface conductor inspection has been carried out by human inspectors. Human visual inspection is still widely in use today, especially in small production volume facilities. The majority of PCB manufacturers in this category derives profits on a low capital base. They cannot afford expensive investment in automatic inspection equipment (see section 1.2.2).

The major manufacturers are more inclined towards using machine vision systems to inspect PCBs [AND88,PAU90,TYL94]. These machines use three alternative image processing approaches [THO88,PAU90]:

1. Comparison Technique
2. Feature Detection Technique
3. Design Rule Verification Technique.

A brief description on the application of these techniques in PCB inspection is given in appendix 3-2.

3.3   PLATED-THROUGH HOLE DEFECTS AND INSPECTION

As pointed out in [BLO89], many PTH defects can be traced back to the original drilling process. In [MIL84], some typical through-hole plating defects are analysed and suggestions on taking certain preventive measures during panel drilling are given. The causes leading to the occurrence of plating voids are identified in [DOU85] as:

- cavities on hole walls originated from drilling problems
- inefficient removal of drilling debris from the hole walls
- problems with desmearing procedures
- drifts in the electroless process.

3.3.1 Common Plated-through Hole Defects

Common PTH defects are:

- Cracked hole walls

- Voids and pinholes in plating

- Blistering

- Contaminated hole walls

- No connection between hole plating and surface plating layers

- Hole not plated.

Some examples of defects taken under a microscope are shown in figure 3.2. The samples were taken out after the electroless plating stage of the production process. Cracks, voids and pinholes are revealed using back light.
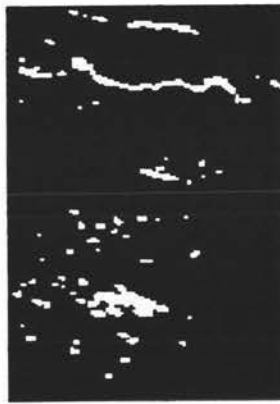
Cracks and voids   Voids and pinholes
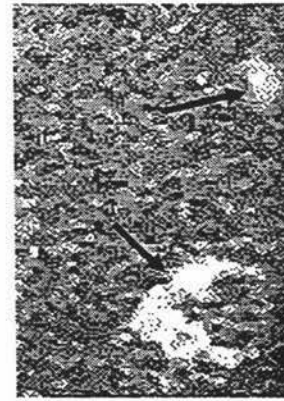
Blistering   Contamination

Figure 3.2   Common plated-through hole defects

3.3.2 Outgassing

Outgassing refers to the release of gas from the PCB substrate underneath the through-hole plating when the components are soldered. This is due to areas of porosity or weakness in the PTH wall electroless plating [LEO81,HOW86]. Leonida [LEO81] explains how this problem can be traced back to the roughness of drilled hole walls: a nick in the wall will not be covered by the thin electroless plating. Subsequent electro-overplating will be uneven due to concentration of current on sharp edges; the cavity will be closed by the overplated copper, but leaving a pocket in it. During soldering, the thermal expansion of the substrate opens the pocket, releasing any trapped compound. This is outgassing and is also known as blowholing. Figure 3.3 (a)-(d) depicts such a sequence of events.
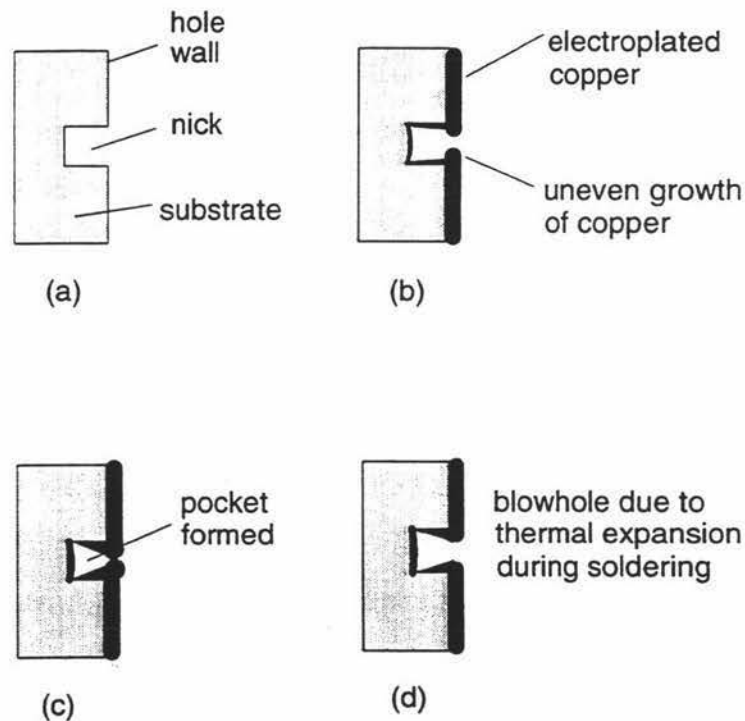
Figure 3.3   Generation and effect of outgassing

Source: [LEO81]

It has been established in [FEL88] that the degree of outgassing faults is proportional to the hole wall roughness and inversely proportional to the copper plating thickness. Given that the drilling process has been optimised, the electroless plating stage is the most important process to be controlled in order to eliminate the outgassing or blowholing problem. In a study when all the drilling parameters were kept constant, it

was found that the outgassing problem varied by a factor of 20, and the variation correlated well with the degree of electroless copper voids present [LEA87]. The study concluded that the outgassing problem could be improved by:

- ensuring a minimum average thickness of 20 µm copper on the hole walls
- the complete absence of electroless voids.

It therefore follows that the electroless plating stage is the single key process in the production of reliable PTHs.

3.3.3 Inspecting Plated-through Holes

Detecting the presence of plating voids is a prime concern in PTH inspection. In a comprehensive survey of possible void formation mechanisms involving 20 panels each containing 3000 PTHs, it was found that virtually all the voids observed were associated with exposed glass fibre [LEA86c]. The large voids were associated with exposed lengths of glass and the small voids with exposed ends of glass.

3.3.3.1   Destructive Testing

The current standard practice of inspecting PTHs is destructive. The common procedure is micro-sectioning and then the backlight test is applied to the sectioned sample. After the through-holes are plated, a row of PTHs is first selected and removed for micro-sectioning. This is done through the centre of the row as shown in figure 3.4 (a), resulting in a thin slice with several half-holes. Appendix 3-3 gives the standard procedure of micro-sectioning as referred to by the IPC-RB-276 standard.

Micro-sectioning can provide a direct linear measurement of the plating thickness, but the process also yields additional information on the nature, uniformity and presence of voids or nodules of the plating [LEO81]. In detecting plating voids, hole walls are exposed and the plated surfaces are inspected directly under a microscope using back illumination as shown in figure 3.4(b). Since copper deposition is opaque to light, plating voids can easily be detected as bright regions against a dark background. This

is known as the backlight test. Figure 3.4(c) shows a PTH with plating voids revealed by the backlight test.
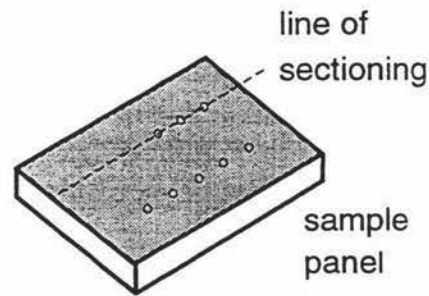
(a) Section through the centre of PTHs
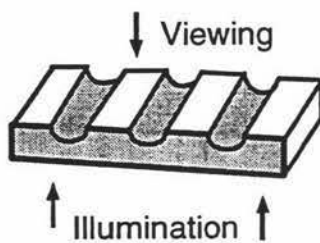
(b) View under microscope
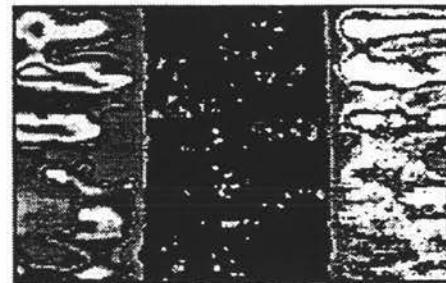
(c) Plating voids revealed

Figure 3.4   The backlight test

The micro-sectioning process is destructive and time-consuming. According to [DAW87], the repeatability, the time required to micro-section and the costs are the major problems of this manual operation. The task of producing acceptable micro-sections has been identified by manufacturers as being a major bottleneck [DAW87]. Typically it takes 1 to 2 hours to prepare a micro-section and requires a highly skilled operator [LEO81]. If applied incorrectly, this elaborate process could induce damage to the plating before inspection. The nature of the test also makes it difficult to automate the process [DAW87].

3.3.3.2   Non-destructive Testing

In contrast to the destructive testing, four non-destructive methods for testing through-hole plating have been found in the literature review. These are:

- **Manual inspection using PTH viewer**

  A PTH viewer is essentially a fish-eye lens that allows a 360-degree view of the hole wall from outside the hole. This instrument has been specially designed for the inspection of drilled and plated-through holes in PCBs. Obviously, trained inspectors equipped with this specialised tool and working under suitable illumination can readily report the presence of cracks or voids.

  The board to be inspected should be placed on a light-table or similar source of diffuse, below-surface, illumination. A typical viewer such as the Mexter™ is positioned on the board until a hole is at the centre of the field of view. By manually zooming in, the wall of a hole can be observed at various levels. The magnification of the viewer varies with the position of the zoom but the maximum is approximately x60. Holes up to a depth of 3 mm can be inspected.

- **Beta ray backscatter**

  This method relies on the emission of electrons from a metallic layer subjected to a beam of beta ray. The emission of electrons decreases with increasing plating thickness [LEO81,WIC87]. The actual arrangement is said to be rather complicated and careful calibration with known standards is essential. This method is reported as popular in the testing of precious metal coating such as gold [LEO81].

- **Micro-resistance**

  This method uses pulses of direct-current to measure precisely the true resistance of the through-hole copper barrels [WIC87,LAT93]. The resistance values involved are typically a few hundred micro-ohms. This method is sensitive in finding circumferential cracks but has limited capability in detecting small but significant voids scattered around the through-hole copper barrel.

- **Leakage light detection**

  This is a method that can be fully automated. Further description will be found in section 3.5.2.

3.4 INSPECTING STUFFED BOARD COMPONENTS

Stuffed boards are PCBs assembled with electronic components. According to [PAU90], the break-down of all electronic assembly errors is as follows:

- insertion errors   55%
- missing components   20%
- wrong polarities   15%
- wrong components   10%

It is reported that no vision systems for checking wrong component values such as reading resistor bands existed then [ROB89]. Table 3.2 lists several commercial stuffed board component inspection systems currently available:

Table 3.2 Some stuffed board component inspection systems

System	Inspection for	Hardware	Comments
CA/V-1000	missing components; component leads	CCD camera (128x128 pixels)	64 grey levels; 80 components /sec
ORS-1000	missing components	x-y table and CCD camera	template matching; inspects 90 locations per minute
Octek	component insertion; component polarity; reading IC part numbers	TV camera; positioning table	section-by-section scanning
CHECK-POINT PCB	component leads; missing, damaged or wrong components; reading IC part numbers	unknown	require specialised (CHECKPOINT) processors
IntellVue DR 2000	component leads; missing components; component polarity	unknown	uses component design rules for inspection
Fujitsu	rectangular capacitors and insertion, positioning and polarity	3 TV cameras; He-Ne laser	highly specialised expensive equipment

Source: [ZUE 87,AND88,ROB89]

These inspection systems are intended for high volume production facilities. Each system is designed for a very specific task. Completely automatic inspection of stuffed boards would mean major capital investment in a number of such systems to cover the wide range of possible assembly errors.

3.5   IMPROVING PLATED-THROUGH HOLE INSPECTION

In 1990, 92.1 percent of the US output of rigid PCBs were either double-sided or multilayer and worth 5 billion US dollars [FLA92]. In 1993, the European Electronic Component Manufacturers Association (EECA) reported that double-sided and multilayer technologies accounted for 80 percent of the total demand within the European Union PCB market valued at 3.5 billion Ecus [INT93].

Notwithstanding the advance of surface mount technology, a huge volume of PCBs having PTHs will be produced each year. Any improvements in the current methods of PTH inspection (excluding via holes in surface mount boards) will have prominent economic significance.

3.5.1 Disadvantages of Using Test Coupons

As mentioned earlier in section 3.1.4, there has been a study on the variation of through-hole plating quality across a panel. It is reported in [HAY89] that the use of test coupons could not truly reflect such variations unless the coupon-to-board correlation had been established properly. The article describes the effort and methodology used to tackle the problem. Approximately US $250,000 was eventually spent by the corporation towards establishing coupon-to-board correlation for a particular family of PCBs. This can be justified by the annual cost saving of about US $ 5 million for the high volume PCB manufacturer. As for the small volume manufacturers, this level of spending will be out of their reach. There are also economic considerations involved in setting up and running a coupon-based process control

system. Such facts are significant to the small PCB manufacturers and warrant the research in non-destructive methods for inspection of PTHs.

3.5.2 Leakage Light Detection

In reviewing the literature on PTH inspection, there have been very few publications on non-destructive methods. A "leakage light detection" system for inspecting PTHs is described in [AND88]. The principle of leakage light detection for PTHs is illustrated in figure 3.5.
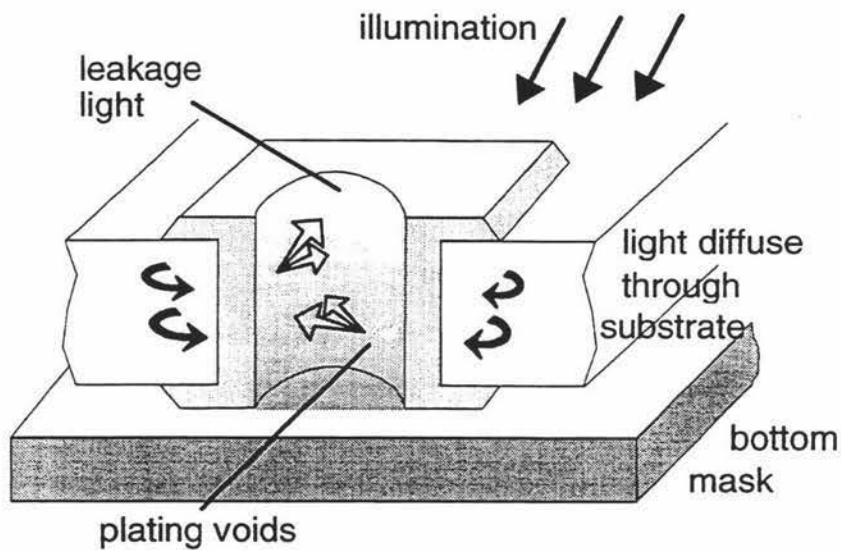
Figure 3.5   Detecting leakage light in defective PTHs

A PTH inspection system has been built and is reported to be in use by the major Japanese PCB manufacturer Fujitsu. The system detects voids, cracks and pinholes in the through-hole plating [AND88]. An area of 300 mm square can be inspected in three minutes. The major specifications for this PTH inspection system are:

Type of board	Multilayer
Size of board	300 mm square
Detectable defects	voids, cracks, pinholes
Speed of inspection	20s per 100 mm square of panel
Physical size of the system	1.4 x 1.6 x 1.3 m

3.6   DISCUSSION

From the literature review, a number of automatic visual systems exist for the inspection of PCB surface conductors and stuffed board component placement. In contrast, the conventional inspection of PTHs relies largely on the micro-sectioning method. This destructive method is the standard practice recommended by the industrial specifications such as the IPC-RB-276.

The absence of electroless voids is an important indicator of good quality PTHs apart from sufficient plating thickness (see section 3.3.2 on outgassing). Unconventional but non-destructive methods including the micro-resistance and beta ray backscatter are primarily directed at measuring the through-hole plating thickness rather than detecting the tiny and scattered voids. Manual inspection using a specialised viewer can only cope with a small output volume of PCBs. Even so the human visual inspection has certain limitations as already outlined in section 3.1.3. The Fujitsu leakage light detection system is automatic and carries out non-destructive inspection. However, this is a system designed for high output volumes and does not necessarily match the small to medium sized production facilities.

Consequently, researching new technology for PTH inspection has the potential of developing cost-effective inspection systems for the small to medium PCB manufacturers. The concept of applying image processing techniques for the non-destructive inspection of PTHs [MAK94], if proven practical in a real production environment, would be a most useful contribution to this subject. The research into this particular topic will be the focus of the next chapter.

PLATED-THROUGH HOLE INSPECTION USING IMAGE PROCESSING TECHNIQUES

This chapter reports on the experimental work targeted at the analysis of images obtained from PTH sections under a microscope. It will be shown that this approach has the potential to develop into a new and useful non-destructive inspection technique.

4.1 INTRODUCTION

Digital image processing is a mature technology which has found applications in many areas. Hodgson [HOD92] gives a wide range of examples on applications that are relevant to New Zealand. The non-contact, non-destructive nature of image processing is particularly appealing for inspection related applications. It is one of the technologies that could bring considerable economic significance to the PCB industry.

Structurally, the interior of a perfect PTH is a copper plated cylinder. This is often referred to as the copper barrel. Plating defects are violations of the integrity of the copper barrel. These defects are local unplated areas where the epoxy-glass substrate is still exposed even after the plating process (see section 3.3.1).

When illuminated, a given surface reflects and absorbs various amounts of light at different wavelengths according to the physical properties of the material and the condition of the surface. Metallic copper and epoxy-glass each reflects light in a distinctive way. Hence a copper barrel with plating voids will exhibit irregular spectral reflectance when compared to a fully plated copper barrel. The degree of irregularity will vary according to the area of plating voids. This hypothesis led to an investigation into the possibility of detecting any such irregularities. The first step was to measure the spectral reflectance of copper and epoxy-glass.

4.2 SPECTRAL REFLECTANCE MEASUREMENTS

4.2.1 Spectral Reflectance of Materials

The spectral reflectance of a surface can be defined as the distribution of returned light relative to the incident light at different wavelengths. Reflectance depends on the wavelength and the angle of incidence of the light, as well as the angle(s) at which reflected light is measured [MEY91].

Opaque materials reflect light in two ways. One is specular reflection and the other is diffuse reflection. Specular reflection depends mainly on the surface conditions of the material. Diffuse reflection is scattered and contains the absorption characteristics of the material. The spectral reflectance of materials other than highly polished surfaces are mainly diffuse reflectance and will vary selectively with wavelength [MEY91].

Measurements of spectral reflectance are made incrementally, wavelength by wavelength, relative to the reflectance of a calibrated standard. This eliminates the need to calibrate the spectral sensitivity of the detector. Spectral reflectance of materials is normally measured by a spectrophotometer.

4.2.2 Equipment

A spectrophotometer is the usual equipment for measuring spectral reflectance of materials. It records the spectral distribution of light reflected or absorbed relative to a standard reference sample at different wavelengths.

A Shimadzu MPS-5000 spectrophotometer was used. This equipment measures the absorbance of incident light relative to a standard reference. The reference sample is usually a piece of white filter paper. Percentage absorbance can be related to percentage reflectance by the simple subtraction:

$$\% \text{ reflectance} = 100 - \% \text{ absorbance}.$$

According to the Shimadzu Instruction Manual, a tungsten-iodine lamp is used as the light source for visible and near infrared wavelengths (320 to 2500 nm) and a deuterium source for the ultraviolet wavelengths (185 to 320 nm). The detectors are a photo-multiplier and a PbS cell. These are designated to operate in the UV-visible and near infrared regions of the spectrum respectively.

When working in the reflectometry mode, the spectrophotometer is designed to eliminate almost all specular reflections using mirrors and a light trap. A large fraction

of the diffuse reflections is captured by the large detecting surface of a photomultiplier placed closely to the sample as depicted in figure 4.1.
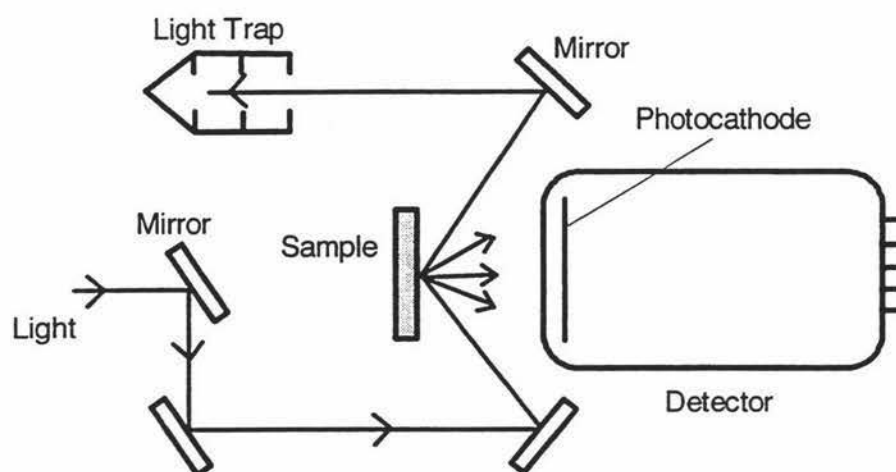
Figure 4.1   Principle of measuring absorbance by the MPS-5000

The manufacturer claims that this arrangement yields better results than those obtainable with an integrating sphere, particularly for glossy opaque samples. The range of incident wavelengths can be varied continuously within each of the selected working ranges:

1. UV (185 to 320 nm)
2. Visible and near IR (320 to 850 nm)
3. Near IR (850 to 2500 nm).

Measurements are recorded automatically in real time through an analogue chart plotter built into the system. No digital output of measurements is available.

4.2.3 Sample Preparation

Four slabs of material were taken from a standard single-sided FR-4 material 1.6 mm thick. Those labelled 1 and 2 were samples of the copper-clad surface. Samples 3 and 4 were two epoxy-glass samples. Sample 3 was the smooth substrate surface of the FR-4 material. Sample 4 was made by sticking together thin slices of cut substrate using an

epoxy resin adhesive. The unpolished cut edges of epoxy-glass jointly formed the surface of sample 4. Figure 4.2 illustrates the three types of surfaces represented by the four samples.

| Copper foil (1 & 2) | Smooth epoxy-glass (3) | Rough epoxy-glass (4) |
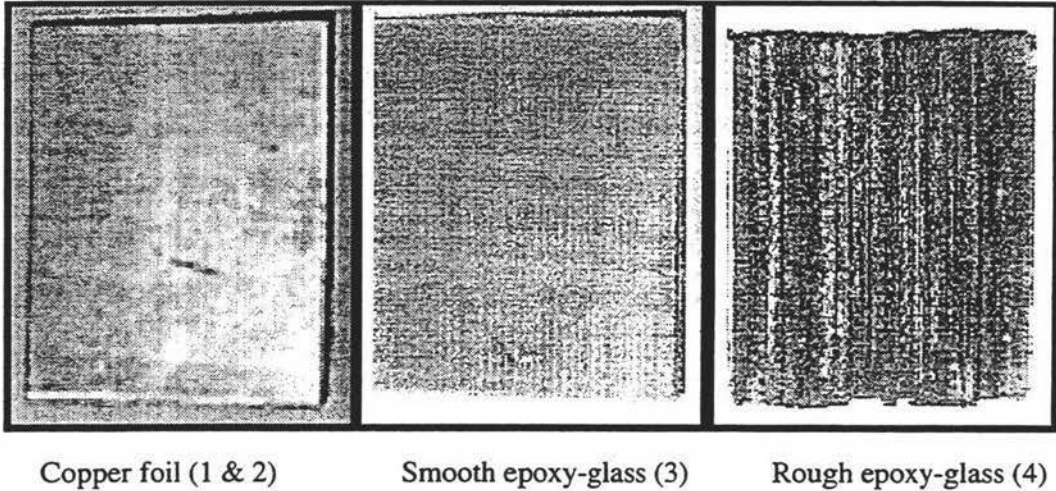
Figure 4.2   The four samples for absorbance measurements

The reasons for having two samples representing the epoxy-glass surface are:

- There is a varying degree of roughness in the drilled hole walls.
- The majority of plating voids are associated with exposed glass fibre: large and small voids are associated with the exposed lengths and cut ends of glass respectively (see section 3.3.3).

Sample 3 was intended to represent the surface of unplated smooth hole walls associated with the lengths of glass. Sample 4, which consisted of unpolished cut edges, was intended to model unplated rough surfaces that are associated with the cut ends of glass fibre. It is believed that the range of surface conditions of any unplated substrate would not normally exceed the extremes set by samples 3 and 4.

Samples 1 and 2 were taken from two different parts of the FR-4 laminate. By having two pairs of samples for each material, the extent to which spectral reflectance is affected by the surface roughness of either copper or epoxy-glass can be examined. All samples were cut into rectangular slabs of approximately 25 mm by 30 mm to fit into the sample slot of the spectrophotometer.

4.2.4 Results

Measurements were taken when the incident light varied from violet to near infrared (or 350 to 800 nm in wavelength). Two independent measurements were made for each sample and were compared. It was found that:

Result 1   The two measurements for each sample agreed to within 2 %.

Result 2   The measured spectral absorbance of the two copper samples (samples 1 and 2) agreed to within 6 %.

Result 3   The two epoxy-glass samples (samples 3 and 4) had similar variation of spectral absorbance within the sensitivity of the spectrophotometer. But the actual absorbance values between these samples at the same wavelength were different (see figure 4.3 below). The smoother surface, or sample 3, had lower values. This difference diminished as the wavelength was increased to the near IR region.
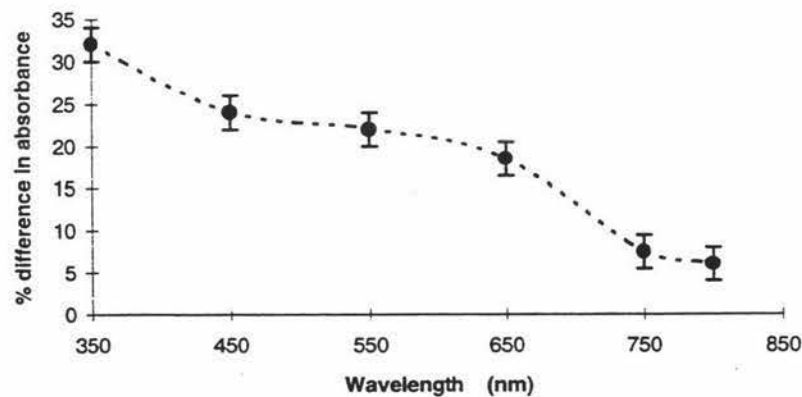
Figure 4.3   **Difference in spectral absorbance between rough and smooth epoxy-glass surfaces**

Result 1 demonstrates that the spectrophotometer performance had been consistent. Result 2 shows that the two copper samples had very similar surface conditions. Result 3 suggests that rough and smooth epoxy-glass surfaces have similar characteristics in spectral absorbance (or reflectance). Variations in surface roughness affect the magnitude but not the change in absorbance (or reflectance) across the incident light spectrum. The smoother the surface, the more light it reflects. The results for copper and rough epoxy-glass are superimposed and summarised in figure 4.4:
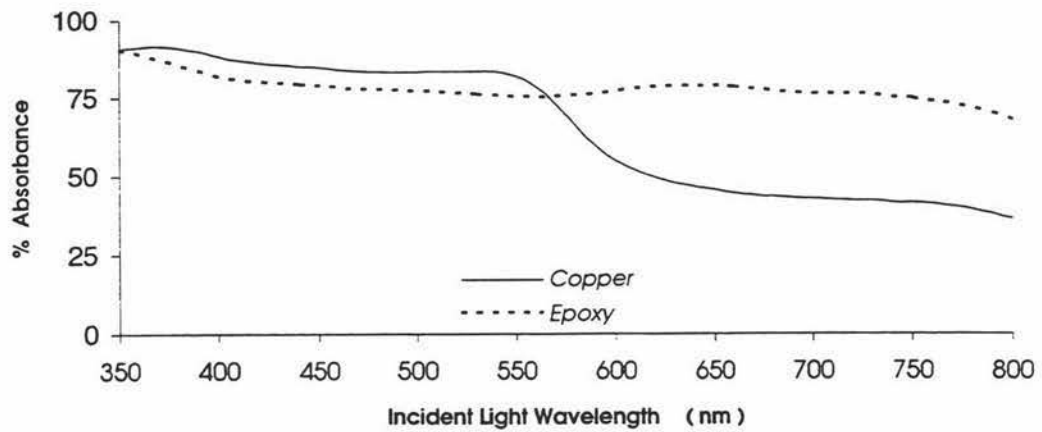
Figure 4.4   Spectral absorbance of copper and epoxy-glass

As seen from the above graph, a comparatively significant difference in spectral reflectance exists between metallic copper and epoxy-glass from 650 to 800 nm. This range is represented by the red and near IR region of the electromagnetic spectrum. It can be concluded that copper reflects red and IR radiation more strongly than epoxy-glass does. This result is perhaps not unexpected given the reddish colour of the fresh copper plating.

4.3   METHODS TO DISCRIMINATE BETWEEN PLATED AND UNPLATED REGIONS

The ultimate objective of having any machine vision inspection systems is to recognise accurately any defects deemed to be unacceptable according to the specifications. This task has to be accomplished within a reasonable duration of time. A secondary but certainly important function of an inspection system is to provide additional information, such as indications of the nature and locations of the defects. In through-hole plating quality assessment, the ultimate objective translates into discriminating between plated and unplated regions within a PTH in the shortest possible time.

As already shown in section 4.2.4, there is a relatively large difference in spectral reflectance between copper and epoxy-glass at wavelengths 650 to 800 nm. This difference offers a possibility to differentiate between the two types of surfaces. In the

case of PTHs, the smallest plating voids to be detected are tiny pockets of exposed ends of glass fibre engulfed in much larger areas of copper. The dimensions of such voids can be 20 μm across [HOW86], depending on the diameters of the glass fibre in the material. However, the intrinsic difference of plated and unplated surfaces in reflecting light creates certain features that can possibly be extracted and classified.

4.3.1 Sample Preparation

Double-sided PCBs of 1.6 mm thickness with PTHs of 1 mm diameters were used. The PCBs have been plated with electroless copper and then sectioned into thin stripes containing a row of half PTHs. These samples were identical to the those intended for the backlight test as already described in section 3.3.3.1.

4.3.2 Equipment

The essential equipment consisted of:

- A microscope at X10 magnification
- A sample holder specially designed to hold the sample stripe under the microscope lens
- A high power cold light source with a flexible circular light guide
- A colour CCD camera fitted to the microscope
- A Macintosh Quadra computer with SCION frame grabber and NIH Image software.

4.3.2.1 Light Source

The Schott KL 1500 cold light source was employed to illuminate the samples. This equipment uses a halogen bulb, operating at around 3000 K colour temperature. At this temperature a substantial proportion of the output will be in the near IR spectrum [WAK86]. The light intensity can be regulated without change in colour temperature. Standard optical filters or user-made special optical glasses may be fitted into the light

source, provided they are of the specified dimensions. Output light is delivered through optical fibre light guides. At the light guide outlet the maximum illumination is 10 Mlx.

4.3.2.2   CCD Camera

A CCD is basically an integrated circuit consisting of an array of photosensor sites that converts incident photons into electrical charge. The charge is proportional to the amount of light absorbed [SCH94]. A row of photosensor sites can be seen as a shift register of capacitors. Each of these holds a charge proportional to the incident light and can be shifted to one end of the row to be read. The CCD has evolved from its earliest form of a simple 8-bit shift register into a complicated integrated device suitable for various imaging applications. It has already out-performed photographic films in sensitivity, spectral range, stability, dynamic range and linearity [SCH94].

The CCD camera used was the Ikegami ICD-835 single chip colour CCD. According to the instruction manual, the camera uses the interline transfer architecture. This arrangement consists of a parallel array of line sensors separated by a transfer electrode from masked CCD read-out registers that lead in parallel into a single output register [SCH94]. The entire image from the line array is shifted simultaneously into read-out registers. The main advantage of this arrangement is fast image read-out. A new image is integrated while the previous one is being read. The camera is equipped with built-in colour filters for capturing colour images. The single chip CCD contains 390,000 pixels.

4.3.2.3   Frame Grabber

The primary function of a frame grabber is to digitise video frames from an imaging device such as the CCD camera. The output from a CCD camera is typically an analogue composite signal that conforms to a certain video standard. This analogue signal needs to be digitised by the frame grabber as a frame of pixels before it can be processed by a computer.

The SCION LG-3 was the frame grabber used for the work. It is designed for the use with RS-170 (or CCIR) CCD cameras and RGB video sources. When connected to an RGB source, the LG-3 can capture frames from each of the colour signals. The LG-3 performs 8 bit (256 levels) analogue to digital conversion. If the incoming signal is greater than or equal to the upper limit of input voltage, it will receive a digital value of 255; conversely, an input less than or equal to the lower limit of input will be assigned a digital value of 0.

The limiting voltage levels can be controlled by adjusting the analogue offset and gain of the digitisation process. For example, if the video signal is low, the limits may be lowered to "brighten up" the captured image. Similarly, if the input signal has poor contrast, the voltages can be squeezed together to increase the overall contrast in the captured image. After digitisation, some processing can be done on the digital image using a look-up table. A look-up table maps each of the possible pixel values to a new value. Up to eight input look-up tables are provided on the LG-3. Each may be read, written and used for processing the incoming video signal.

Some specifications for the LG-3

Video signal type: RS-170 or CCIR

Digitising speed: 1/30 s (RS-170); 1/25 s (CCIR)

Image resolution: 640x480 (RS-170); 768x512 (CCIR)

Capture mode: field or frame

Source: SCION LG-3 Technical Manual

4.3.2.4   NIH Image Software

NIH Image is a public domain image processing and analysis software for the Macintosh. It can acquire, display, edit, annotate, enhance, analyse, print and animate images. The software reads and writes a range of image file formats including TIFF, PICT, PICS and MacPaint. NIH Image supports many standard image processing functions such as histogram equalisation, contrast enhancement, edge detection, median filtering, density profiling and spatial convolution with user defined kernels up to

63x63. More complicated image processing functions including morphological operations can also be implemented. The software incorporates a PASCAL-like macro programming language to automate complicated and frequently repetitive tasks.

The LG-3 will initially process the digitised image by inverting the pixel values to make the image compatible with the NIH Image software. In contrary to the usual practice, this software interprets grey scale values with black as 255 and white as 0.

4.3.3 Image Capture

The samples need to be illuminated by incident as well as back light. Incident light was provided by a flexible circular light guide placed directly above the sample. Back lighting was achieved by the built-in illuminating system of the microscope underneath the sample. The images captured under incident and back illumination are referred to as the frontlit images and the backlit images respectively. Figure 4.5 shows the setup for image capture under a microscope.
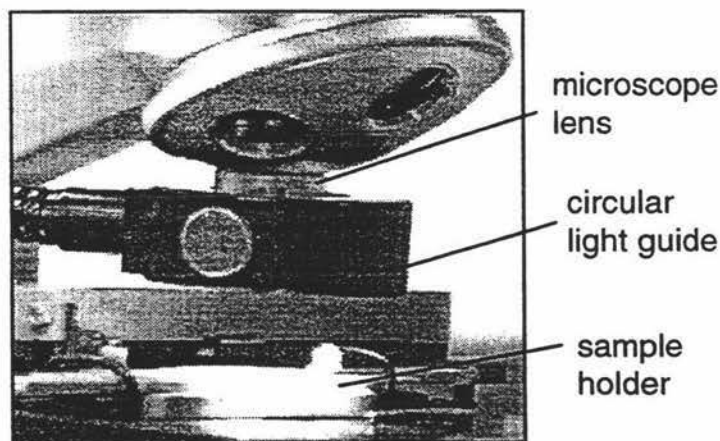
Figure 4.5   Setup for image capture under a microscope

A pair of frontlit and backlit images for each sample was captured. Although only the frontlit images are analysed, the results need to be verified using the corresponding backlit images. Each sample was placed under the microscope. At a magnification of x10, the microscope will have less than 0.3 mm depth of focus. Since the samples were half-holes of approximately 0.5 mm depth, focusing was aimed at the bottom part of the

groove while the upper parts remained out of focus. Figure 4.6 depicts the portion of each sample being in-focus. Effectively an area covering about 75 percent of a sample could be captured.
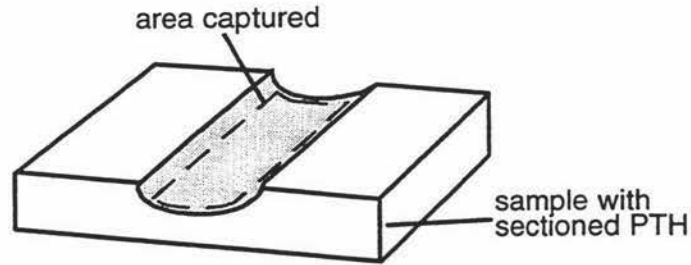
Figure 4.6   Area of a sample to be captured

A backlit image of the sample was first captured using back illumination. Then with front illumination turned on and back illumination turned off, a corresponding frontlit image was captured. For perfect matching of the pair of images, no relative motion between the camera and the sample was allowed during the entire process. This procedure was repeated for a number of samples. A typical image pair is shown in figure 4.7.
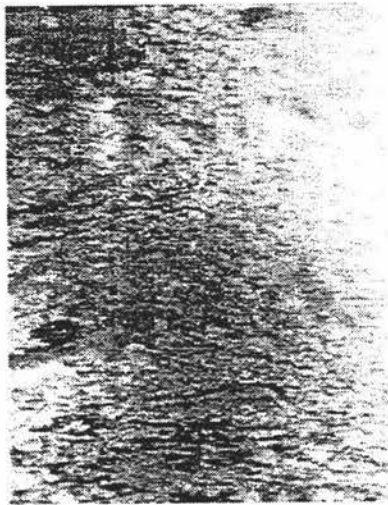
(a) frontlit   *(b) backlit*

Figure 4.7   A pair of captured images

Since subsequent analysis could involve images at different wavelengths of the visible spectrum, a colour CCD camera was used. The NIH Image software provides a

function to separate a colour image into its red, green and blue components if that is desirable.

4.3.4 Image Enhancement Analysis

It can be hypothesised that some correlation exists between a pair of frontlit and backlit images of the samples taken. When reflectance properties are concerned, at the visible red band of the spectrum, unplated regions (exposed epoxy-glass) should appear relatively dark against the plated copper. This reasoning led to the application of image enhancement techniques to the red component of frontlit images to highlight those dark areas. The actual processing was implemented by the NIH Image software in PASCAL like macro commands. Appendix 4-1 gives the listing of macros for the image enhancement method.

Figure 4.8(a) shows the red component of a frontlit image covering a PTH section. The result of enhancement is given in figure 4.8(b). The dark regions indicate problem areas of the plated surface. This pattern can be compared to the actual plating voids as revealed by the backlit image, figure 4.8 (c).

(a)   (b)   (c)
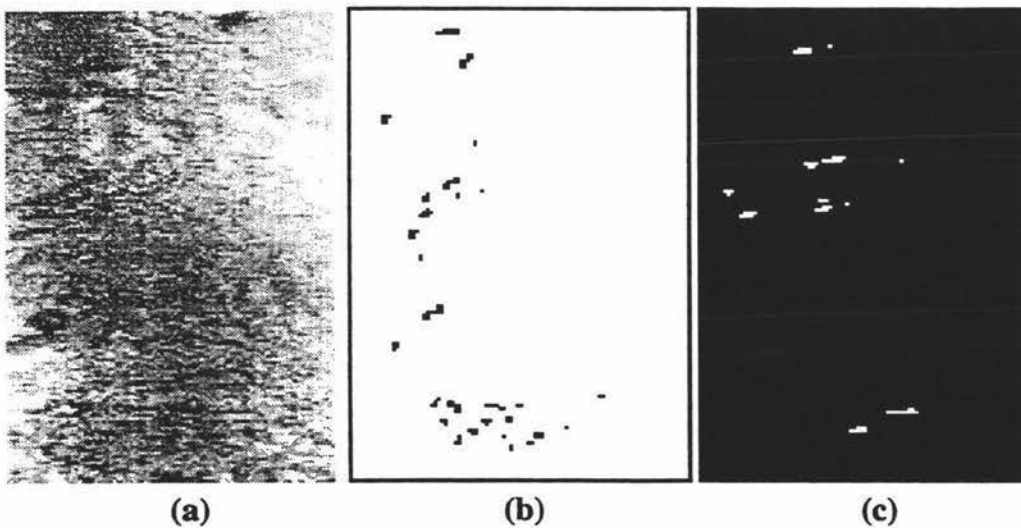
Figure 4.8   Image enhancement result compared to the actual plating voids

The pattern in figure 4.8(b) does not constitute an exact match to the voids shown as white in figure 4.8(c) but is fairly close for some of the voids to be detected. It indicates that the current image enhancement techniques still need some refinement. This method

is also sensitive to uneven illumination. To ensure repeatable and reliable results, illumination must be carefully controlled to minimise the presence of shadows when the frontlit images are captured.

The same technique had been applied to the green and blue components of the frontlit samples taken under white light. Results were much less promising than the red component. It confirmed with the deductions from spectral reflectance measurement that images at the red band of the visible spectrum should yield the best discrimination.

4.3.5 Local Histogram Analysis

The variation of light intensity in the frontlit images can be analysed using histograms of pixel intensity values. Essentially each histogram is a frequency distribution of intensity levels within a clearly defined area on an image, or the region of interest (ROI). This distribution varies according to conditions such as illumination, material and surface roughness. Every histogram has certain features that can be analysed. Jain [JAI89] provides a list of common histogram features which includes moments, dispersion, mean, median, mode, variance, mean square value, skewness and kurtosis.

In the case of PTHs, the presence of defects will affect the distribution of light intensities and hence some of the associated histogram features. Consequently the histogram for an unplated surface will exhibit certain features as distinct from the histogram for a surface that is completely plated with copper. These distinctive features can be regarded as signatures associated with either the plated or unplated surfaces. By plotting the appropriate histogram features in multi-dimensional feature space, a plating void may be readily recognised by its characteristic signature. Industrial applications of this technique have been found in the literature; one example is the inspection of IC and LSI (large scale integration) packages for potential defects such as holes, hollows and protrusions [EJI89].

In applying this technique to PTH inspection, the first step is to extract certain histogram features from the frontlit images and to construct the signatures associated

with the plated and unplated surfaces. Initially a total of 87 sample ROIs were taken from different frontlit images. The corresponding backlit images were used as templates to guide the selection. In this way, each ROI can be classified as plated or unplated. The optimum ROI size suitable for discriminating between the two types of surfaces was found to be 55 pixels. The method used to establish this number is outlined in appendix 4-2. The histogram features useful for constructing the signatures were found to be the sample size, the range (the number of grey levels or contrast) and the standard deviation (S.D.) of the pixel intensities. These features were then extracted from the histograms of those ROIs that consisted of more than 55 pixels. Data from 45 samples are plotted into a 2-dimensional scatter diagram as shown in figure 4.9.
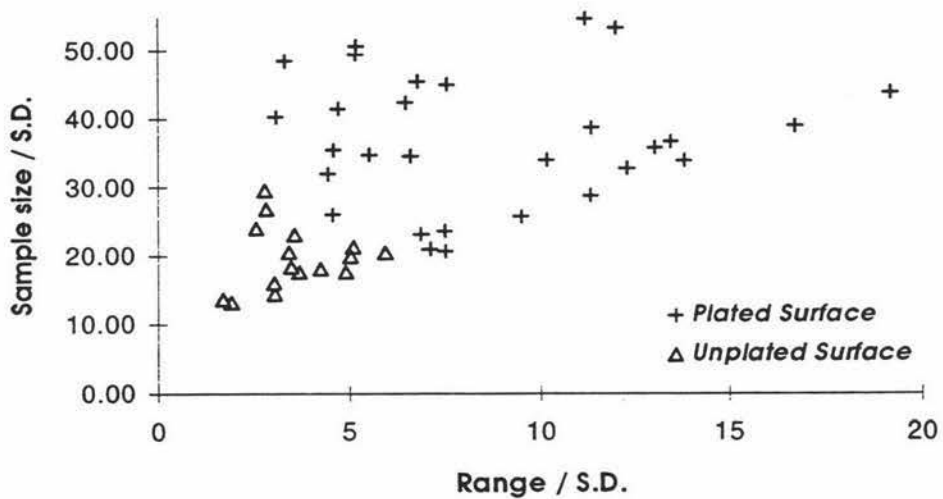
Figure 4.9   Scatter diagram for classifying plated and unplated surfaces

It is observed that the plated and unplated regions fall into two distinct groups. By plotting a large amount of data obtained from different PTH samples, the boundaries of the plated and unplated regions in the diagram will be defined more clearly.

4.4   DISCUSSION

Both the techniques described in sections 4.3.4 and 4.3.5 require a frontlit image of a PTH. The image enhancement technique is a straight forward strategy that uses the variation of pixel intensities to identify the presence or absence of specific features on

the entire image. It seeks to highlight the difference in reflectance between plated and unplated surfaces.

The local histogram analysis technique partitions the captured image into smaller ROIs each consists of at least 55 pixels. The selected local histogram features are plotted for every ROI. Each entry in the plot will be classified as a normal or defective surface according to its location in the feature space. This classification is expected to be more accurate after the boundaries separating the plated and unplated regions have been established more precisely using a larger number of samples.

As in all image processing applications, the quality of the acquired images is vital to the subsequent analysis. The techniques described are subjected to the following practical constraints:

- **Evenness of illumination**

  The image enhancement technique is particularly susceptible to any shadows present in the captured image. This is because the method seeks to highlight areas reflecting less light as defects. Given the dimensions and geometry of PTHs, it is difficult to arrange for uniform incident illumination without the problem of image shading.

- **Focusing**

  The microscope used has less than 0.3 mm depth of focus at the magnification of x10 (see section 4.3.3). Hence only about 75 percent of the area in each sample can be captured and hence analysed. Should a higher magnification be desirable, the depth of focus will be further reduced. The use of two or more images at different depths of focus is required to build up a series of image sections covering the entire plated surface. Alternatively, confocal scanning light microscopy [RUS92] can be employed to overcome the problem.

- **Resolution of the images**

  The required resolution will depend on the dimension of the smallest void that needs to be detected. Such small voids are invariably associated with the exposed ends of

glass fibre [LEA86c]. According to [HOW86] this should be no greater than 20 μm across. For the image enhancement technique, a reasonable minimum requirement would be having two pixels to represent such an area of void. An image of a typical PTH copper barrel (5 mm^2 in surface area) will hence contain a minimum of 32,000 pixels. This can be handled sufficiently by the 390,000 pixels per frame capacity of the CCD camera.

As in the case of the local histogram analysis technique, it requires a minimum of 55 pixels for each ROI. Suppose a ROI of 55 pixels is used to cover an area 20 μm across, a typical PTH image will then contain approximately 880,000 pixels. This situation not only demands a higher magnifying power of the imaging system, but also requires more than two camera frames to cover a complete image of the hole wall. If a higher resolution is desirable for raising the defect reporting confidence, more pixels must be processed hence the more time it takes to inspect a PTH.

- **Time required to inspect a PTH**

  A typical PCB may have hundreds if not thousands of PTHs depending on the circuitry design. Even if one PTH can be inspected in one second, it will take 15 minutes to inspect 900 holes. This is common to any inspection system that evaluates the quality of PTHs one at a time.

4.4.1 Prospect for a Prototype Inspection System

One major advantage in applying image processing techniques to inspect PTHs is that the information about the locations and dimensions of the defective features can be obtained. This will be useful for identifying the possible causes of the defects.

The results obtained from the work described in this chapter have demonstrated that there exists the potential for applying image processing techniques in assessing the plating integrity in PTHs. However, further refinement of the method of analysis is deemed necessary to improve the reliability of defect detection. In particular, before a

prototype non-destructive inspection system for PTHs can be constructed, the following problems will have to be resolved:

- A viewing device will be needed which enables image capture of the interior of a PTH with suitable resolution, perhaps similar to the Mexter™ viewer described in chapter 3, section 3.3.3.2.

- A lighting system delivering suitable incident illumination inside a PTH while an image of the hole wall can be captured.

These technical difficulties demand investment in acquiring new equipment if a practical inspection system for PTHs has to be developed. The next chapter will describe the search for other schemes for the non-destructive inspection of PTHs.

ALTERNATIVE SCHEMES FOR NON-DESTRUCTIVE INSPECTION OF PLATED-THROUH HOLES

Various alternative schemes that might develop into non-destructive inspection methods for plated-through holes have been considered. This chapter is a description on how these ideas have evolved and explains why some of the ideas are not practical when applied to the inspection of PTHs.

5.1   THE PCB PANEL AFTER ELECTROLESS PLATING

A PCB panel immediately after the electroless process is covered entirely by copper. If the plating process has been successful, no substrate will be exposed anywhere on the panel, including the hole walls.

However, due to possible drifts in the manufacturing process, the coverage of copper may not be complete. The objective in carrying out the inspection after the electroless process is to detect such defects.

5.2   PENETRANT FLAW DETECTION

Penetrant flaw detection methods have been widely in use for detecting surface discontinuities [BIC75,BET86,HAL91]. Penetrants are usually solutions of coloured or fluorescent dyes that must be compatible with the material being inspected. This technique can be very sensitive and extremely fine cracks of 1 μm width may be detected [HAL91].

At first thought, fluorescent dye seems to be a suitable penetrant for detecting PTH voids. It is because the dye would give off light in response to incident radiation such as UV [BET86]. If fluorescent dye is applied to the walls of the drilled holes before plating, any subsequent unplated areas inside a PTH could possibly be revealed by exposing the hole wall to UV radiation.

However, some components in the penetrant are also solvents, and these may attack certain resins [BET86] including the epoxy resin that is abundant in the PCB substrate. In addition, the fluorescence of dyes is seriously affected by contact with acids and acid vapours [BET86]. Given the process of the electroless plating (see appendix 2-3), the contact of fluorescent dye with acids cannot be avoided. This has rendered the idea of using fluorescent dye unworkable.

5.3   ELECTROMAGNETIC RADIATION AS PENETRANT

The use of penetrants to detect surface defects usually has one disadvantage. It is the need for pre-cleaning the surface to be inspected and removal of the penetrants after test [BIC75,BET86,HAL91].

A defective PTH can be thought of as a copper barrel having voids on its walls that allows certain radiant energy to leak through. The radiant energy therefore acts as a suitable penetrant that does not require pre-cleaned surfaces and the subsequent process of penetrant removal. Any type of radiation suitable for PTH inspection will have to satisfy the following criteria:

- it penetrates the substrate material to a certain distance
- it is effectively blocked off by the copper plating
- it can be conveniently generated and detected.

Ordinary visible light, laser light, microwaves and the radio waves have been considered. The remaining chapter will describe attempts to utilise these types of electromagnetic radiation to inspect PTHs.

5.4   VISIBLE LIGHT

An inspection system for PTHs using the method known as leakage light detection has been outlined in section 3.5.2. Visible light is an obvious first choice as the penetrant. It is readily available and is cheap to generate when compared with other forms of electromagnetic radiation.

5.4.1 Experiments

Two types of visible light were used in the experiments, ordinary or incoherent light and a red laser light. The objective was to measure the distance of penetration of both

ordinary light and laser light in the widely used PCB laminate FR-4. The equipment used were as follows:

- A Schott KL 1500 cold light source with flexible light guide operating at full power
- A 35 mW He-Ne pulse laser source (wavelength centred at 632 nm)
- A CCD camera
- Macintosh Quadra computer
- Two test panels, one was a single copper-clad material FR-4, the other was a slab of substrate material (epoxy-glass).

Two rounds of experiments were conducted. At first, ordinary white light from the cold light source was used. The same set of experiments was later repeated using the laser source. Each of the two panels had two of its four edges polished using sandpaper. The other two edges remained unpolished.

Experiments were carried out in a dark enclosure. Light was directed at the four edges of each rectangular panel at several angles. The CCD camera was used to capture images of the light penetration into the substrate. This camera requires a minimum illumination of 3 lx at an aperture of F1.4 for image registration. The maximum distance of penetration as recorded by the camera was marked on the panel and then its distance from the edge of the panel was measured.

5.4.2 Results

It was found that:

- For the single copper-clad panel, the distances of penetration ranged from 25 to 30 mm for ordinary light; 35 to 40 mm for laser light.
- Entry of light into the substrate through a polished edge consistently resulted in a slightly longer distance of penetration.
- For the panel consisted of substrate material only, the distance of penetration was about 20mm for ordinary light and 30 mm for laser light. No significant difference was noted when the different edges of a sample were subjected to illumination.

- The maximum penetration occurred when the light beam was perpendicular to the edge of the test panel.

In one occasion when laser was directed at about 70 degrees to a polished edge of the single copper-clad panel, the red light entered the cut end of a glass fibre and was observed to emerge from the opposite edge of the panel. The distance between the edges was 75 mm. This phenomenon occurred only once and was not repeatable. No systematic method in choosing a similar cut end of glass fibre to produce the same effect appeared to exist.

These results indicate that:

- The presence of copper foil on one surface of the panel increases the penetration distance of the light. This is probably due to reflections from the metallic surface prevent escape of light from the substrate.
- The greater distance of penetration for the laser light suggests that the laser source performs better than the cold light source among the available equipment. If it had been possible to increase further the intensity of the cold light source during the experiment, the distance of penetration for ordinary light would have been increased accordingly.

Apart from the indications above it should be noted that the spectral characteristics of the two light sources are very different. While the laser emits red light centred at 632 nm, the cold light source provides a wide range of wavelengths across the visible and possibly part of the near IR spectrum. It is therefore important to know how light of different wavelengths is transmitted or absorbed in the epoxy-glass substrate.

5.5   SPECTRAL TRANSMITTANCE

The laser used in the experiment emitted red coherent light (wavelength centred at 632 nm). Therefore, the estimated distance of penetration is valid for light at that wavelength only. It would be possible to increase the distance of penetration further if

the transmittance characteristic of epoxy-glass as a function of incident light wavelength is known. Then both the radiant source and the detector could be selected according to the desirable spectral sensitivity distribution to match the maximum transmittance of the substrate material.

5.5.1 Transmittance of Light in Epoxy-glass Substrate

According to [BOO93], the spectral transmittance of a medium is defined as the ratio of the transmitted flux through the medium to the incident flux at a particular wavelength. Spectral transmittance can be measured using a spectrophotometer. A description of the spectrophotometer can be found in section 4.2.2 on absorbance measurements. The equipment used was identical to those already described, except that it was set up to measure transmittance.

The sample used was a slab of epoxy-glass material fitted into the sample slot of the spectrophotometer. The light source was scanned automatically from 200 nm to 1100 nm. Figure 5.1 shows that the graph of transmittance varies as a function of wavelengths.
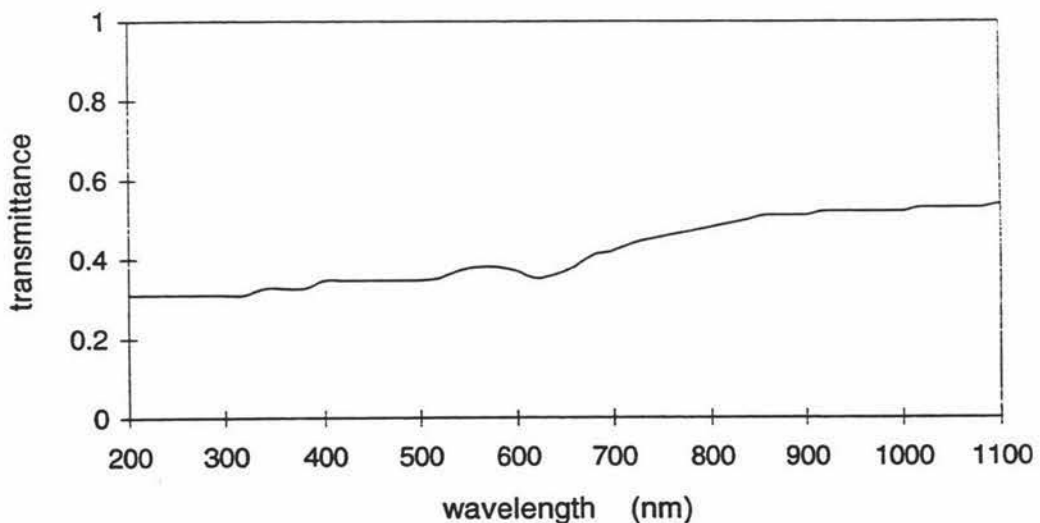
Figure 5.1   Spectral transmittance of epoxy-glass

It can be observed from the above graph that:

- Transmittance increases progressively from the UV region (the lowest value at 200 nm) to the IR region (peak value at 1100 nm) of the spectrum
- The increase of transmittance is most significant between 620 and 700 nm, within the red region of the spectrum
- The value of transmittance at 632 nm (wavelength of the laser) is roughly 20 % less than the peak transmittance recorded at 1100 nm.

Compared with the results from section 5.4.2, it can be deduced that the distance of penetration for an IR source having the same intensity at 1100 nm will be larger than 40 mm. Experiments to confirm this prediction have not been performed due to the lack of radiation sources with the required power at 1100 nm or in the near IR region.

5.6 MICROWAVES

The microwave region of the electromagnetic spectrum begins at roughly 1 GHz and extends up to 300 GHz. Microwave radiation can be generated by a klystron or magnetron with a waveguide coupling or antenna. The detector may be a silicon crystal, a detector horn-shaped antenna, cholesteric liquid crystals or even a specially prepared photographic film [HAL91].

5.6.1 Preliminary Conjecture

Conducting materials such as copper, are practically opaque to microwave radiation. However, microwaves can propagate in a dielectric medium such as epoxy-glass material which is a common PCB substrate. A PCB panel may be thought of as a thin, flat slab of dielectric waveguide for microwave radiations. The substrate allows the microwave energy to propagate inside the panel. Depending on the thickness of copper, the radiation may be confined by the copper foils on both surfaces of the laminate and the plated copper inside the PTHs.

The widely used double-clad laminates for double-sided PCB manufacture have a copper foil thickness of at least 35 µm as specified in the IPC-D-275 design standard. The usual plating thickness of PTHs is at least 20 µm (refer to section 2.4.1.2).

An expression is given in [JOR68] for the skin depth or depth of penetration of electromagnetic radiation into a good conductor such as copper:

$$\delta \approx \sqrt{\frac{2}{\omega\mu\sigma}}$$

where δ : depth of penetration
ω : angular frequency of radiation
μ : conductivity of copper, 5.8×10^7 mΩ^{-1}
σ : permeability of copper, $\approx 4\pi \times 10^{-7}$ Hm^{-1}

If the frequency of radiation is 3.6 MHz which makes $\omega = 2\pi \times 3.6$ MHz, then δ is roughly 35 µm. This frequency is in the radio waves region and the skin depth will decrease as the frequency of radiation increases. For example, at 100 MHz, δ becomes 6.7 µm, only a fraction of the thickness of the copper foil. This frequency is still below the lower end of the microwave spectrum. Therefore, the laminate can be treated as a waveguide for microwaves without leakage at its surfaces.

If arrangement can be made to send microwave radiation into the substrate through the edges of the panel, it is perhaps possible to detect any leakage of energy inside a defective PTH. The reasoning is that at places where plating voids occur, the substrate will be exposed. These voids may be thought of as small apertures between two types of waveguides. The laminate acts as a flat rectangular waveguide while the defective PTHs as tiny cylindrical waveguides. Microwave energy contained in the laminate may leak through small apertures by diffraction. Such localised leakage can probably be detected as an indication of defective plating.

5.6.2 Expert Advice

Expert advice on this conjecture was sought. Appendix 5-1 shows a list of answers in reply to the approach described in the last section. It was prepared by a microwave

expert, Dr Rick Keam, from the Microwave Engineering team of Industrial Research Limited, Auckland. The key points are summarised below:

- Although it is possible to send microwave radiation into the PCB substrate through the edges of the board, the PTH copper barrels would appear as inductive scatterers rather than waveguides.

- Given the dimensions of a PTH, any microwave energy that is coupled into it will be below the cutoff frequency.

- The required frequency of radiation to leak through a typical plating void will be higher than the microwave frequencies.

It is concluded that microwave techniques cannot provide a practical solution to the problem of detecting defects in PTHs.

5.7 RADIO WAVES

The radio waves occupy a wide range of the electromagnetic frequencies. They extend from very low frequencies (VLF) of several KHz to the short waves (SW) of several MHz, to very high frequencies (VHF) and ultra high frequencies (UHF) at hundreds of MHz.

It follows from the discussion on skin depth that the radio wave frequencies below 3.6 MHz will obviously not be suitable for PTH leakage energy detection. The radiant energy can leak out from the thinner (20 µm) electroless copper-plated hole wall even if there is no void. Also as given in [THU92], if the diameter of a circular aperture is less than half the wavelength of radiation, any leakage through the aperture will be rapidly attenuated. The wavelength of the shortest radio wave is in the order of centimetres. This is very much larger than the dimension of many plating voids which is in the order of ten's or hundred's of micrometres. Consequently at higher radio frequencies, there will be no leakage of energy to be detected. This deduction is consistent with the advice given by the microwave expert presented in the last section.

5.8   DISCUSSION

Either visible light or near IR radiation can be used as a penetrant for detecting defects in PTHs. A PCB panel immediately after the electroless process is covered entirely by copper. By cutting the edge of a panel and illuminating the substrate with light, a defective PTH is identified by the presence of leakage light inside the hole. But with little more than 40 mm distance of penetration, the application of this technique will be severely restricted to small boards 40 mm in width.

One possible approach to extend this method to larger panels is to illuminate the copper barrels of PTHs individually and detect leakage energy at the nearest edge of the panel from the hole. A practical arrangement for this scenario would be to employ two sensors at opposite edges of a panel. Leakage energy from any PTHs can be detected at either one or both edges. Inspection of panels up to 80 mm in width is possible.

Another obvious way to improve the situation is to increase the intensity of the illumination. However there are practical limits to the level of power that can be used. In the case of laser, there will be a point beyond which increasing the power would generate excessive heat and result in damaging the panel. Whether the source is ordinary light, laser or IR, it is preferable to have the incident radiation arranged in short but very intense pulses. This has the advantage of overcoming the effect of ambient light by coupling the detection electronics to the frequency of the pulsing radiant source.

A CCD camera was used in the experiment described in section 5.4.1. Its function was merely a light sensor. Better results will be achieved if a more sensitive photodetector is available. If such experiments are to be pursued in the future, it may be worthwhile to use an image intensifier synchronised with a pulsing light source.

A suitable device could be a single channel electron multiplier or a microchannel plate. A channel electron multiplier is a hollow glass tube typically 1 mm in diameter. The tube is coated on the inside with a resistive film of a secondary-emitting material. With

an applied electric field across the film, a photoelectron that enters the tube and strikes the coated side wall will generate secondary electrons. These in turn multiply and accelerate along the tube in an avalanching process. The current gain can reach 10^8 for a 3 kV electric field [DEN86] for this type of multipliers.

A microchannel plate is a large bundle of single channel electron multipliers used as a high gain image intensifier. In that situation each channel has been scaled-down and the diameter can be reduced to 10 μm [DEN86].

PLATED-THROUGH HOLE INSPECTION USING LEAKAGE LIGHT DETECTION

A practical PTH inspection system using the leakage light detection technique is already in use by the major Japanese PCB manufacturer Fujitsu (section 3.5.2). This chapter first reports on the technique with a view to the development of a low cost alternative suitable for the small batch PCB manufacturers. A demonstration system for PTH inspection using leakage light detection is then described.

6.1 LEAKAGE LIGHT DETECTION

It follows from the last chapter that visible light is a suitable penetrant for detecting voids in PTHs. This method is therefore referred to more precisely as leakage light detection (LLD) for PTHs and can be considered as a visual inspection method. It has the merits of eliminating complications such as surface pre-cleaning and removal of penetrant after test.

6.1.1 The Principle

With the surface of a PCB illuminated and both ends of a PTH masked, light diffuses into the substrate. If the masked through-hole has defective plating, the external light will leak into the hole. The leakage light inside may be detected by a suitable sensor. Figure 3.5 in chapter 3 has already illustrated this scenario. The Fujitsu inspection system uses this configuration [AND88]. Another possible configuration implementing the same principle is shown below:
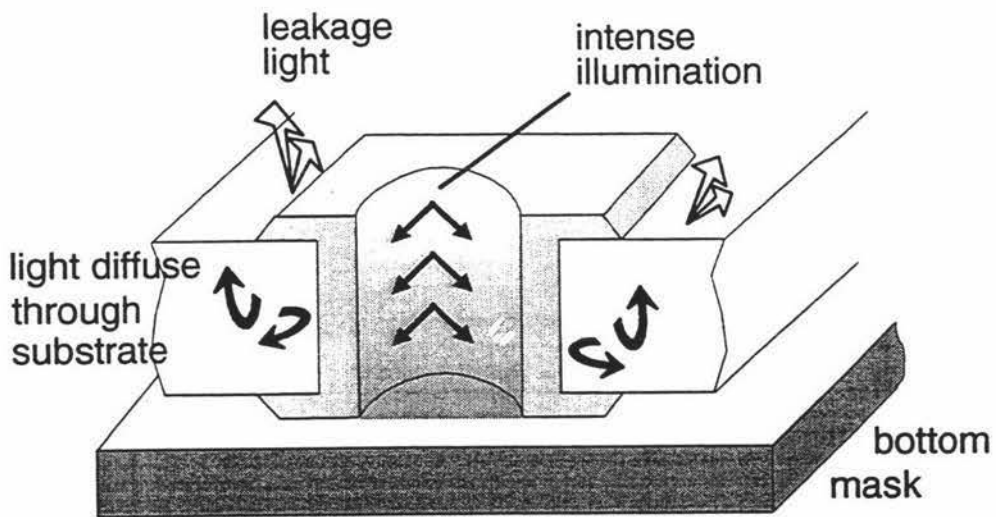
**Figure 6.1   Alternative arrangement for detecting leakage light
in defective plated-through holes**

In figure 6.1, a light source is illuminating the masked PTH internally. Plating voids allow the light to leak into the substrate. Not all the light will be absorbed by the

substrate but some light will reach the PCB surface. One advantage of this arrangement is, rather than sensing the leakage light inside a PTH, the photodetector may be located more conveniently outside the confinement of the PTH.

6.1.2 Assumptions

The following assumptions are made for the arrangement in figure 6.1:

- The required minimum thickness of copper plating (20 to 25 μm, refer to section 2.4.1.2) inside PTHs is effectively opaque to the applied illumination.

- Although light absorption occurs in the PCB substrate, a significant fraction of light is transmitted over a reasonable distance to the panel surface around the PTH.

- Any plating voids inside a PTH will allow light to penetrate into the substrate.

- On the PCB panel surface, the unwanted copper has already been etched away and the area surrounding each PTH has exposed substrate so that leakage light can be detected.

6.1.3 Technical Requirements

The practicality of LLD for PTHs is subject to these technical requirements:

- **Adequate masking of the PTHs**

  The efficiency of masking affects the signal to noise ratio (SNR) of the sensing system directly. Incomplete masking leads to light leakage through one or both ends of the hole instead of the defect sites. This has the effect of reducing the SNR or would lead to the false detection of plating voids.

- **Reliable detection of weak light**

  Some of the defective PTHs have voids covering as little as 10 percent of the total area of hole wall. This can be represented by a single window of 0.5 mm^2 in a 1 mm diameter PTH 1.6 mm deep. Even with intense illumination, the amount of light leaking in or out of this window will still be very small. Only a fraction of the total

leakage light will reach the photodetector. Ando suggests that the detected leakage light is weaker than the incident light by typically six orders of magnitude [AND88].

6.2   SELECTION OF A SUITABLE SENSOR

The sensing device is a key element in detecting the weak leakage light. Commonly used photodetectors convert electromagnetic radiation energy into an electrical output. These detectors are square-law devices: the input optical power is converted into an electrical current. Thus the electrical detected power is proportional to the square of the optical power [CUL84].

Photodetectors are available in several categories: photoconductive sensors, junction photodetectors and photoemissive devices [WAS86]. The photoconductive sensor such as the photoresistor is less versatile than the junction detectors and has a slower response. There are a wider variety of output characteristics with different biasing arrangements available with the junction detectors [NOR69,CUL84,WAS86]. Photo-emissive devices such as the photomultiplier or microchannel plates have the best sensitivity and highest gain (typically 10^5 to 10^7) [CUL84,DEN86] but they require a high voltage supply and are much more costly [NOR69].

6.2.1 The Criteria

The selection of a suitable sensor for the detection of weak light must take into consideration its sensitivity, spectral response, required SNR, the versatility of signal conditioning, speed, stability, size and cost. The junction photodetector is the optimum choice for this particular application because it has a broad spectral response and is compact. It has good stability over a range of temperature and electrical bias conditions [CUL84].

Photodiodes and phototransistors are the commonly available junction detectors, whereas the CCD is a highly integrated planar sensor for imaging applications. Both line

and area CCDs are available. The choice from the family of photojunction devices will be dependent upon the proposed arrangement of the inspection system and the resources available.

6.2.2 Experiments

Some experiments were conducted to test the feasibility of detecting leakage light in PTHs using available equipment. The experience gained through the investigation has contributed to the design of a demonstration system for PTH inspection using LLD. The three sets of experiments described involve a linescan camera, a photo-darlington transistor and a photodiode.

6.2.2.1   OPCON Linescan System

The OPCON is an industrial inspection system using a linescan camera. The camera has a 1024 element CCD line sensor and associated electronics to control the time of exposure. As in an ordinary camera, lens aperture adjustment is possible. Measurements in terms of the illumination intensity at each of the 1024 photosites can be made and recorded on chart. All measurements, programming and controls are handled by a computer that is linked to the OPCON.

The OPCON system was initially used to detect the leakage light from the PTHs on a test panel. All the PTHs were 1 mm in diameter. A varying degree of unplated areas was deliberately introduced into some of the hole walls using a very fine drill. These manually introduced voids may not resemble the manufacturing defects. However, this method has been found to be sufficient for the preparation of test samples at this stage.

Two light-proof masks are required, one for each side of the panel surface. These masks were made using a dark plastic sheet and dark adhesive tape. One mask (the top mask) covered the entire panel except the PTHs under inspection. This was made by punching 1 mm holes on the plastic sheet to match the pattern of PTHs to be inspected.

The other mask (the bottom mask) was a thin slice of dark adhesive tape large enough to seal off the bottom ends of a row of PTHs.

Due to the relatively weak intensity of the leakage light involved, the experiment had to be conducted in a darkened environment. The test panel was laid flat with the camera lens looking down. Backlighting was provided by a fluorescent tube underneath the test panel. Figure 6.2(a) illustrates this setup. The positions of the top and bottom masks are shown in figure 6.2(b).

(a) **The experimental setup**   (b) **The top and bottom masks**
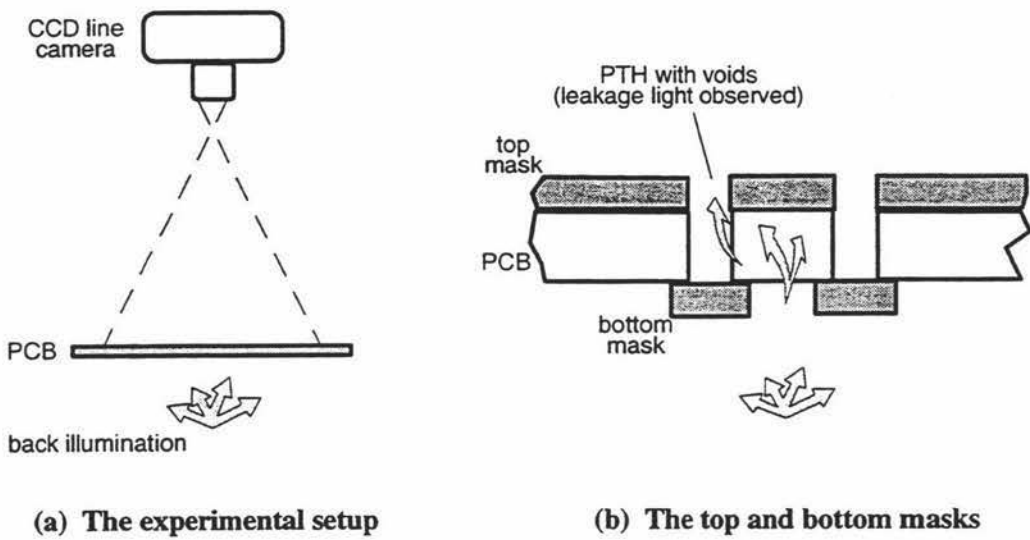
Figure 6.2   Setup for PTH leakage light detection using the OPCON system

The experiment began by applying only the top mask to the panel. The CCD line sensor was manually aligned with the row of PTHs. By applying illumination under the panel, light leaked through all the eight holes. The record of the OPCON system is reproduced in figure 6.3(a) with the vertical axis of the chart representing the light intensity detected by the sensor. The row of eight PTHs spans over a distance of 20 mm. The observed varying intensities were due to the unevenness of the illumination.

(a)

(b)

(c)

(d)
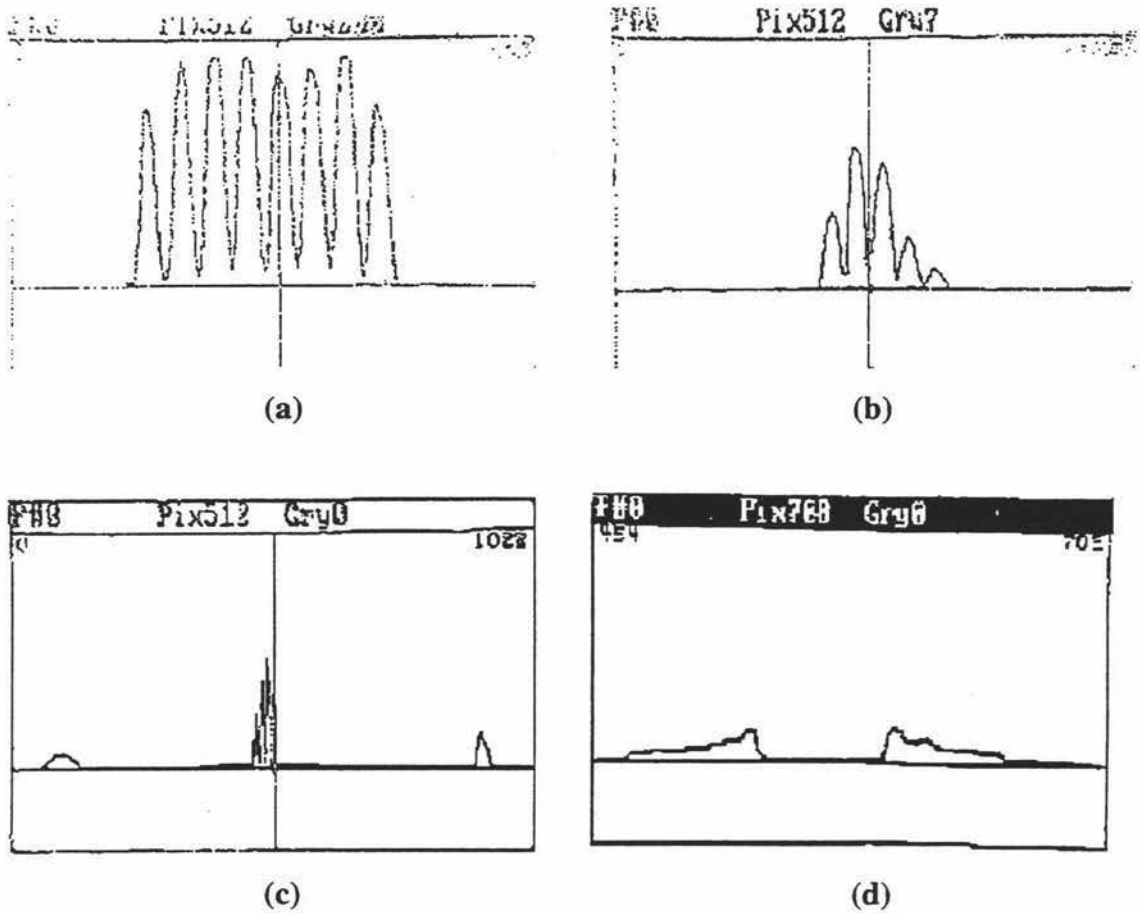
Figure 6.3   Results of PTH leakage light detection using the OPCON system
(a)   With top mask only, light passed through all eight holes
(b)   With both top and bottom masks, five defective holes were revealed
(c)   A zoom-out view of (b)
(d)   A zoom-in view of two defective PTHs

When both top and bottom masks were applied, all the five defective holes in the row were detected and located by the imaging system as in (b). Figure 6.3 (c) is a zoom-out view of the row of PTHs in (b). The edges of the test panel are clearly marked by the two intensity peaks located on opposite ends of the chart. The actual distance between these two peaks is 130 mm. In (d), a zoom-in view of another row of PTHs is shown. Two defective holes appear on the chart. The central non-defective hole can be located by the corresponding zero-intensity area in between the intensity peaks.

6.2.2.2   Using a Phototransistor

Compared with CCD arrays, the phototransistor is a low cost device. The detector used was the Motorola MFOD73 photo-darlington transistor. This device is specially

designed for coupling with optical fibre. The phototransistor was tested using a one mm diameter optical fibre coupled to the sensing window of the MFOD73. The other end of the optical fibre was used for probing into the open end of a PTH. Any leakage light inside the hole can be detected by the MFOD73 through the optical fibre.

Not all the known defective PTHs were detected when this method was applied to the same test panel and masks already described in the last section. Only leakage light from those PTHs having substantial amount of voids had been detected. The amount of voids in each PTHs was independently assessed using a PTH viewer.

This detection system is therefore relatively insensitive to weak light. This has been confirmed by a test conducted to find the response of the MFOD73 under different light intensities. Appendix 6-1 shows the result of the test. Since very low light levels are common to the PTH LLD situation, it has been concluded that the MFOD73 phototransistor is not suitable for this application.

6.2.2.3   Using a Photodiode with Built-in Amplification

Another relatively low cost light sensor is the IPL 10530DAL hybrid photodetector. This device consists of a photodiode and an amplifier with a feedback circuit mounted on a ceramic substrate. The photodetector is encapsulated in a TO5 package with a biconvex lensed window. The lens allows incident light to be focused on the photodiode chip, thus offering improved gain and sensitivity. Since both amplifier and detector are close together within a screened can, the arrangement effectively reduces the amount the electrical noise picked up by the circuit. The characteristics of this detector can be found in appendix 6-2.

A metal coupler was made for coupling an optical fibre of one mm diameter to the lensed window of the IPL photodetector. This arrangement was necessary for testing the sensor under similar situations to the MFOD 73 phototransistor in the last section. Any leakage light to be detected would have to travel through the optical fibre before reaching the sensor.

The result showed that the IPL sensor responded to every known defective PTH on the test panel. Once the preliminary feasibility of this sensor had been established, further work on the response at different light levels was to be found by another test. Since no light intensity meter was available, only relative light levels were used. This was implemented by using a 35mm CCD camera lens to control the amount of light from reaching the photodetector. The lens has aperture adjustment from f22 to f1.7, thus representing a nine-step change of relative light intensity from x1 to x250. With the lens placed immediately in front of the optical fibre which in turn was coupled to the IPL sensor, the amount of light reaching the sensor could be easily controlled by the aperture of the lens.

Since the IPL photodetector has a built-in amplifying circuit (refer to appendix 6-2), it is possible to test the device with a 9 V DC power supply and record the output voltage without any external amplification. Three light intensity levels were selected. These are referred to as strong, medium and low light levels. These levels were achieved by pointing the camera lens directly at a 75W light bulb, towards a distant window and at a wall respectively. Nine readings, each corresponding to one f-stop of the aperture, were taken at each light level. The plot in figure 6.4 shows the output voltage increases with the incident light intensity. The response at low light level is approximately linear.
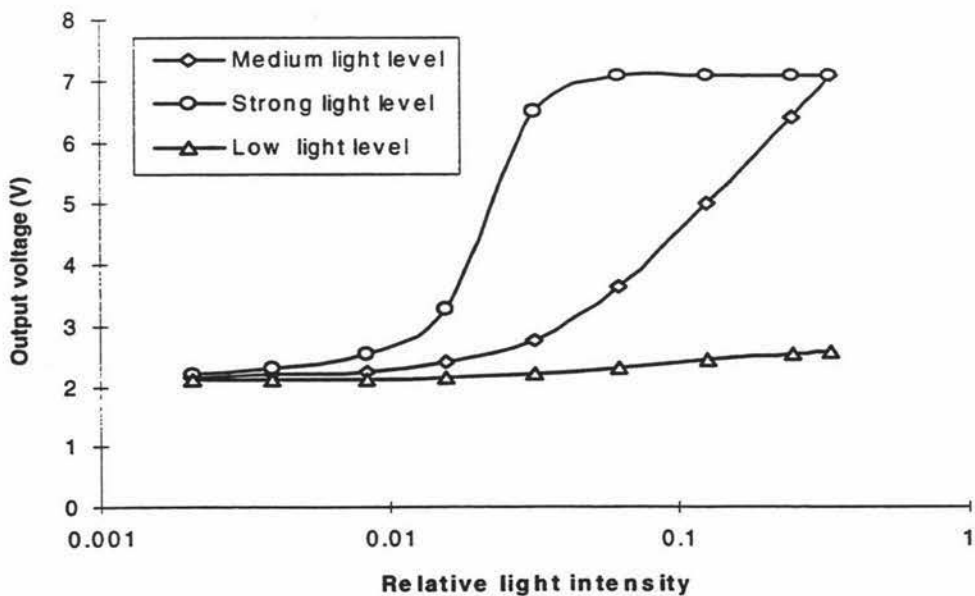
Figure 6.4   Response of the IPL photodetector

6.2.3 Discussion

The test has concluded that the MFOD73 photo-darlington is unsatisfactory for LLD in PTHs. Both the CCD line sensor and the IPL photodetector can be used for this application. The advantage in using the CCD line sensor is the capability of inspecting a row of PTHs at a time. Individual defective holes on the panel may also be located. When equipped with a suitable lens system, it is possible to allocate each photosite along the line sensor to inspect a tiny stretch of the panel. This may be approximately 1 mm across. Hence a 1024 element sensor may be used to inspect any practical PCB panels by scanning action.

The CCD array is a more sophisticated device and hence costs much more than a relatively simple photodetector such as the IPL 10530DAL. A conveyer mechanism is also required to transport the panel under scan. An alternative solution is to probe PTHs one at a time using an optical fibre connected to a photodetector. A major disadvantage of this arrangement is that it will be much slower than the panel-scanning action. Accurate positioning of the optical fibre is also required but there are some advantages over a scanning system using a line CCD:

- The IPL sensor is cheaper and it eliminates the need for a precisely adjusted lens system.

- No conveyor mechanism is required.

- There are difficulties in providing light-proof masks for a scanning system similar to the type in use for the experiment with OPCON. An efficient method in producing such masks will have to be investigated. In contrast, to mask the PTHs one at a time for the photodiode is relatively simple, as in the example of the demonstration system to be described later.

- The software and the CNC drilling table for PTH manufacture can be utilised as part of the PTH inspection system, further cutting down on the cost of installation.

6.3   A DEMONSTRATION SYSTEM FOR PLATED-THROUGH HOLE LEAKAGE LIGHT DETECTION

A PTH inspection system has been designed and built to demonstrate the application of LLD using relatively simple but reasonably sensitive light sensing devices such as the IPL photodetector.

6.3.1 Overview of the Design

The configuration described in section 6.1.1 is implemented. This system consists of a sensing head coupled to the light source and an external electronic circuit for analogue signal processing. The system is designed to utilise the Techno™ computer numerically controlled (CNC) drill table available in the Department of Production Technology. The CNC drill table is intended for drilling holes in PCB panels. By using existing equipment as the positioning mechanism, this design has the advantage of reducing the overall cost of the system.

The sensing head is made as compact as possible to reduce overall weight and is designed to be firmly attached to the drill head. Thus it can be positioned with identical precision as the CNC drill table (typically 0.01 mm in Cartesian space) at any designated location on the pinned PCB panel. Inspection of the PTHs is done one at a time. Provided the PCB under inspection was initially drilled by an identical drilling machine, the precise locations of all the PTHs to be inspected are obtainable from the original drilling information file. Only minor modification to this file is necessary. Selective or repetitive inspection of specific PTHs can also be achieved.

The sensing head accommodates three IPL photodetectors and an optical fibre. The optical fibre is used for delivering illumination inside the PTH to be inspected. The sensing head is coupled to the light source through a flexible light guide. External leads are used to connect the photodetectors inside the sensing head to a separate signal processing circuit. Figure 6.5 is a photograph showing the sensing head being attached to the drill. The CNC drilling machine can be operated as normal but having the drill bits replaced by the sensing head throughout an inspection session.

6.3.2 The Sensing Head

The sensing head is a cylindrical structure made of aluminium. Figure 6.5 shows the construction and the approximate dimensions of the unit. It consists of two portions. The upper portion has a stem that fits into a quarter inch (or 6.35 mm) collet. The collet is originally intended for securing drill bits and thus provides firm attachment between the drill and the sensing head. The rest of the upper portion is a cavity providing sufficient space for the photodetector leads, essential wiring and the optical fibre coupling.
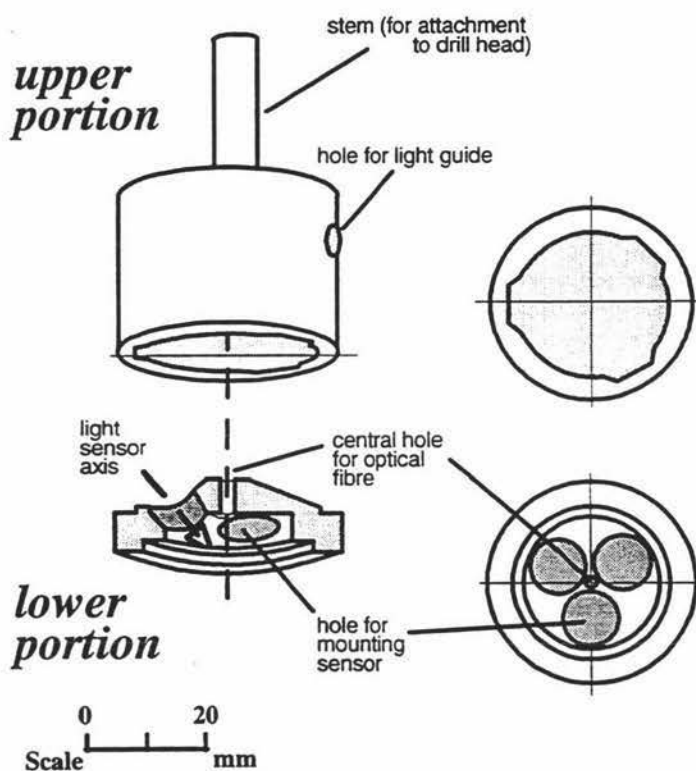
Figure 6.5   Construction of the sensing head

Three photodetectors are mounted on the three holes inside the lower portion of the unit. The holes are machined to hold the photodetectors at the pre-determined mounting positions: 7 mm above the panel surface, 30 degrees to the vertical and each situated 120 degrees apart along the circle centred at the PTH under inspection. This arrangement is shown in figure 6.6. Given each lens of the IPL sensors has a 28-degree angle of view, such mounting positions have been optimised for monitoring the widest possible area (a 360-degree view with some overlap) immediately surrounding the PTH

under inspection. The central hole is designated for threading the optical fibre. The upper and lower portions of the sensing head are held together using three screws.
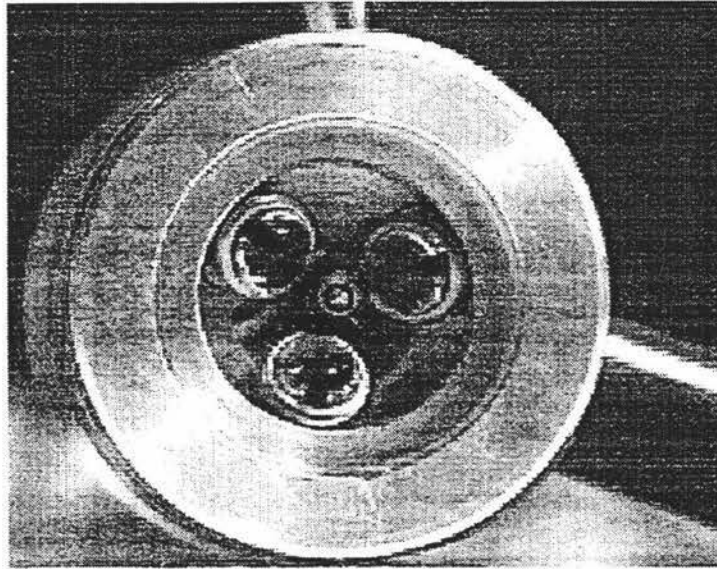
Figure 6.6   Location of the three photodetectors

6.3.3 The Illumination System

Sufficient light must be delivered to the inside of the PTH under inspection to ensure that any leakage light will be detectable. The illumination system consists of four elements: the light source, a flexible light guide, a coupler and an optical fibre.

A Schott KL 1500 cold light source is employed to provide strong illumination. This is an available device in the Image Processing Laboratory. A flexible light guide is used to direct the light into the sensing head (the light source has already been described in section 4.3.2.1).

The coupler is a one-piece cylindrical plastic component which is a press-fit in the circular opening of the sensing head. Its primary function is to secure the flexible light guide to the sensing head and to hold the upper end of the optical fibre so that light passes into it.

Optical fibre transmits electromagnetic energy at optical wavelengths. It is small in diameter, strong, lightweight and inexpensive. Properly protected optical fibre is intrinsically a high strength and durable material. It is also highly flexible and can negotiate bends with a radius as small as a few millimetres [KAO82]. The range of optical fibre diameters available makes it possible to thread them through PTHs of various sizes. Optical fibre is therefore a convenient and desirable tool for carrying the necessary illumination into the PTHs. Figure 6.7 below shows how an optical fibre is positioned inside the sensing head.
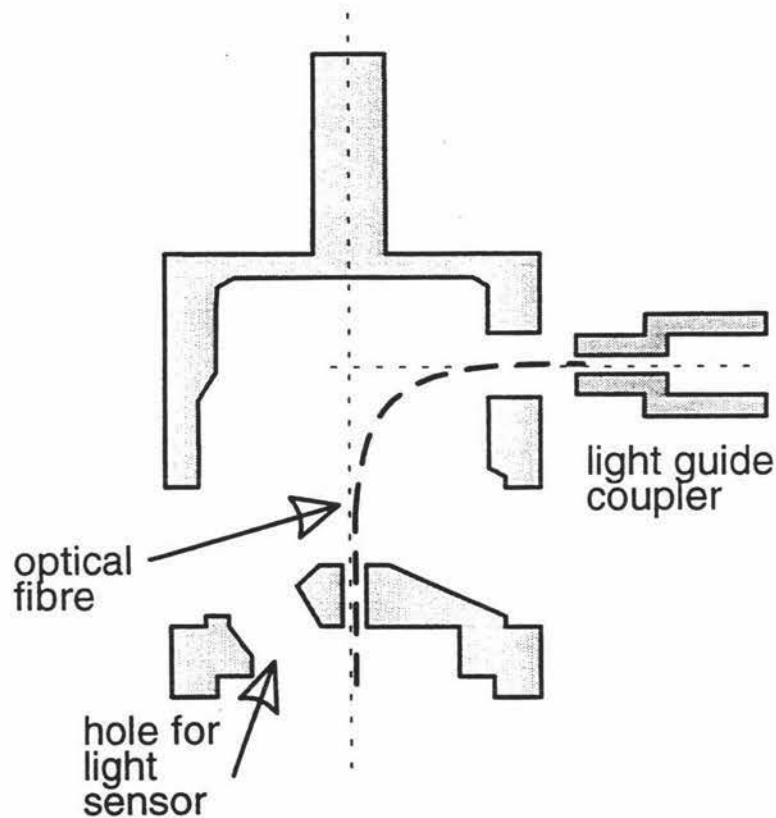
Figure 6.7   A cross-sectional view of the sensing head

Figure 6.8 (a) depicts the inspection action. For clarity, only one of the three sensors is shown. The lower end of the optical fibre has its protective plastic jacket removed, thus exposing the cladding that allows light to diffuse out. This is the portion of the fibre that goes into the PTH. The length of the exposed cladding is chosen to match the thickness of the PCB. The end of the plastic jacket having a larger diameter than the hole remains outside and acts as an effective light blocking mask covering the top of the PTH as shown in figure 6.8 (b).

A light proof mask is essential as it prevents light from escaping through the bottom opening of a PTH. Otherwise false outputs may be generated. From practical experience it is sufficient to use a dark plastic sheet matching the size of the PCB to be inspected. This is referred to as the bottom mask in the following figure.

(a)

light sensor

optical fibre

circuit board

bottom mask

(drawings not to scale)

(b)

optical fibre

plastic jacket as top mask

circuit board with PTH

bottom mask
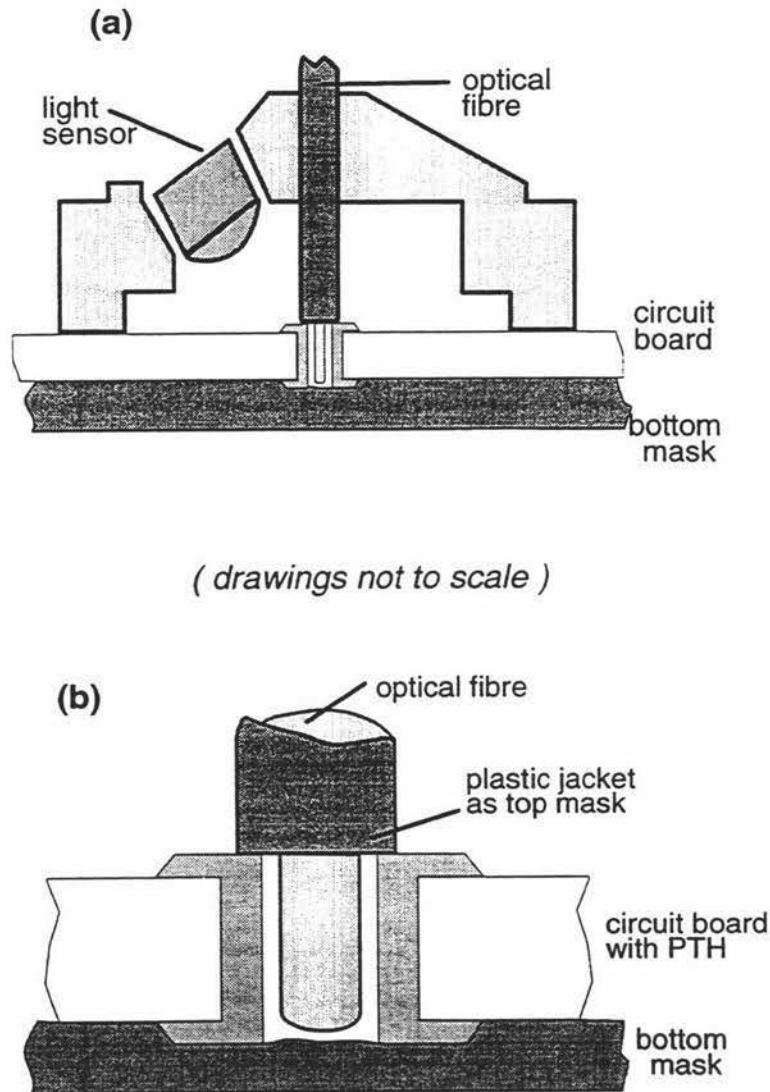
Figure 6.8   The inspection action

In figure 6.8 (a), the cavity under the sensors becomes a dark enclosure whenever the sensing head is pressed against the PCB. Thus LLD is possible without the need for a darkened operating environment.

6.3.4 Signal Processing Electronics

The IPL 10530DAL photodetector generates a positive output voltage proportional to increasing incident light level. For completeness the basic circuit diagram for this device is reproduced in figure 6.9 from the data sheet.
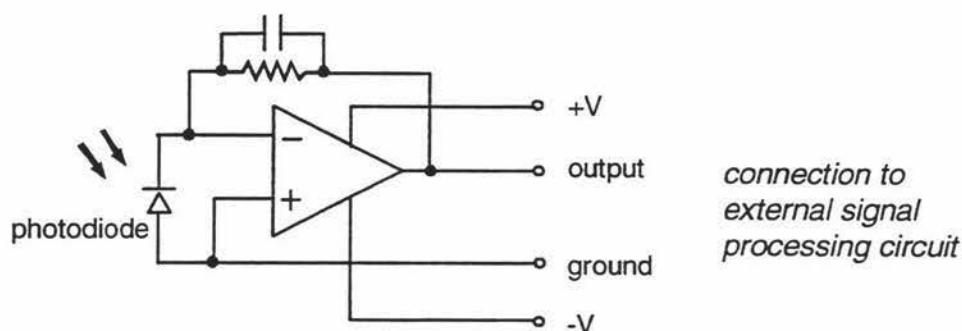
Figure 6.9   Basic circuit diagram for the IPL photodetector

The three independent outputs of the IPL sensors are connected to the precision instrumentation amplifier LM363D as shown in figure 6.10.
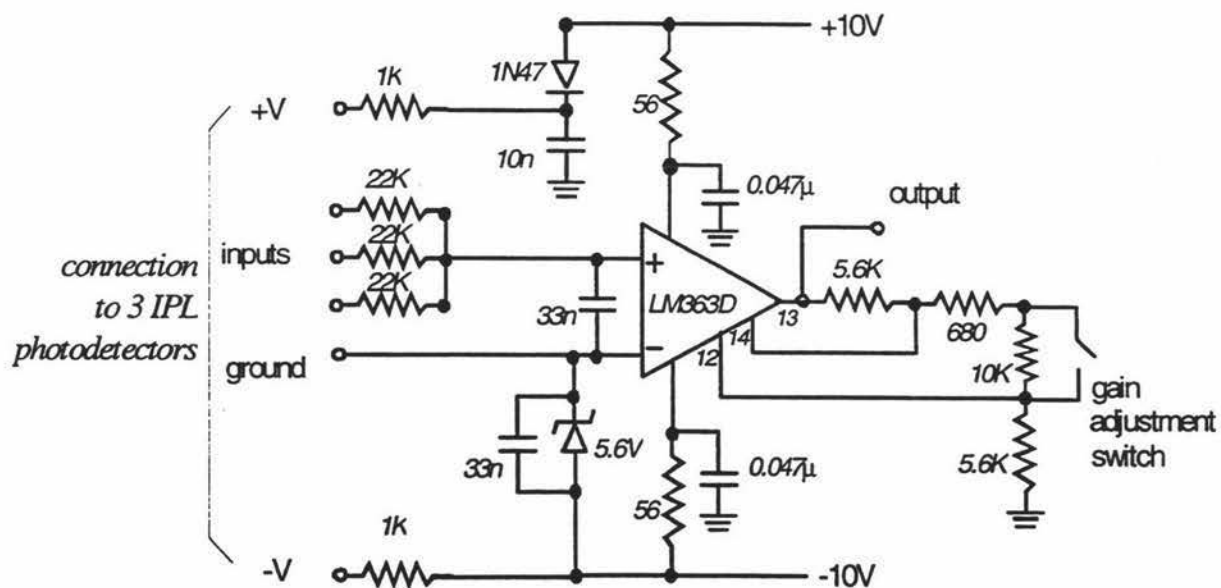
Figure 6.10   The signal processing electronics

The circuit is driven by a ±10 V DC power supply. The LM 363D is a 16-pin DIP instrumentation amplifier having fixed gains of 10, 100 and 1000. The required voltage gain of this circuit is set at two fixed values: either 10 or 30 when the gain adjustment switch is closed or opened respectively. Normally a gain of 30 is used with the switch open. However, some PTHs may have a substantial amount of voids present, for example, 30 to 50 percent of the total area of hole wall. Under such circumstance the output voltage will be driven to saturation at about +9 V. The lower gain value is intended for obtaining an output voltage that reflects the degree of plating voids in these PTHs.

6.4   OPERATING THE SYSTEM

6.4.1 Inspection Software

The drilling information file originates from the design layout of the PCB panel. This file contains all the information essential for panel drilling such as the diameters and the precise locations of all holes to be drilled on the panel. The drilling control software that is supplied with the system translates the information into a sequence of commands. This sequence instructs the drill head to position above a specific location above the panel (x-y positioning) and then move downward to carry out the drilling (z positioning). The downstrokes are repeated until all the holes are drilled.

With the sensing head attached to the drill, the inspection actions are controlled by a sequence of commands generated from a revised version of the original drilling information file. The only revisions required for the file are the extent of the z-movement of the drill head and the duration of drill head to remain in its down-most position. Since both parameters have uniform values for all panels of the same design, the revisions can be done by simply replacing the two parameters with the specific values.

6.4.2 Calibration

Calibration was conducted with a test panel with PTHs. The PTHs had a varying degree of plating voids. Some were zero-defect holes. The amount of voids in each hole had been estimated as a percentage of the total area of hole wall using the Mexter ™ PTH viewer. The results are summarised in figure 6.11.
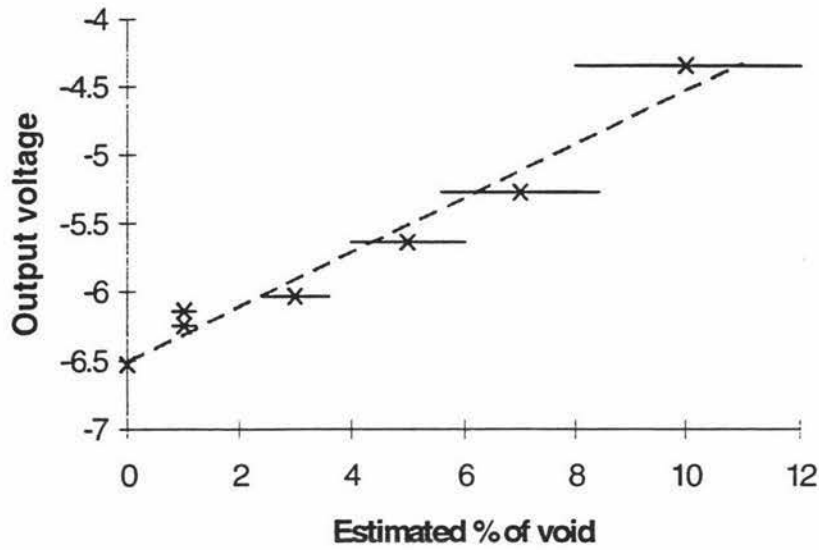
Figure 6.11   Curve for calibrating the inspection system

The error bars shown in the plot represent the inherent uncertainties involved in the PTH percentage-void estimation process. The output for the zero-defect holes was averaged at -6.53 V. For the holes having 5 percent and 10 percent voids, the output voltages were averaged at -5.64 V and -4.345 V respectively.

6.4.3 Operating Procedure

The operating procedure of the inspection system is as follows:

1. Attach the sensing head securely to the drill head.
2. Using the flexible light guide, connect the light source to the light guide coupler of the sensing head. Operate the light source at the maximum output level.

3. Place the panel to be inspected on the flat bed of the drill table. The original tooling holes intended for panel drilling are used for the accurate positioning of the panel. Clamp the panel to ensure no movement is possible.

4. Connect the output of the sensing circuit to a digital multimeter measuring DC voltages.

5. Start the inspection action by running the inspection program from the controlling computer of the drill table.

6. The output of the sensing circuit for each PTH inspected is to be monitored manually by an operator.

6.4.4 Performance

- The system has the capability of reliably detecting PTHs having a total area of voids as little as 5 percent of the total wall area.
- The SNR of the system for 5 percent-void hole detection is 6 dB.
- The system output voltage is proportional to the through-hole plating coverage, within limits of the subjective estimation of the percentage voids.
- The inspection time for a PTH is averaged at 2.5 seconds.

6.4.5 Limitations

- One major limitation with the demonstration system is that it only works with PCB panels which have their excess copper already etched away, thus exposing the surface conductor tracks and substrate. Consequently, panels immediately after the electroless process cannot be inspected. However, it is most desirable for in-process inspections to be carried out immediately after any manufacturing process so that corrective measures may be taken as early as possible.
- Another major limitation is that the PTHs are inspected one at a time. Given that the number of PTHs on a typical panel may easily reach hundreds if not thousands, considerable time (typically three quarters of an hour for 1000 PTHs) is needed if it is required to have every PTH inspected individually. This system is therefore much slower than a machine that scans the whole panel at once.

- A threshold has to be set on the analogue output of the circuit in deciding whether a particular PTH is acceptable or not. This relies on careful calibration of the system.

- Since the calibration of this system depends on the light transmission characteristic of the substrate and a constant light level inside the PTHs under inspection, re-calibration is necessary should any one of these situations occur:

  1. Panels of a different design or made from another type of substrate material are inspected.

  2. A different illuminating source is used.

  3. Optical fibre of a different diameter is used.

6.5   DISCUSSION

The demonstration system has exhibited several advantages:

- It is relatively simple in design and uses existing equipment whenever possible. Therefore this system minimises both the costs of initial installation and subsequent maintenance.

- With the sensing head positioned by the CNC drill table, the inspection actions are entirely controllable by software and the positioning accuracy of 0.01 mm in Cartesian space can be achieved.

- It works faster and is certainly more reliable than human inspectors equipped with optical viewers.

- It can be utilised to create a percentage-void contour map of all PTHs for each PCB panel. This would help the production personnel to identify existing problems and to monitor drifts in the through-hole plating process.

- The system can be used manually without attachment to the drill table. This offers flexibility and has the potential of being converted into a hand-held inspection probe.

The demonstration system has been operated with a constant level of illumination and under ambient light. To realise a higher system sensitivity, two further improvements can be implemented:

- Replacing the present constant source of illumination with intense light pulses would enable the system to operate at a specific pre-determined frequency.

- Adding a suitable lens in the light guide coupler. Light emerging from the flexible light guide is to be focused at the end of the optical fibre, hence increasing the light intensity level inside a PTH significantly.

It is expected that the improved detection system would result in a higher SNR. This will be achieved by minimising both the effects of ambient light and electrical noise.

Comparing with an inspection system using image processing techniques, the demonstration system cannot provide information regarding the exact location of the voids inside a PTH. In addition, defects such as blistering hole walls cannot be detected. These are the major shortcomings of a LLD system.

INSPECTION OF
STUFFED BOARD COMPONENTS

Stuffed printed circuit boards are boards populated with electronic components. In the literature search, it has been found that the automatic inspection of stuffed PCB components is well documented and that many commercial inspection systems are available. A list of inspection systems for stuffed PCBs is given in table 3.2 of chapter 3. This chapter reports on the experimental work aimed at establishing the software and hardware requirements of a low cost inspection system for checking component orientations.

7.1 JUSTIFICATION FOR INSPECTION

Inspection of stuffed boards involves checking for missing or improperly mounted components. This is carried out after the component insertion stage and prior to the soldering stage. The reason for inspecting the stuffed boards at this stage is to prevent assembly faults from reaching later stages of the production process. Boards rejected at the end of the production process contain the maximum added value of a company's profit and loss account [TYL94]. Once a stuffed board is soldered with a component incorrectly inserted, there would only be two possible remedies:

1. Discard the board, or
2. Rework the rejected board.

Both options may be costly, but this does not imply inspection before soldering can always be justified as the inspection process may be even more costly. The cost ratio of reworking or scraping a board versus inspection has to be determined before a decision is made [NOB89]. In low volume production facilities, stuffed board inspection can be justified for either high value boards or boards with high value non-socketed components. Under such circumstances, the costs of either producing a number of boards in excess or reworking a board could exceed the cost of inspection [NOB89].

7.2 CHECKING COMPONENT ORIENTATIONS

Those electronic components that have polarities and therefore need to be properly mounted include ICs, diodes, transistors and electrolytic capacitors. The polarities of such components are commonly denoted by certain distinguishing features on the packages. For example, dual in-line package (DIP) ICs have at least one of the following features to indicate the polarities: bands, dots or notches. The two DIPs in figure 7.1 have all the three features; while the remaining IC has only dots.
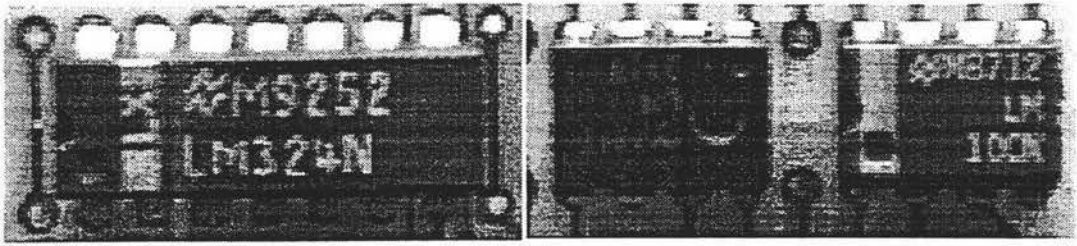
Figure 7.1 Features indicating the polarities of DIPs

Preliminary work has been done on identifying the polarities of DIPs and diodes using image processing techniques. Through these experiments some of the software and hardware requirements for an inspection system have been established, and are described in the following sections.

7.2.1 Equipment Setup

The following is a description of the equipment setup for capturing images of stuffed boards:

Imaging device   CCD camera

View   Camera on top, pointing down

Illumination   (1)   Side lighting at a low angle, typically 15-25 degrees

                               above the panel using several directional sources

                       (2)   Diffused lighting

Frame grabber   SCION LG-3

The captured images were analysed using a Macintosh Quadra computer loaded with the NIH Image software.

7.2.2 Image Processing Techniques Involved

The objective is to extract features from the captured image of a component that convey polarity information. Such features are bands, dots or notches on DIPs and dark bands on diodes. The sequence of commands used for processing the images is listed in appendix 7-1. The main steps are outlined here:

1. Define region of interest

Presumably the locations, boundaries and the component types can either be extracted or calculated from the information contained in the CAD file of the PCB layout. For the work described here, all regions of interest (ROIs) were defined manually.

2. Noise filtering

Filtering removes most of the noise present in the captured image. This was implemented by using the "median filter" supplied with the NIH Image software. This filter replaces each pixel of the original image with the median value of its 3x3 neighbourhood. The advantages of using the median filter in image noise suppression are discussed in [HOD85].

3. Thresholding

The aim of this operation is to segment the ROI into a binary image, highlighting such features that can be recognised as the polarity information of a component. In practice, the actual thresholding values need to be determined locally for each ROI due to the variations in surface reflectance of different components and the unevenness of illumination across a panel.

4. Morphological operations

Up to nine iterations of erosion-dilation, otherwise referred to as an opening operation, were necessary to remove undesirable pixels obscuring the features being sought. These pixels could not be distinguished from those making up the features by simple thresholding because of similar pixel intensity levels.

Figure 7.2 illustrates the tests with three DIPs having different features as polarity indicators: (a) a white band, (b) a notch and (c) a white dot. For each DIP the original image, the image after thresholding and the final image are shown. The arrows point to the polarity features that can be extracted in the final images. It is assumed that further processing will lead to the recognition of these particular features.

white band across

notch at one end

white dot
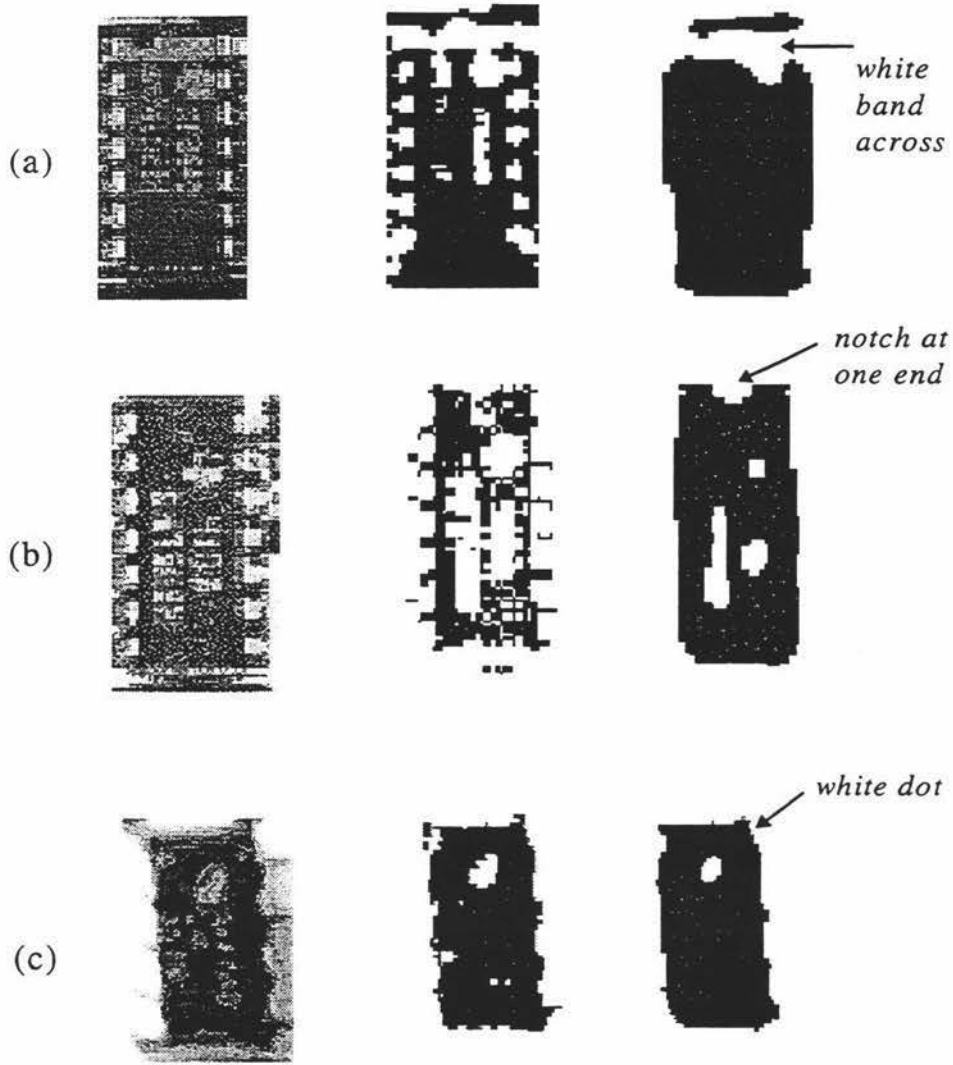
Figure 7.2   Images of DIPs before and after processing

Tests on diodes were also conducted using the same technique. Figure 7.3(a) shows the captured image of six diodes in a row. The polarities of the diodes are depicted by the arrows in (b) and the corresponding positions of the dark bands are also drawn. After processing, the result is given in (c). Each ROI becomes binary due to thresholding. The number of black and white pixels was counted on each side of a line bisecting the ROI. In (d) this is illustrated by the dotted line that cuts across the diodes. For each ROI, the side having a higher ratio of black-to-white pixels indicates the presence of a dark band on that side. In (d) arrows were drawn to represent the results of the comparison. These arrows match the directions of those in (b) and hence show that recognition of polarity is successful for all the six diodes.

(a)

(b)

(c)

(d)
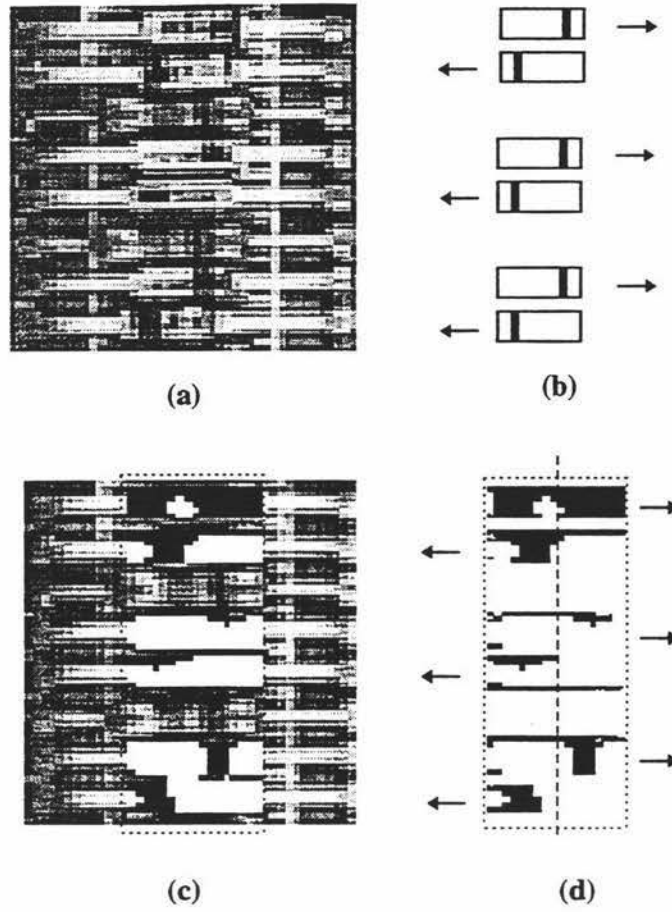
Figure 7.3   Images of diodes before and after processing

7.2.3 Limitations

The method described in the last section can only work under operator intervention. It was used mainly for establishing the hardware requirements for stuffed board component inspection. The major limitations are:

- **Individual thresholding**

  The fact that each ROI needed local thresholding has shown that the simple method used is inadequate for an automatic inspection system. Even if illumination is uniform over the entire panel, components have varying surface reflectance due to the wide range of packaging materials present. A single threshold value does not suit every type of components to be inspected.

- **Illumination requirements**

  Directional illumination at a low angle, typically 15-25 degrees above the test panel, provided more than 80 percent success rate for identifying DIP polarities. However, with diodes the directional lighting often introduced dark bands (shadows) in the ROI. This problem became more acute when the direction of illumination was either parallel or perpendicular to the diodes. Diffused illumination was found suitable for the diodes but then the success rate for the DIPs would drop to only around 50 percent.

- **Resolution requirements**

  Under identical conditions, the higher the resolution of the captured images, the more successful the polarity identification would be. In practice, a minimum resolution requirement had to be selected. Images captured at 75 DPI resolution had generated more than 80 percent success rate for the DIPs under directional illumination. At that resolution, a typical 14-pin IC is represented by approximately 60 by 20 pixels. It is thought that a suitable resolution should be 150 DPI if neither the illumination nor the algorithm could be improved further. Further tests showed that images at 150 DPI yielded at least a 90 percent success rate for all the DIPs tested.

7.3   SELECTION FROM AVAILABLE EQUIPMENT

Experiments were conducted to facilitate the selection of a combination of imaging device and frame grabber suitable to carry out component orientation inspection. This has to be selected from the range of equipment available in the Image Processing Laboratory.

7.3.1 Available Equipment

Imaging Devices: CCD camera, Akai Hi 8 Video camera and Chinon document
                        scanner.

Frame Grabbers: MaxVideo20, SCION LG-3 and Data Translation frame
                        grabbers.

Tests were conducted using different combinations of imaging devices and frame grabbers to capture images of a test panel. Appendix 7-2 gives the detail of such tests.

7.3.2 Summary of Results

It is found that among the combinations of existing equipment, either a CCD camera or a commercial video camera is a good choice for component polarity inspection. The maximum achievable resolution of the Chinon scanner is only 75 DPI for an undithered image. A more desirable resolution can only be achieved by employing either the CCD or the video cameras. However, the SCION-video camera combination generates excessive noise due to the synchronisation problem (see appendix 7-2). It is therefore recommended that using the CCD camera with either the SCION or Data Translation frame grabbers are the optimum selections from the available equipment.

7.4   DISCUSSION

As pointed out in [PAU90], the commercial inspection systems for stuffed boards usually operate by thresholding and template matching or image subtraction. This would require knowledge bases containing reference patterns or boards. Special lighting is often used. It is claimed that the most robust method is the presence-from-shade approach, which involves checking the presence and orientation of components from the shade they project onto the substrate from known directions [PAU90]. Such arrangements are usually achieved by laser or collimated beams. The reason dark shades are used is that they are easier to detect and more reliable than the use of component surfaces with varying reflectance. Ray tracing algorithms are employed to calculate the

nominal shade outlines on the basis of the 3-dimensional component outline, the component identification and the location of the light sources.

For a low cost inspection system, it may not be possible to have all the sophisticated features and algorithms designed for large scale inspection systems. However, it is anticipated that the use of structured light can further enhance the performance of the simple image processing algorithms described in this chapter.

A single photodetector laser imaging system has recently been developed in the Department of Production Technology. This system can be directed to scan specific locations and areas. It can be thought of as a high resolution imaging system that incorporates programmable structured lighting generated by computer. This feature is obviously useful in stuffed board inspection as different illumination requirements can be set for different electronic components on the same board.

SUMMARY AND DISCUSSION

This chapter summarises the important issues identified in the preceding chapters. The aim is to provide an overview on PCB inspection and then examines the inspection strategy of PCB manufacturers. The research on non-destructive inspection of plated-through holes described in this thesis is also summarised and discussed.

8.1   OVERVIEW

PCB inspection requires specific tests conducted to determine whether a particular product meets the specifications. Electrical testing and visual inspection are by far the most frequently used methods of testing.

8.1.1 Electrical Testing

It can be represented by the typical "bed-of-nails" test fixture briefly described in section 3.1.2. Electrical testing verifies the electrical integrity of a PCB by detecting unwanted opens, shorts and capacitive coupling. However, not all PCB defects are testable electrically. For example, insufficient spacing of conductor tracks may not produce an electrical short immediately during test but it is a potential hazard since failure might occur under certain operating conditions such as a high-humidity environment.

8.1.2 Visual Inspection

Visual inspection is very effective in detecting and locating a wider range of PCB defects. It has been estimated that as many as 80 percent of all PCB inspections are visually based (section 3.1.2). Unlike electrical testing, visual inspection is a non-contact method, hence avoiding any possible damages to the circuit board such as by direct contact with the tips of probes.

The simplest form of visual inspection is human visual inspection with or without optical aids. Human visual inspection is subject to error, fatigue, limits in repetitive speed, emotional stress and precision movements [ARA89]. Given the huge quantities of PCBs that are produced in large scale facilities each year, the major manufacturers invest heavily in automatic visual inspection systems [TYL94].

8.1.3 Automatic Visual Inspection Systems

As described in chapter 3, specially designed automatic visual inspection systems are now widely available for the inspection of both bare boards and stuffed boards. A typical visual inspection system consists of:

- an imaging device such as a CCD camera
- an illumination system
- a display
- a panel handling mechanism
- a host computer.

These systems require image processing algorithms to implement one of these techniques: template matching, feature extraction and design rule verification. Some sophisticated systems combine two or even all the three techniques for improved accuracy and thus achieving reduced false detection rates [PAU90]. The cost of an inspection system is proportional to the number of options installed and the speed of operation [ARA89]. Given the high cost of installation, the more sophisticated automatic inspection systems are suitable for large scale production of high design complexity boards. This is a situation where human inspectors have difficulties in coping with either the structural complexity or the rate at which the products need to be inspected.

8.1.4 Plated-through Hole Inspection

Despite the high degree of sophistication, it is to be noted that only one of the automatic inspection systems discovered in our literature search (the Fujitsu system as reported in [AND88]) can verify the integrity of plating in through-holes. The conventional destructive practice of micro-sectioning is still the recommended standard procedure for inspecting PTHs. The sectioned specimens are seen as the most important means of determining the process quality and final product acceptability [DAW87], although any defects not shown by the cut of the micro-section remain unexposed [SID93].

Test coupons are used in order to avoid removing production boards from a production line and destroying the boards for quality assessment. A test coupon is a specially designed sample for destructive testing. It is located on the same panel as the production board and therefore has been subjected to identical processes. The common practice is to include two coupons at opposite corners of each panel for PTH testing. Some opinion such as [MCO92] strongly favours their use. However, as already discussed in chapter 3, the variation of hole-plating quality across a panel is sometimes large enough to introduce uncertainty even when test coupons are inspected. The location of test coupons is the single factor in assuring that these coupons will be representative of the entire panel. It is so critical that optimisation of coupon-to-board correlation for individual PCB designs using statistical process control is recommended [HAY89]. However, the cost incurred in carrying out such optimisation for a particular family of PCBs can be very high (see section 3.5.1).

Hence, the use of test coupons reflects the compromise between the need to inspect as many products as necessary and that the inspection method itself is destructive. This can introduce uncertainties into confirming the inspection result. As Harry [HAY89] suggests, optimisation of the coupon-to-board correlation is required to minimise the uncertainties. Using test coupons is not as straightforward as it may appear but extra work is required to prevent the inspection effort from defeating its original purpose of assuring quality.

8.2   INSPECTION STRATEGY OF PRINTED CIRCUIT BOARD MANUFACTURERS

The availability of automatic visual inspection systems does not necessarily provide ready solutions for all sectors of the PCB industry. The nature and the scale in which the products are manufactured determine the degree and the extent of inspection as well as the choice of human or automatic visual inspection. The inspection strategy has to be established from an economic standpoint [NOB89] and is therefore influenced by the following factors:

- The complexity of the design and technology involved - single-sided, double-sided PTH or multilayer high density boards.

- The intended use of the board - general consumer products, dedicated service products or long-term high reliability products.

- Output volume - low or high.

Automatic inspection is obviously required for large volume production of sophisticated PCBs with stringent performance and long-term reliability requirements. The reason is that extensive product inspection will be mandatory and the only way to minimise the cost will be to maximise the efficiency of the inspection through automation.

8.2.1 Possible Impact of Low Cost Automatic Inspection Systems

Contrary to the high volume manufacturers, the prototype and small batch sector is characterised by selling 'service' rather than commodities (section 1.2). These producers can be regarded as generally operating in the 'service' sector where price is less of an issue and the customers are prepared to pay more for the smaller volume but require rapid response [TYL94]. The fast-turn-around type service typically involves small batches of general electronic products relatively simple in design and less complicated to manufacture, such as single-sided or double-sided PTH boards. Due to the small volume production, even if extensive inspection of the products is desired, this can be handled adequately by human vision but the limitations outlined in section 8.1.2 cannot be avoided.

This situation can be improved by the introduction of low cost automatic inspection systems. Such a system typically utilises the basic essential manufacturing equipment whenever possible. Consequently, both the costs of initial installation and subsequent maintenance are relatively low. These systems can be seen as simplified versions of the more sophisticated inspection systems currently in use by the major PCB manufacturers, but at a much reduced cost. It may be argued that a low cost automatic system which

may perform faster and certainly more reliable than human inspectors will better serve the needs of the PCB manufacturers in the prototype and small batch sector.

8.3   RESEARCH ON NON-DESTRUCTIVE INSPECTION OF PLATED-THROUGH HOLES

It follows from the discussion in section 8.1.4 that non-destructive inspection of PTHs is needed. The research work described in this thesis was carried out with this major objective.

8.3.1 Image Processing Techniques

Chapter 4 describes the work on using the difference of spectral reflectance properties between copper-plated and unplated surfaces for through-hole plating quality assessment. Two independent image processing techniques were applied to the captured images of PTH walls under incident light. Image enhancement analysis (section 4.3.4) works on the difference in spectral reflectance between plated and unplated regions. This intrinsic difference is enhanced to a highly contrasted image with the defective regions highlighted. Local histogram analysis (section 4.3.5) first requires partitioning of an image into small blocks. Selected histogram features of each partitioned block are plotted in a two-dimensional feature space. Blocks consist entirely of plated areas grouped into one region against those blocks containing a varying degree of unplated areas. Hence any defective areas can be located by referencing the feature space.

The results have demonstrated the potential to apply image processing techniques to assess the quality of a copper plated surface. However, before these techniques can be used for a practical non-destructive inspection system for PTHs, the following problems will have to be resolved:

1. The difficulty in delivering the required incident illumination inside a PTH.
2. A suitable imaging device to capture a 360-degree view of the hole wall while it is being illuminated.

3. The techniques need to be refined further for raising the defect reporting confidence.

8.3.2 Leakage Light Detection

Leakage light detection (LLD) is similar to penetrant flaw detection. It is also a visual inspection method and can be regarded as the detection of penetrant light. The method has all the merits of penetrant testing but it eliminates complications such as surface pre-cleaning and removal of penetrant after test.

The success of the Fujitsu system as reported in [AND88] has already demonstrated the validity of this approach as a panel-scanning solution for the inspection of PTHs (section 3.5.2). As discussed in chapter 6 of this thesis, the principle of LLD can also be implemented in a non-scanning version but at a much reduced cost. The demonstration system built for this purpose is suitable for small batch production facilities.

8.3.3 Justification for Focusing on a Leakage Light Detection System

The Manufacturing Pilot Plant in the Department of Production Technology is a typical example of a small scale PCB manufacturer. This research work has been consistently aiming at the development of a low cost inspection system. Such a system can be tested conveniently with the existing facilities.

The principle of LLD has led to a relatively simple solution for the non-destructive inspection of PTHs. The validity of this has already been confirmed by the demonstration system purposely built for this project. This situation does not imply that the image processing techniques initially developed in chapter 4 are less desirable than the LLD technology. The application of image processing techniques is a solution that requires more time and higher costs than this project could have been allowed.

CONCLUSIONS AND FUTURE WORK

9.1 CONCLUSIONS

1. The status of PCB inspection has been reviewed. Image processing techniques are being applied in a wide range of PCB automatic inspection tasks. The inspection of PTHs is still dominated by destructive testing that involves much manual effort. The major objective of this research is to develop a non-destructive method for the inspection of PTHs.

2. Various methods that could lead to this objective have been investigated. In researching the application of image processing techniques positive results have

been obtained. The results suggested that copper-plated and unplated areas of a surface can be discriminated by using the difference in surface reflectance between the two types of areas. The research also indicated that special equipment would be required for inspecting PTHs. It is therefore a relatively expensive solution and will require further research.

3. In contrast, leakage light detection (LLD) is a technique that is based on a simple principle but has already been proven to be workable for the non-destructive inspection of PTHs. By implementing the same principle in a simplified version as compared to the Fujitsu system, a low cost demonstration system has been designed and built. The prototype system is particularly relevant to the small batch manufacturers in the PCB industry.

4. Such an LLD inspection system does not provide information regarding the location or shape of the defects reported. Yet the system output is proportional to the degree of unplated areas in each PTH. Consequently, a map showing the location and degree of through-hole plating voids can be constructed. This may carry helpful indications about the manufacturing process.

5. The Manufacturing Pilot Plant for electronic products in the Department of Production Technology has provided a suitable environment for testing the performance of the demonstration system. Both the design and the operation of this prototype have already demonstrated the simplicity and reliability of the technology. The potential to further improve this inspection system is realistic. It will therefore offer a practical low cost solution for the non-destructive inspection of PTHs.

9.2 RECOMMENDATIONS FOR FUTURE WORK

*   Further research into applying image processing techniques to the inspection of PTHs is desirable. Corresponding images from several bands including orange, red

and IR may be used to construct a multi-dimensional feature space for better discrimination of plated and unplated areas.

- Future improvement of the demonstration system may include:
    1. Modulate the source of illumination to reduce the effect of ambient light and electrical noise, thus improving the sensitivity of the system.

    2. Modify the design to inspect PTHs with higher aspect ratios. This would enable the system to cope with smaller diameter PTHs and multilayer boards.

    3. Use single channel electron multipliers or microchannel plates to replace the integrated photodiodes. With the more sensitive devices, it may be possible to relocate the sensors to the edges of a panel and detect leakage light at the edges.

    4. Investigate the possible use of other forms of penetrant energy such as IR radiation or an IR pulsing laser.

    5. Suggestions 3 and 4 are specifically aimed at seeking alternative arrangement for an LLD system. This is one which would allow a tiny amount of leakage energy from any PTHs to be detected at the edges of the panel. If that is possible, the new arrangement will increase the overall cost of the inspection system. However, the extra cost should be balanced against the advantages to be gained:

        ♦ The present hole-by-hole inspection system can easily be converted into a panel scanning system. This would increase the efficiency of the inspection process.
        ♦ Panels immediately after the electroless stage of the manufacturing process may be subjected to inspection. This would prevent defective panels from entering the next processing stage.

APPENDICES

Appendix 1-1
Some of the early printed circuit patents granted to Eisler

Source: [EIS85]

British Patent	Year	Title
245 43	1936	Printed Circuits
639 111	1943	Three-dimensional Printed Circuits
639 178	1943	Foil Technique of Printed Circuits
639 179	1943	Powder Printing
690 328	1948	Printed Circuit Capacitors
690 360	1948	Dielectric Materials
690 691	1949	Multilayer Materials for Printed Circuits

Appendix 2-1
Panel size to manufacturing operation relationships
Source: IPC-D-275

Operation	Typical maximum panel size (mm)
Drill	457 x 610
Scrub, deburr and most conveyorised finishing equipment	610 x (open)
Plating equipment	custom sized
Exposure equipment	610 x 610
Routing equipment	457 x 610
Screening equipment	508 x 762
Bare board test	457 x 457

Appendix 2-2
The manufacturing process for double-sided PCBs with PTHs
(Steps of panel rinsing and in-process inspections are not listed)
Source: [NIL91]

- **Cut panels**

1. Cut panels - to the required format size

- **Drill panels**

2. Drill tooling holes
3. Drill all other holes
4. Deburr/desmear

- **Electroless copper**

5. Soak clean
6. Mild etch
7. Sulphuric acid dip
8. Hydrochloric acid dip
9. Activator
10. Accelerator
11. Electroless copper deposition
12. Sulphuric acid dip

- **Flash plating**

13. Electroplate copper
14. Copper drag out
15. Post dip
16. Anti-tarnish
17. Dry panels
18. Drill non-PTHs - if any

- **Laminate resist and expose**

19. Laminate dry film (photoresist)
20. Expose circuit pattern - onto panel using UV source
21. Develop

- **Electroplate copper**

22. Acid clean
23. Mild etch - promote adhesion of electroplated copper
24. Sulphuric acid dip
25. Electroplate copper - build up to required thickness
26. Copper drag out
27. Acid dip
28. Electroplate tin/lead - etch resist

- **Strip and etch**

29. Strip resist - from all surfaces
30. Etch unwanted copper - with tin/lead protecting the circuit pattern
31. Condition panel
32. Flux
33. Reflow tin/lead
34. Deflux - hot rinse

- **Apply solder mask and legends**

35. Apply on to the panels by screen printing

- **Panel division**

36. Cut panels into individual PCBs

Appendix 2-3
Steps of electroless copper plating
Source: [LEO81,HED87,NIL91]

1. **Soak clean panels**

2. **Rinse**

3. **Mild etch**　　- to promote adhesion of copper by providing a mat finish

4. **Rinse**

5. **Sulphuric acid dip**　- to stop the etching action and remove etchant residue

6. **Rinse**

7. **Hydrochloric acid dip**　　- to prevent drag-in of chemicals to the bath

8. **Activator**　　- to create a catalytic film of Pd to initiate the deposition of Cu

9. **Rinse**　- with deionised water

10. **Accelerator**　- to increase the initial speed of Cu deposition by removing Sn

11. **Rinse**　- with deionised water

12. **Deposit electroless copper**　- reduction of copper ions into metallic form

13. **Rinse**

14. **Sulphuric acid dip**　- to remove electroless copper residues

15. **Rinse**

Appendix 2-4
Chemistry of electroless copper plating
Source: [LEO81]

1.   A panel is immersed in a solution containing stannous and palladium ions.

2.   Stannous ions are absorbed onto the surface of the epoxy resin and hence the drilled hole walls.

3.   The palladium ions are reduced to metallic form by the stannous ions which are oxidised to stannic ions:

$$Sn^{2+} + Pd^{2+} \rightarrow Sn^{4+} + Pd$$
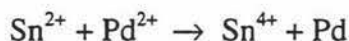
4.   The metallic palladium produced replaces the stannous ions on the hole walls and form thin films which act as a catalyst for copper deposition.

5.   Copper reduction:

- A solution containing copper sulphate, sodium hydroxide and formaldehyde is used. Dissociation of copper sulphate and sodium hydroxide produce these ions:

$$CuSO_4 \rightarrow Cu^{2+} + SO_4^{2-}$$
$$NaOH \rightarrow Na^+ + OH^-$$
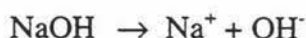
- Formaldehyde is oxidised, giving two electrons:
$$HCHO + 3OH^- \rightarrow HCOO^- + 2H_2O + 2e^{-1}$$

- Copper ions provided by the copper sulphate solution are reduced to metallic form:

$$Cu^{2+} + 2e^{-1} \rightarrow Cu$$
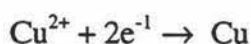
The metallic palladium produced at stage 3 and the freshly deposited copper act as catalysts for the transfer of the electrons.

Appendix 3-1
Sample of a plated-through hole test pattern
Source: IPC-D-275

Microsection Aids (Optional)
See Dimensions on Enlarged Version.

Microsection Aids (Optional)
Enlarged Version

IPC-I-0009X
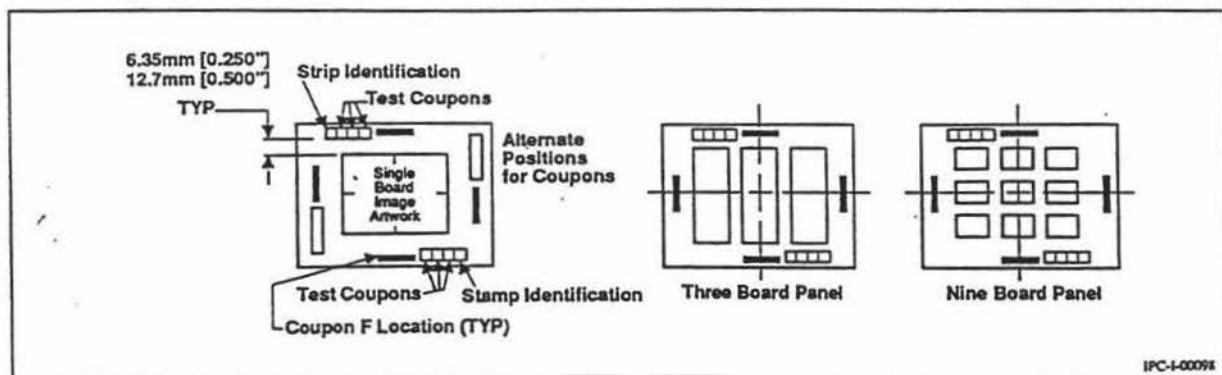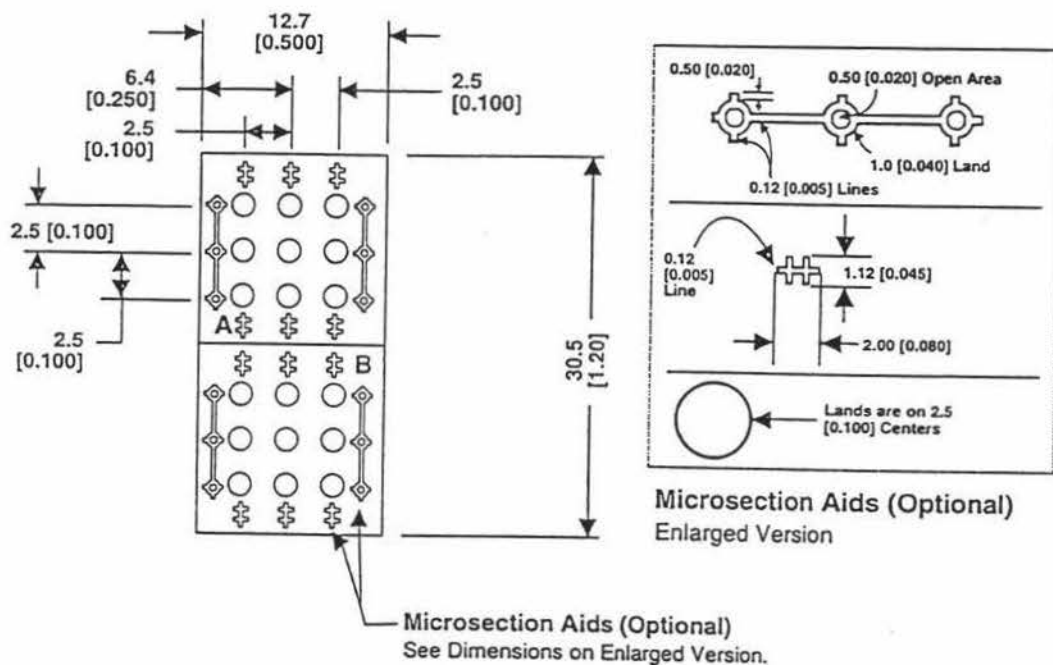
Appendix 3-2
Image processing techniques for surface conductor inspection
Source: [THO88,PAU90]

1.   Comparison technique

This technique is also known as template matching. It uses a "perfect" board as reference and the board under inspection is then compared with the reference either pixel-by-pixel or boundary-by-boundary. A difference image is produced by image subtraction. Any discrepancies from the reference board will be considered as defects. Features of this technique are:

- requires precise alignment of two images by applying correlation algorithms
- works well with very uniform objects
- computationally intensive but can be implemented by hardware
- requires storing a high resolution image of the reference board.

2.   Feature detection technique

This technique uses either hardware or software, each of which is programmed to extract a number of distinguishing features that correlate to the defects of interest. For example, attributes such as area, centre of gravity, perimeter and moments can be used to distinguish between a track and a pad. This technique:

- does not require a reference board.
- needs to identify a set of features that sufficiently define a defect
- feature extractors require tuning to find subtle defects.

3.   Design rule verification

This technique measures geometrical features and compares directly with known physical dimensions such as the design criteria for track width or track spacing. Features of the technique are:

- accurate and straightforward as physical quantities are measured
- detects a wide range of defects
- possible problems with non-standardised board design.

Appendix 3-3
Standard micro-sectioning procedure
Source: IPC-D-275

Microsectioning

2/88   C

1.0 Scope This procedure is to be used for preparing the metallographic specimen for evaluating the quality of the plated through hole and for evaluating plating and/or coating thickness on the printed board surface and in the hole. The same basic procedures may be used for mounting and examination of other areas.

2.0 Applicable Documents

ASTM-E3-58T

3.0 Test Specimens Cut the required specimens from a printed wiring board or test coupon. Allow sufficient clearance to prevent damage to the area to be examined. It is recommended that a minimum of one microsection containing at least three of the smallest size plated-through holes shall be made for each specimen tested.

4.0 Apparatus

- sample cutter (jeweler's saw)

- punch press with a relief on punch (*caution:* may cause board damage)

- router or diamond saw

- mount rings

- smoothflat mounting surface

- release agent

- sample supports

- metallographic polishing table

- belt sander (180 grit paper)

- metallograph

- room temperature curing potting material

- emery paper, (grit numbers 180–220 320, 400 and 600)

- cloth for polishing wheels alumina 5 and 0.3 micron

- polishing lubricant

- etching solution

- cotton swabs for cleaning and etchant application

- methanol

- engraver

5.0 Procedure

5.1 Preparation of Specimen Grind sample on 180–220 or 320 grit wheel to within approximately 0.050 inches of final polish depth. Deburr all edges prior to mounting.

5.2 Mounting Metallographic Sample Clean mounting surface and dry thoroughly, then apply release agent to the plate and mounting rings. Stand specimen in mount ring, with sample supports. If necessary. The surface to be examined should face the mounting surface. Fill the mounting ring carefully with potting material, assuring the sample remains upright and the holes are filled with encapsulating material. Epoxy potting materials may require vacuum degassing. Allow specimen to cure at laboratory temperatures (ambient), and remove hardened mount from ring. Identify the specimen by engraving or other permanent method.

5.3 Grinding and Polishing Using the metallographic equipment, rough grind the mount on the 180 grit belt sander. *Note:* Water flow must be used to prevent sample burning. Fine grind specimen to center of plated-through holes utilizing 240, 320, 400 and 600 grit discs in that order, until scratches and smear disappear. Rotate specimen 90° between each successive grit size and grind until marks from coarser grit have disappeared. Rinse sample with running tap water* and blow dry with air hose. Polish specimen with alumina polish to show a clear, sharp image of the various platings. Use a 5 micron paste to remove scratches left by 600 grit, followed by a 0.3 micron slurry (note 6.4). Rinse in methanol and blow dry. Examine, and repolish if necessary until a scratch-free mount is obtained. Swab specimen with suitable etching solution, (see 6.5) (typically applied for 2–3 seconds) to highlight demarcation lines. Rinse in running tap or deionized water to neutralize etchant. Rinse in methanol and blow dry.

* Optional—may use ultrasonic cleaner between polishing operations to reduce drag out of polishing media.

5.4 Examination Set the magnification at 100X minimum and measure the plating thickness of at least three plated- through hole sections. Total surface copper thickness can also be determined on the same specimen cross-section.

5.5 Evaluation Record average plating thickness determinations and quality of the plating.

Appendix 3-3   Standard micro-sectioning procedure (continued)

2.1.1   Microsectioning

C

6.0 Notes

6.1 Plating thickness determination should not be determined at nodules, voids, cracks, or irregular and thin platings.

6.2 Plating quality observations may include the following: blisters, laminate voids, cracks, resin recession, plating uniformity, burrs and nodules, and plating voids. In addition, plating quality for multilayer PWBs may include: innerplane bond to plated-through hole, resin smear, glass fiber protrusion, and epoxy etchback. Some of these conditions may be observed on the polished specimen prior to etching.

6.3 Overplating the specimen as per ASTM method E3-58T with a thin layer of nickel or other hard plating, prior to encapsulating, considerably improves sample quality and readability.

6.4 Diamond paste is preferred over alumina because PWBs are being evaluated for high reliability applications. A 6 micron and 1 micron diamond paste can be substituted for the alumina pastes called out in Section 5.3. Diamond paste substantially reduces the risk of specimen smear or burnishing.

6.5 Recommended solution for etching:

• 25 ml concentrated ammonium hydroxide

• 25 ml distilled water

• 3 drops of 30% hydrogen peroxide wait 5 minutes before using. Prepare fresh every day. (This is a typical etchant for tin-lead).

Appendix 4-1
Listing of macros for the image enhancement method

ReduceNoise;	*Apply built-in 3x3 median filter to image*
ApplyFilter;	*Invoke procedure 'ApplyFilter' - see listing below*
ShowHistogram;	*Display histogram of image to facilitate manual choice of threshold level*
SetThreshold(level);	*Enter threshold level manually*
MakeBinary;	*Convert into a binary image*
Erode;	*Apply the morphological operations*
Dilate;	

```
procedure ApplyFilter;
begin
  writeln('0 -1 0');
  writeln('-1 8 -1');
  writeln('0 -1 0');
  Convolve(");
  Dispose;
end;
```

Appendix 4-2
Establishing an optimum number of pixels for each ROI

The optimum number of pixels in each ROI is the minimum number of pixels necessary to identify a ROI as plated or unplated. Some of the voids found in through-hole plating are tiny (20 µm across), but a practical inspection system still needs to detect such voids. Hence, it is necessary to have a ROI to cover an area equivalent to the smallest void. If the number of pixels used for each ROI is large, to detect the smallest voids using the local histogram analysis technique would be computationally expensive. In addition, equipment having a higher magnifying power will be required. The following is a description on how the optimum number of pixels was found.

Stage 1.   Separate each captured colour image into its red (R), green (G) and blue (B) components. This can be done using the built-in macro in NIH Image. From amongst the R component of the frontlit images, more than 30 sample ROIs were selected using the corresponding backlit images as templates. Thus, the ROIs can be labelled as normal (plated) or defective (unplated). A histogram is compiled for each ROI. The maximum (*max*), minimum (*min*) and mode of the pixel intensities in each ROI were extracted (the

NIH Image software provides another macro for this purpose). The data obtained for the samples were plotted on a scatter diagram; with the x- and y-axes representing the quantities *max-mode* and *mode-min* respectively. The same procedure was applied to the G and B component images, resulting in three separate scatter diagrams. It was found that the plot from the R component data gave the best discrimination between plated and unplated regions. The scatter diagram for the R component is shown in figure A-1.

Stage 2. Using only the R component of the frontlit images, 87 sample ROIs were obtained. Various histogram features of the pixel intensities in the ROIs were again extracted. These included the maximum, minimum, mode, median, mean, sum (the sample size), range (the number of grey levels, or image contrast), variance (including standard deviation or SD), skewness and kurtosis. Microsoft Excel was used for the computation of the parameters and the plotting of diagrams.

The plot shown in figure A-2 involves three features: sum (sample size), max and SD. The sample size is also drawn on the plot as contours. It can be observed that for a sample size larger than some number between 50 and 100, the data points representing the normal and defective ROIs group into two areas in the diagram. The approximate boundary that partitions the normal and defective ROIs is depicted by the dotted line. As for the data points representing sample sizes less than 50, no discernible pattern of grouping exists.

Figure A-3 shows another plot of sample size v. SD using the same set of data. Grouping of the data points representing the plated and unplated surfaces is observed above a certain sample size between 50 and 100. This confirms the result as stated in the last paragraph.

Stage 3. Concentrating on ROI samples sized between 10 and 100, different features were plotted against one another. One of such plots is given in figure A-4. The minimum number of pixels required was narrowed down to between 50 and 65. It was observed that this minimum number varied with the particular histogram features selected to construct the diagram.
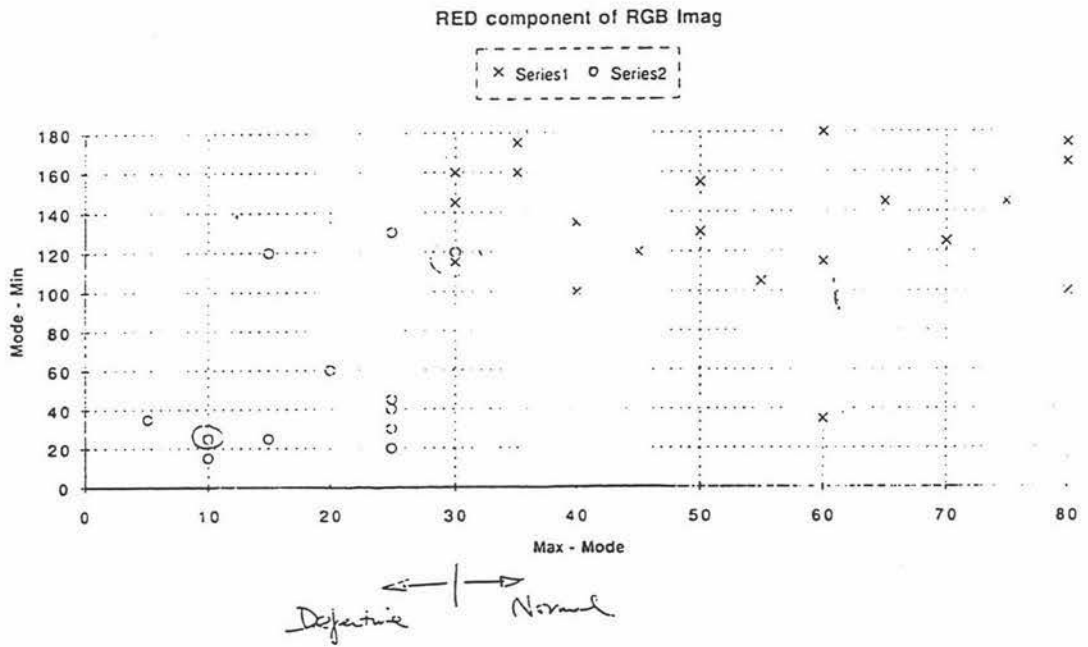
Figure A-1

RED component of RGB Imag

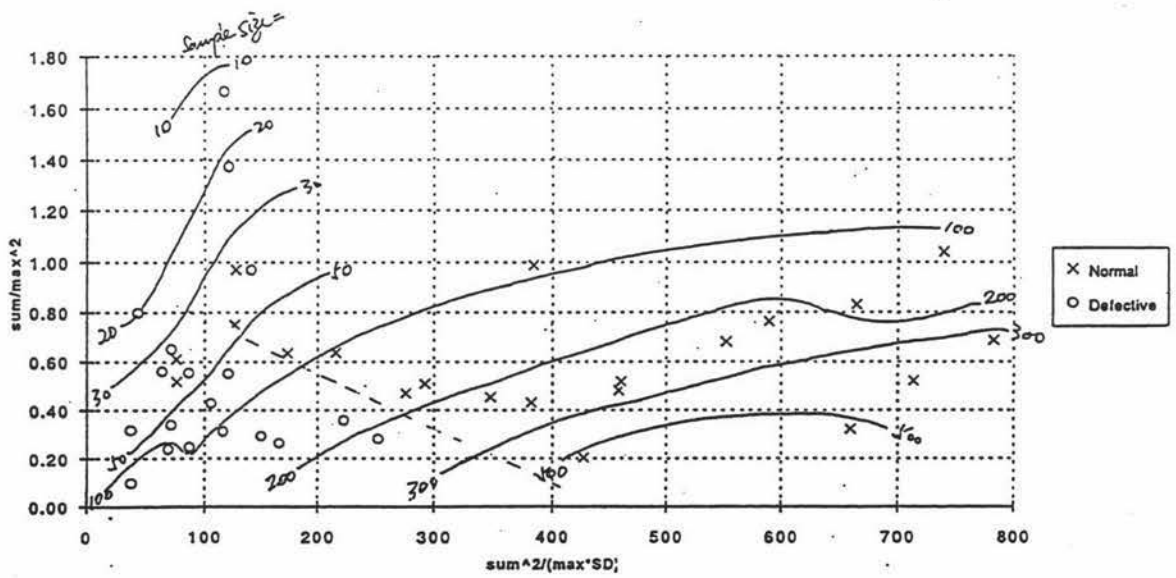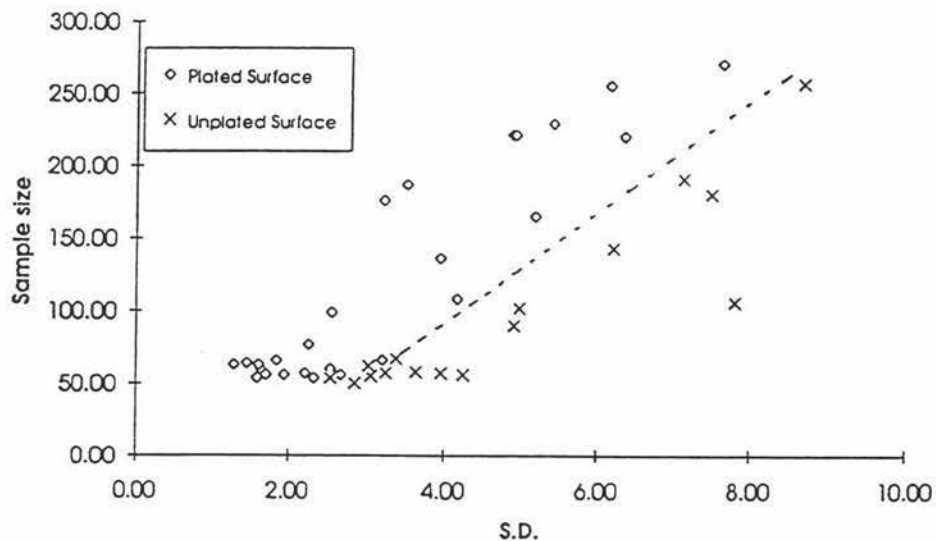Defective ←—|—→ Normal

Figure A-2

Figure A-3

Figure A-4
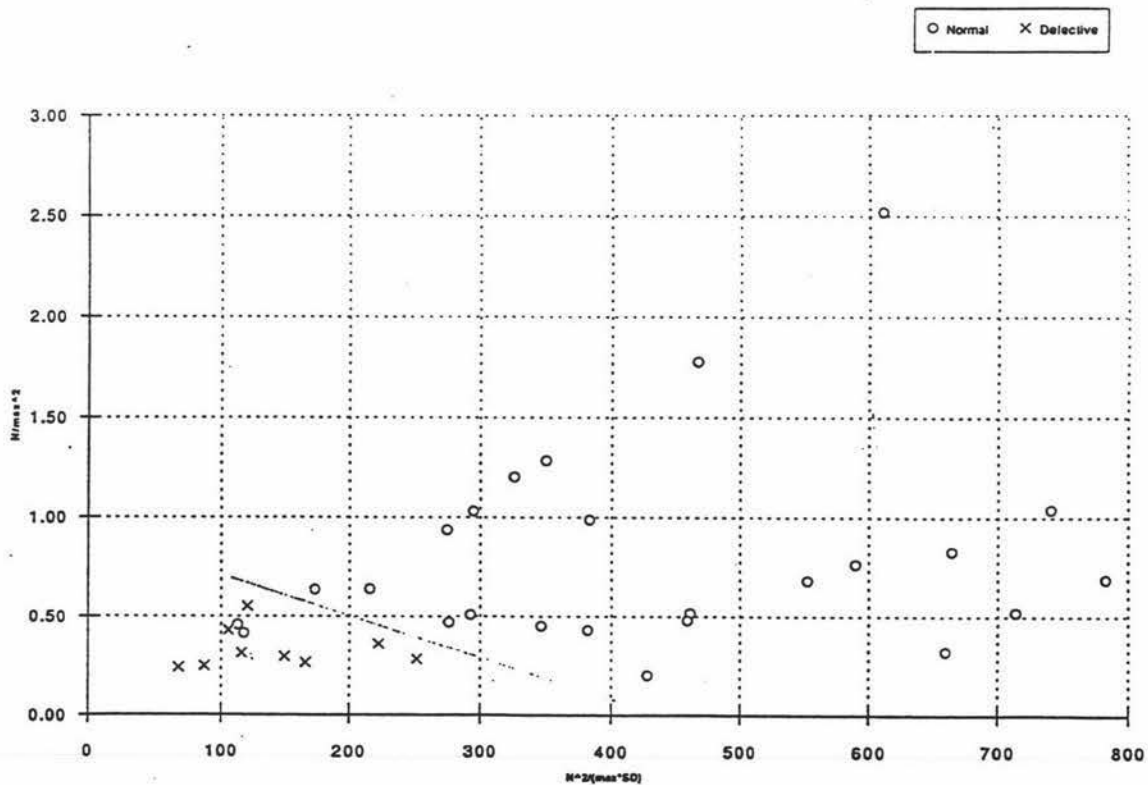
Figure 4.9 in section 4.3.5 of the main text gives the optimum result: a minimum sample size of 55 pixels using the parameters sample size, range and SD of the local histogram.

The following Image macros were written to facilitate some of the image manipulations described in this appendix. These procedures can be loaded as macros. For example, pressing the function key F1 invokes the macro number one ("adjust x-y") as defined in the corresponding *macro* statement found in the listing below:

```
procedure ShiftXY;   { procedure for shifting the position of an image so that the frontlit }
                     { and backlit images can align properly }
var
  width, height, m, n :integer;
  nWidth, nHeight, dx, dy :integer;

Begin
  GetPicSize(width,height);
  dx:=GetNumber('Number of pixels to shift left',0);
  dy:=GetNumber('Number of pixels to shift up',0);
  m:=0; n:=0;
  nWidth:=width-dx;
  nHeight:=height-dy;
  if dx<0 then begin
    nWidth:=width+dx;
    m:=abs(dx);
    dx:=0;
    end;
  if dy<0 then begin
    nHeight:=height+dy;
    n:=abs(dy);
    dy:=0;
    end;
  MakeRoi(dx,dy,nWidth,nHeight);
  Copy;
  KillRoi;
  MakeNewWindow('X-Y Shifted');
  SetNewSize(width,height);
  SelectWindows('X-Y Shifted');
  MakeRoi(m,n,nWidth,nHeight);
  Paste;
  KillRoi;
  SelectWindow('X-Y Shifted');
End;

macro 'Adjust X-Y [F1]'; begin ShiftXY; end;

macro 'ClearOutside';
begin
  Copy;
  SelectAll;
  Clear;
  RestoreRoi;
  Paste;
  KillRoi;
end;
```

```
procedure MakeGrid;
{ draw grid on an image }
begin
  SetForeground(0);
  SetLineWidth(1);
  DrawBoundary;
 end;

procedure pHistogram (m:integer);
var
   i,  p, dip : integer;
begin
  dip:=9999;
  for i:= m to max do begin
     if histogram[i] < dip then begin
          thres:=i;
          dip:=histogram[i];
           rUser2[rCount]:=dip;
          end;
   end;
end;

procedure ApplyFilter;
{invoke the built-in smoothing filter to implement 'unsharp masking'}
begin
  SaveState;
  Duplicate('B/G');
  Smooth;
  SelectAll;
  Copy;
  Dispose;
  SelectWindow('Temp');
  Paste;
  Subtract;
  RestoreState;
end;

procedure Partition;
{ partition an image into smaller blocks- block sizes to be specified by user }
var
  i, j, hloc, vloc, Width, Height, thres :integer;
  RoiWidth, RoiHeight, dx, dy :integer;
  n,mode,max,min,Xoffset, Yoffset :integer;
  mean:real;

Begin
  ResetCounter;
  Duplicate('Temp');
  RoiWidth:=GetNumber('X increment',0);
  RoiHeight:=GetNumber('Y increment',0);
  GetPicSize(width,height);
  dx:=width div RoiWidth;
  dy:=height div RoiHeight;
  Xoffset:=(width-dx*RoiWidth) div 2;
  Yoffset:=(height-dy*RoiHeight) div 2;
  hloc:=Xoffset;  vloc:=Yoffset;
  for j:=1 to dy do begin
     for i:= 1 to dx do begin
        MakeRoi(hloc,vloc,RoiWidth,RoiHeight);
        Measure;
```

```
                    GetResults(n,mean,mode,min,max);
                    pHistogram(round(mean));
                    MakeGrid;
                    rUser1[rCount]:=thres;
                    SetThreshold(thres);
                    MakeBinary;
                    hloc:=hloc+RoiWidth;
                end;
                vloc:=vloc+RoiHeight;
                hloc:=Xoffset;
            end;
            SelectWindow('Temp');
            ShowResults;
            SelectWindow('Results');
End;

macro 'Partition Image [F2]'; begin  Partition; end;

procedure EstimateVoid;
{ estimate the area of void as a percentage of the ROI}
var
    i, j, hloc, vloc, Width, Height :integer;
    RoiWidth, RoiHeight, dx, dy :integer;
    area, Xoffset, Yoffset :integer;

Begin
    ResetCounter;
    Duplicate('Temp');
    RoiWidth:=GetNumber('X increment',0);
    RoiHeight:=GetNumber('Y increment',0);
    GetPicSize(width,height);
    area:=RoiWidth*RoiHeight;
    dx:=width div RoiWidth;
    dy:=height div RoiHeight;
    Xoffset:=(width-dx*RoiWidth) div 2;
    Yoffset:=(height-dy*RoiHeight) div 2;
    hloc:=Xoffset;  vloc:=Yoffset;
    AutoThreshold;
    MakeBinary;
    SetPrecision(1,8);
    SetOptions('User1');
    SetUser1Label('% of voids');
    for j:=1 to dy do begin
        for i:= 1 to dx do begin
            MakeRoi(hloc,vloc,RoiWidth,RoiHeight);
            Measure;
            rUser1[rCount]:=Histogram[0]/area*100;
            MakeGrid;
            MarkSelection;
            hloc:=hloc+RoiWidth;
        end;
        vloc:=vloc+RoiHeight;
        hloc:=Xoffset;
    end;
    ShowResults;
    SelectWindow('Results');
End;

macro 'Area of Void [F3]'; begin EstimateVoid; end;

macro 'Adjust X-Y [F1]';
```

```
var
   width, height, m, n :integer;
   nWidth, nHeight, dx, dy :integer;

Begin
   GetPicSize(width,height);
   dx:=GetNumber('Number of pixels to shift left',0);
   dy:=GetNumber('Number of pixels to shift up',0);
   m:=0; n:=0;
   nWidth:=width-dx;
   nHeight:=height-dy;
   if dx<0 then begin
     nWidth:=width+dx;
     m:=abs(dx);
     dx:=0;
     end;
   if dy<0 then begin
     nHeight:=height+dy;
     n:=abs(dy);
     dy:=0;
     end;
   MakeRoi(dx,dy,nWidth,nHeight);
   Copy;
   KillRoi;
   MakeNewWindow('X-Y Shifted');
   SetNewSize(width,height);
   SelectWindows('X-Y Shifted');
   MakeRoi(m,n,nWidth,nHeight);
   Paste;
   KillRoi;
   SelectWindow('X-Y Shifted');
End;

macro 'Variance Image [F4]';
var
  x,y,xinc,yinc,width,height : integer;
  cellwidth,cellheight,value : integer;
  maxstd,max : real;

begin
  Duplicate('Variance');
  GetPicSize(width,height);
  xinc:=GetNumber('Cell Width:',15);
  yinc:=GetNumber('Cell Height:',xinc);
  max:=GetNumber('Max SD:',50);
  maxstd:=0;
  y:=0;
  repeat
    cellheight:=yinc;
    if (y+cellheight)>height then cellheight:=height-y;
    x:=0;
    repeat
      cellwidth:=xinc;
      if (x+cellwidth)>width then cellwidth:=width-x-1;
      MakeRoi(x,y,cellwidth,cellheight);
      measure;
      if rStdDev[rcount]>maxstd
        then maxstd:=rStdDev[rcount];
      value:=trunc(rStdDev[rcount]/max*253)+1;
       if value>254 then value:=254;
      SetForeground(value);
```

```
        fill;
        ResetCounter;
        x:=x+xinc;
      until x>=width;
      y:=y+yinc;
    until y>=height;
    KillRoi;
    ShowMessage('Max SD =',maxstd:1:2);
end;

macro 'Make Mean Image [F5]';
var
  x,y,xinc,yinc,width,height : integer;
  cellwidth,cellheight,value : integer;
  maxmean, max : real;

begin
  Duplicate('Mean');
  GetPicSize(width,height);
  xinc:=GetNumber('Cell Width:',16);
  yinc:=GetNumber('Cell Height:',xinc);
  max:=GetNumber('Max mean:',128);
  maxmean:=0;
  y:=0;
  repeat
    cellheight:=yinc;
    if (y+cellheight)>height then cellheight:=height-y;
    x:=0;
    repeat
      cellwidth:=xinc;
      if (x+cellwidth)>width then cellwidth:=width-x-1;
      MakeRoi(x,y,cellwidth,cellheight);
      measure;
      if rMean[rcount]>maxmean
        then maxmean:=rMean[rcount];
      value:=trunc(rMean[rcount]/max*253)+1;
       if value>254 then value:=254;
      SetForeground(value);
      fill;
      ResetCounter;
      x:=x+xinc;
    until x>=width;
    y:=y+yinc;
  until y>=height;
  KillRoi;
  ShowMessage('max mean=',maxmean:1:2);
end;
```

Appendix 5-1
Expert comments on the application of microwave to PTH inspection

The following is a transcript of the correspondence with Dr Rick Keam of Microwave Engineering Team, Industrial Research Limited, Auckland. Questions are set in italics type.

We shall limit our problem to double-sided board < 2mm thick with epoxy-fibreglass substrate sandwiched by copper foil. PTHs are 1 mm in diameter and all copper plating are > 30 μm in thickness.

This structure is somewhat similar to either radial-line, strip-line or microstrip transmission lines.

1. Is it possible to send microwave into the PCB substrate through the edges of the board?

Probably yes.

2. If then, is it true that we can treat the substrate as a high aspect ratio rectangular dielectric waveguide and the cavity within a PTH as a hollow cylindrical waveguide?

Yes, the substrate may be modelled as a transmission line, however the PTHs will act more like inductive post scatterers in the substrate. For frequencies below many ten's of GHz an energy that is coupled into the PTH will be below the cutoff frequency of that cylindrical guiding structure.

3. If both are ok and plating voids (may be as small as a disc having a diameter of 20 μm) do exist in a PTH, is it true that we practically have 2 waveguides coupled through a small hole in a copper partition?

Due to the small size (20 μm) relative to the wavelength the coupling between these waveguides will be extremely small, furthermore the PTH waveguide will be below cutoff.

4. Will some suitable choices of wavelength enable leakage of microwave energy from the PCB substrate into PTH cavities through the plating voids?

This frequency would have to be very high.

5. Will it be possible to detect the microwave energy inside a PTH?

It would be difficult to prevent the microwave energy coupling into the PTH by means other than faults (eg. Through surface waves along the top of the board etc).

Appendix 6-1
Response of the MFOD73

The photo-darlington was connected to an inverting amplifier powered by a 6 V power supply. The output saturated at about 4 V when no light was detected. A 35mm CCD camera lens was used to control the amount of light falling on the photo-darlington. The lens has aperture adjustment from f22 to f1.7, thus representing a nine-step change of relative light intensity from x1 to x250. With the lens placed immediately in front of the optical fibre which in turn was coupled to the MFOD73, the amount of light reaching the sensor became controllable.

Relative light levels were used throughout. Three light intensity levels were selected. These are referred to as strong, medium and low light levels. These levels were achieved by pointing the camera lens directly at a 75W light bulb, towards a distant window and at a wall respectively. Nine readings, each corresponding to one f-stop of the aperture, were taken at each light level. The results are presented in figure A-5.
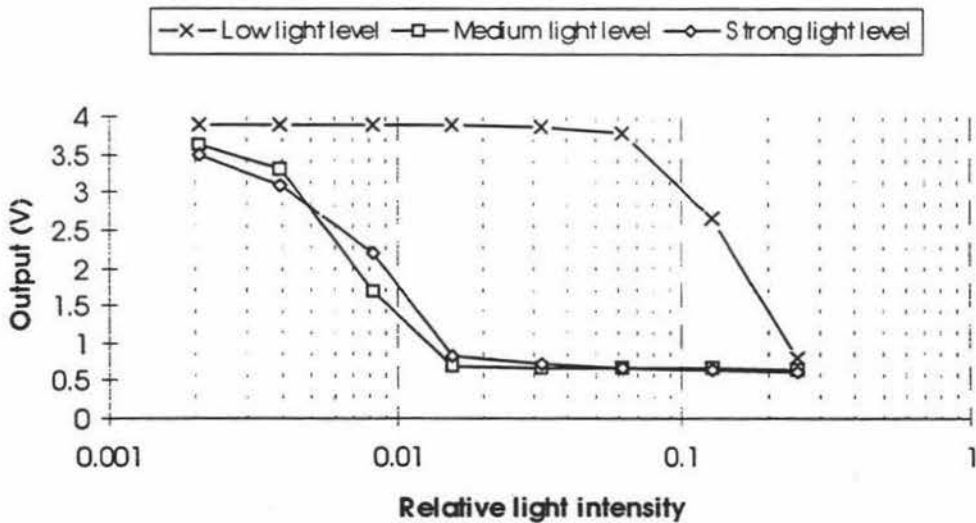

Figure A-5   Response of the MFOD73 photo-darlington

IPL 10530DAL
HYBRID DETECTOR

APPLICATIONS

- General purpose detection
- Short and medium distance data links
- Light level monitoring.

Photodiode

Amplifier Chip

FEATURES

- Hybrid construction
- Easy to use and interface
- Analogue amplified voltage output
- High interference rejection
- Low thermal drift
- Response from 400 to 1200nm.
- Positive going output for increasing light level

The IPL 10530DAL Hybrid Photodetector provides an output voltage proportional to the incident light level.

The device will operate from single or dual power supplies, allowing simple interface with logic circuit or voltage comparators.

The 10530DAL consists of a photodiode and an amplifier with a feedback circuit mounted on a ceramic substrate. The feedback circuit is designed to provide a unique gain/bandwidth performance characteristic

The device is encapsulated in a four lead to TO5 package with a biconvex lensed window. The lens allows all normally incident light to be focused on the photodiode chip, offering improved gain and scattered light immunity.

The metal TO5 package is especially suitable for high electrical noise environments, since both amplifier and detector are close together within a screened can.
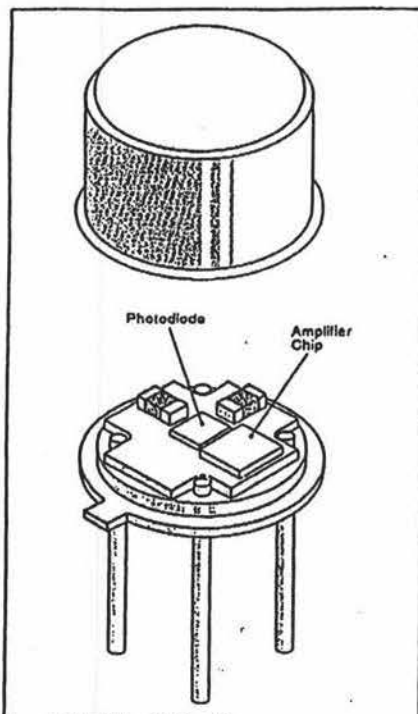
## IPL 10530DAL HYBRID DETECTOR

DEVICE CHARACTERISTICS

Absolute maximum ratings	DC supply voltage	+4v to +36v
		±2v to ±18v
	Output Short Circuit Duration	Indefinite
	Output Current	Sink 1mA
		Source 10mA
	Dissipation up to 55°C	630 mW
	Dissipation above 55°C	Derate linearly 6.67mW/°C
	Temperature Range	Operating -40 to +85°C
		Storage -50 to +100°C

General Characteristics	Output Voltage	860mV/μW/cm^2 at 900nm.
	Noise Dark Level	0.75 mV pk-pk.
	Output Offset	±10mV max
	Frequency Response	65 khz (-3db)
	Photodiode Active Area	1.75 mm^2
	Detection Angle	28° (Total Angle between 3db points)
	Temperature Coefficient of Output Voltage	-0.03%/°C
	Temperature Coefficient of Output Offset	+ 2.5 μV/°C
	Responsivity	Peak 900nm
		50% 570nm, 1050nm
		10% 390nm, 1190nm.

All characteristics are typical values at 22°C. IPL reserve the right to change the product shown on this leaflet in the interest of improved specification. No responsibility is assumed for the use of information contained herein, nor for any infringement of patent or rights of others which may result from such use. No licence is granted by implication or otherwise under any patent or patent right of Integrated Photomatrix Limited or others.
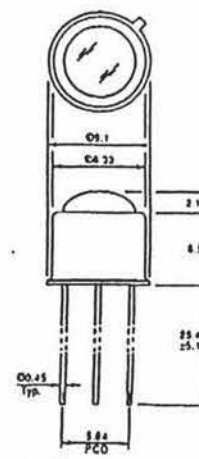

BASIC CIRCUIT DIAGRAM
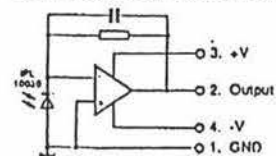
PINOUT DIAGRAM
(pin view)
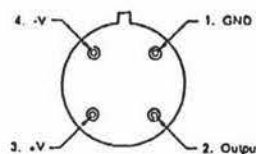
PACKAGE OUTLINE

Appendix 7-1
NIH Image commands for component polarity inspection

MakeRoi (left, top, width, height);   *define ROI manually*
ReduceNoise;   *apply built-in 3x3 median filter to ROI*
ShowHistogram;   *display histogram of ROI to facilitate choice of*
    threshold level
SetThreshold(level);   *enter threshold level manually*
MakeBinary;   *convert ROI into a binary image*
Erode;   *apply the morphological operations*
Dilate;   *and repeat if necessary*
MoveRoi(dx,dy);   *move the ROI by dx and dy pixels to the right and*
    down to cover the next component

Appendix 7-2
Selection of equipment for stuffed board component inspection

1.   Available Equipment

Imaging Devices: CCD camera, Akai Hi 8 Video camera and Chinon document scanner.

Frame Grabbers: MaxVideo20, SCION LG-3 & Data Translation frame grabbers.

Computers: Macintosh Quadra and SPARC Workstation. The Macintosh Quadra was fitted with both the SCION and Data Translation frame grabbers. The MaxVideo20 frame grabber can only be used with the SPARC Workstation.

Components for test: Test board populated with 2 ICs, 2 diodes and a transistor.

Combination of imaging device and frame grabber tested:

	CCD camera	Akai Video camera
MaxVideo 20	yes	yes
SCION LG-3	yes	yes
Data Translation	yes	yes

The Chinon document scanner works independently without a frame grabber. It was connected to the Macintosh Quadra computer during the experiment. The software for scanning was supplied by Chinon along with the document scanner.

- **Document Scanner**

The Chinon DS-2000 is a flat bed document scanner that can be used to capture images of stuffed PCBs vices such as the CCD camera. The purpose was to compare the performance of the various combinations of equipment.

Specifications of the Chinon DS-2000 flat bed document scanner:

Scanning system	*flat surface scanning using linear 1024 element CCD sensor*
Resolution	*75 DPI to 200 DPI*
Greyscale	*3 bits, 8 dithering levels*
Area of scan	*equivalent to A4 size*
Interface with computer	*SCSI*
Scanning software	*specially supplied by the manufacturer*

The scanner was found to be unsatisfactory for capturing PCB images for inspection purposes. One of its fundamental limitations is that the user has no other choice than either the pre-set thresholding or the dithering of grey levels. Both actions will throw away important information at an early stage and thus are not suitable for subsequent image processing. Attempts to make the scanner work with a frame grabber failed due to the lack of a well-defined standard sync signals from the scanner. Another limitation of the scanner is that no available frame grabber can phase lock to a slow device such as the Chinon DS-2000 scanning at around 200 Hz.

- **SCION LG-3**

The SCION LG-3 is designed for the use with CCD cameras and RGB video sources. However it has limited tolerance towards recognising video signals with imprecise timings. This means that the LG-3 may be difficult to synchronise with certain imaging equipment such as a consumer quality video camera. The resulting images were found to be unsatisfactory.

2. Experiments

The experiments were aimed at finding out which of the devices, namely the CCD camera, the Akai Video camera and the Chinon document scanner, would be the best for component polarity inspection. The combinations described in section 7.3.1 were used to capture images of the test board. Three aspects of the captured images were assessed:

- **Image noise level**

  These are subjective ratings graded by two persons. The test images of boards to be used for comparison were first captured using the different hardware combinations then displayed at the same time on screen for grading.

- **Overall image contrast**

  Comparison of image contrasts was made by referring to the histogram of intensities for the images involved. The histograms were generated by the software NIH Image. An image with a wider range of intensity distributions would be considered as having a higher contrast.

- **Image resolution**

  Image resolution was determined by measuring the actual areas and lengths of certain features on the test board. The results were used to divide the number of pixels corresponding to such features in the images. Image resolutions are expressed in either pixel per mm or DPI.

3.   Results

Result 1: Image noise levels

	CCD camera	Akai Video camera
MaxVideo 20	*low*	*low*
SCION LG-3	*medium*	*high*
Data Translation	*medium*	*medium*

Chinon scanner	*low*

Key:	**high**	*unacceptable*
	medium	*noticeable but acceptable*
	low	*barely noticeable*

Result 2: Image contrast

The Akai video camera gave better contrasts than the CCD camera under similar lighting conditions. This result was obtained by comparing the range of pixel intensity variations in the images concerned. The histogram of the image captured by the video camera had a slightly wider range than a similar image captured by the CCD camera. Images obtained from the Chinon scanner had similar contrasts to those captured by the CCD camera. However, the lighting setup was different, and so the results may not be directly

compared. The document scanner has its built-in light sources directed at approximately 45 degrees to the object under scan.

Result 3: Image resolution

The Chinon scanner delivered a fixed resolution of 75 DPI (8 bit undithered). As already discussed in section 7.2.3 of the main text, this is inadequate. The area covered by each scan is equivalent to a page of A4. Both the CCD and the Akai Video cameras had similar image resolutions. When the cameras were zoomed to cover an area about 12x15 cm, the resolutions were about 150 DPI (6 pixel/mm). This is a satisfactory resolution. When made to cover an A4 area, the resolutions for both cameras dropped to below that of the scanner (less than 60 DPI or 2.3 pixels/mm).

4.   Findings and Conclusions

- The SCION LG-3 frame grabber works with an imaging device that generates precise timing signals (such as the CCD camera) in order to capture acceptable quality images. It produced very noisy images when used with a video camera.

- The Data Translation grabber has more flexible timing requirements than the LG-3. Much less noise were found in the images when it was used with the video camera.

- The performance of the MaxVideo 20 frame grabber is apparently superior to the other frame grabbers. The timing specifications are programmable for devices operating from 3.3 KHz to 26 MHz. However, it cannot work with very slow devices like the Chinon scanner, which operates at only about 200 Hz.

- The Chinon scanner offers undithered 8 bit grey images covering an A4 area, but only at a relatively low resolution of 75 DPI. This resolution is regarded inadequate for a practical inspection system.

- Both the CCD and Akai video cameras can be made to deliver a desirable resolution, such as 150 DPI. However, that would mean looking at an area roughly 12x15 cm at a time. Consequently, two or three images need to be acquired to cover an A4 sized PCB entirely.

REFERENCES

[AND88]   M.Ando, M.Nakashima, T.Inagaki, 'Automated visual inspection for printed circuit boards', *Fujitsu Sci. Tech. J.*, **24**, 1, March 1988, pp. 1-23.

[ANG87]   A.Angstenberger, 'Optical inspection of printed circuits:requirements placed on AOI in the manufacturing process', *Circuit World*, **13**, 3, 1987, pp.8-10.

[ANG94]   A.Angstenberger, 'Desmear - the key processes for reliable through-plating of printed circuitry', *Circuit World*, **20**, 4, 1994, pp.8-15.

[ARA89]   J.Arabian, *Computer integrated electronics manufacturing and testing,* Marcel Dekker, New York, 1989.

[BER84]   A.J.Berlin, 'Drilled hole wall quality standards', *Printed Circuit Fabrication*, March 1984, pp.68-73.

[BET86]   C.E.Betz, *Principles of penetrants*, 2nd ed., Magnaflux, Chicago, 1986.

[BIC75]   D.Birchon, *Non-destructive testing*, Oxford University Press, London, 1975, pp.10.

[BID87]   P.W.Birdsall, 'Application of electrochemical principles to acid copper plating', *Circuit World*, **13**, 4, 1987, pp.33-36.

[BLO89]   J.P.Block, 'The ideal hole', *Printed Circuit Fabrication*, February 1989, pp.32-40.

[BOO93]   C.J.Booth (ed.), *The new IEEE standard dictionary of electrical and electronic terms*, IEEE, New York, 1993.

[BOS83]   W.C.Bosshart, *Printed circuit boards design and technology*, Tata McGraw-Hill, New Delhi, 1983.

[BRI94]   P.L.Britton, 'PCB fabrication technologies for improved performance and cost', *Circuit World*, **20**, 4, 1994, pp.16-18.

[COO88]   C.F.Coombs, *Printed circuits handbook*, 3rd ed., McGraw-Hill, New York, 1988.

[CUL84]   B.Culshaw, *Optical fibre sensing and signal processing*, Peter Peregrinus, London, 1984.

[CUS94]   W.D.Custer, R.C.Linsdell, S.W.Shoemaker, The world printed circuit industry, *Circuit World*, **20**, 3, 1994, pp.42-45.

[DAW87]   T.F.Dawson, 'Automatic microsectioning of multilayer PTH coupons', *Printed Circuit Fabrication*, July 1987, pp.62-68.

[DEN86]   P.N.J.Dennis, *Photodetectors*, Plenum, New York, 1986, pp.67-69.

[DOU85]   J.J.Doubrava, 'The black hole and beyond: the production of void-free plated through holes', *Printed Circuit Fabrication*, August 1985, pp.14-29.

[DOY84]   K.G.Doyle, 'Automatic optical inspection of printed circuit boards', *Circuit World*, **11**, 1, 1984, pp.38-40.

[EIS85]   P.Eisler, 'Reflections on my life as an inventor, part 3, patents & judgment', *Circuit World*, **11**, 3, 1985, pp.16-20.

[EJI89]   M.Ejiri, *Machine vision*, Gordon and Breach, New York, 1989.

[FEL88]   M.Feldin, C.Zevnik, I.Kovac, 'A new approach to outgassing study of plated through hole printed boards', *Circuit World*, **15**, 1, 1988, pp.22-27.

[FLA92]   M.O.Flatt, *Printed circuit board basics,* Miller Freeman, San Francisco, 1992.

[HAI91]   D.B.Harris, P.Lall, 'Printed wiring board design and fabrication'. In M.Pecht (ed.), *Handbook of electronic package design*, Marcel Dekker, New York, 1991.

[HAL91]   R.Halmshaw, *Non-destructive testing*, 2nd ed., Edward Arnold, London, 1991, pp.262-271, 302.

[HAY89]   M.J.Harry, 'PCB plated through hole optimisation: a case study in SPC', *Circuit World*, **16**, 1, 1989, pp.33-43.

[HED87]   R.P.Heddon, *Cost engineering in printed circuit board manufacturing*, Marcel Dekker, New York, 1987, pp.44-45.

[HOD85]   R.M.Hodgson, D.G.Bailey, M.J.Naylor, A.L.M.Ng, S.J.McNeill, 'Properties, implementations and applications of rank filters', *Image and vision computing*, **3**, 1, February 1985, pp.3-14.

[HOD92]   R.M.Hodgson, 'Digital image processing - a developing technology for enhancing productivity', *Proc. Control 92*, (invited paper), Perth, Australia, November 1992.

[HOW86]   F.H.Howie, C.Lea, 'Blowholing in PTH solder fillets, part 2: the nature, origin and evolution of the gas', *Circuit World*, **12**, 4, 1986, pp.20-25.

[INT93]   'International institute news', *Circuit World*, **19**, 3, 1993, pp.59.

[JAI89]   A.K.Jain, *Fundamentals of digital image processing*, Prentice Hall, NJ, 1989.

[JOR68]   E.C.Jordan, K.G.Balmain, *Electromagnetic waves and radiating systems*, 2nd ed., Prentice-Hall, NJ, 1968, pp.130.

[KAO82]   C.K.Kao, *Optical fiber systems: technology, design and applications*, McGraw-Hill, New York, 1982.

[KEA87]   F.W.Kear, *Printed circuit assembly manufacturing*, Marcel Dekker, New York, 1987.

[LAT93]   T.D.T.Latter, 'Measurement of coating thickness via micro-resistance', *Circuit World*, **20**, 1, 1993, pp.29-30.

[LEA86a]   C.Lea, 'The importance of high quality electroless copper deposition in the production of plated-through-hole PCBs', *Circuit World*, **12**, 2, 1986, pp.16-21.

[LEA86b]   C.Lea, M.P.Seah, F.H.Howie, 'Blowholing in PTH solder fillets, part 4: the plated copper barrel', *Circuit World*, **13**, 1, 1986, pp.28-34.

[LEA86c]   C.Lea, F.H.Howie, 'Blowholing in PTH solder fillets, part 5: the role of the electroless copper', *Circuit World*, **13**, 1, 1986, pp.35-42.

[LEA87]   C.Lea, F.H.Howie, M.P.Seah, 'Blowholing in PTH solder fillets, part 8: the scientific framework leading to recommendations for its elimination', *Circuit World*, **13**, 3, 1987, pp.11-20.

[LEO81]   G.Leonida, *Handbook of printed circuit design, manufacture, Components & assembly*, Electrochemical, Ayr, 1981.

[MAK94]   K.C.Mak, R.M.Hodgson, R.F.Browne, R.R.Nilson, 'Image processing techniques for nondestructive testing of printed circuit boards', *Proc. 2nd New Zealand Conf. on Image Vision & Computing*, Palmerston North, August 1994, pp.2.5.1-2.5.5.

[MAT90]   B.S.Matisoff, *Handbook of electronics packaging design and engineering*, 2nd ed., Van Nostrand Reinhold, New York, 1990.

[MCO92]   B.M.McCormack, 'Test coupons as an aid to process control of the PCB manufacturing and assembly processes', *Circuit World*, **18**, 3, 1992, pp.17-20.

[MEY91]   R.A.Meyers (ed.), *Encyclopedia of lasers and optical technology*, Academic Press, San Diego, 1991, pp.37-38.

[MIL84] J.Miller,W.Archer-Burton, 'Quality products: the bottom line', *Printed Circuit Fabrication*, November 1984, pp.22-34.

[MNA92] J.McNaughton, *Adding value in New Zealand (vol. 2): the role of technology - industry case studies,* Ministry of Research, Science and Technology, Wellington, 1992, pp.85-87.

[NAK92] H.Nakahara, 'Fine line conductor formation', *Circuit World*, **18**, 2, 1992, pp.42-46.

[NIL91] R.R.Nilson, A.J.Collett, 'Some technical aspects of a manufacturing pilot plant', *Proc. 28th National Electronics Conference*, Palmerston North, August 1991, pp.48-54.

[NOB89] P.J.W.Noble, *Printed circuit board assembly- the complete works*, Open University Press, Milton Keynes, 1989, pp.95-96.

[NOR69] H.N.Norton, *Handbook of transducers for electronic measuring systems*, Prentice-Hall, NJ, 1986.

[OST91] M.D.Osterman, M.Pecht, 'Introduction'. In M.Pecht (ed.), *Handbook of electronic package design*, Marcel Dekker, New York, 1991.

[PAU90] L.F.Pau, *Computer vision for electronics manufacturing*, Plenum Press, New York, 1990.

[POL84] M.E.Pole-Baker, 'Printed circuits-origins and development', *Circuit World*, **10**, 4, 1984, pp.4-6.

[ROB89] S.L.Robinson, R.K.Miller, *Automated inspection and quality assurance*, Marcel Dekker, New York, 1989.

[RUS92] J.C.Russ, *The image processing handbook.* CRC Press, Boca Raton, 1990, pp.381-382.

[SCH94] A.R.Schaefer, J.A.Janesick, 'Charge coupled devices'. In L.Ristic (ed.), *Sensor technology and devices*, Artech House, Norwood MA, 1994, pp.341-343.

[SEN86] W.D.Senecal, 'Looking for a few good holes: an in-house drilling test for printed circuit shops', *Printed Circuit Fabrication*, April 1986, pp.46-50.

[SID93] D.Siddons, 'Inner-layer registration testing system', *Circuit World*, **19**, 3, 1993, pp.54.

[THE62] J.Thewlis (ed.), *Encyclopaeic dictionary of physics*, Pergamon, Oxford, 1962, pp.653.

[THO88]   D.Thompson, T.Stroebel, 'Designing electronics for automated inspection', *Circuit World*, **14**, 4, 1988, pp.13-20.

[THU92]   J.Thuery, 'The laws of radiation'. In E.H.Grant (ed.), *Microwaves: industrial, scientific and medical applications*, Artech House, MA, 1992, pp.77.

[TSU88]   H.Tsuzaka, T.L.Taylor, 'The big picture of drilling small holes', *Printed Circuit Fabrication*, March 1988, pp.25-33.

[TYL94]   R.L.Tyler, 'PCB investment strategy into the 1990s', *Circuit World*, **20**, 3, 1994, pp.46-52.

[VAN88]   H.Vandervelde, 'The game is small hole drilling, the rules are strict', *Printed Circuit Fabrication*, March 1988, pp.18-22, 102-103.

[WAK86]   L.S.Watkins, P.Pleshko, M.Wolf, 'Optical devices and displays'. In C. Belove (ed.), *Handbook of modern electronics & electrical engineering*, John Wiley & Sons, New York, 1986, pp.383.

[WAL86]   C.I.Wall, 'Screenprinting in the printed circuit board industry', *Circuit World*, **12**, 3, 1986, pp.36-40.

[WAT86]   J.Watson, 'Photodetectors & electronics'. In A.R.Luxmoore(ed.), *Optical transducers and techniques in engineering measurement*, Applied Science, Barking, 1986.

[WEI89]   M.Weinhold, 'Quo Vadis Printed (circuit) board? Seeking the most cost-effective interconnect solution for electronic equipment', *Circuit World*, **16**, 1, 1989, pp.13-18.

[WIC87]   C.Wick, R.F.Veilleux (ed.), 'Quality control and assembly', *Tool and manufacturing engineers handbook, volume 4 (4th ed.)*, Society of Manufacturing Engineers, Michigan, 1987, pp.6-106.

[ZUE87]   N.Zuech, R.K.Miller, *Machine vision*, Fairmount, Lilburn GA, 1987.