UNIVERSITI TEKNIKAL MALAYSIA MELAKA

A DEVELOPMENT OF TIME DOMAIN REFLECTOMETRY (TDR) METHODOLOGY TO DETECT WIRE SWEEP DEFECT IN NEARLY SHORT CONDITION

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DOCTOR OF ENGINEERING

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A dissertation submitted
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DEDICATION

To my beloved parents, Mr. Ng Heyau Jin and Madam Yeo Ai Chee; my wife Ms Swee Siew Fiew; my daughter Ng Shi Yi and lastly my son Ng Shi Hong.

ABSTRACT

Wire sweep is a common defect observed in power semiconductor devices, especially when bonded with thin aluminium wire (< 100µm). The conventional methods for detecting the wire sweep defect are Automatic Optical Inspection (AOI), Real-Time X-ray and Automatic Test Equipment (ATE). However, all three methods are having capability limitations to detect the wire sweep defect, especially in nearly short conditions. The objective of this research is to develop a new test methodology to detect the wire sweep defect using Time Domain Reflectometry (TDR) that can overcome the limitations of these conventional methods. The focus of the wire sweep defects is on the wire-wire sweep and wire-lead sweep. The research is using power semiconductor device bonded with 75µm thin aluminium wire as test samples and consists of three experiments and a case study. The first experiment is to select the optimal TDR probe measurement methods that can be used to detect wire-related failure in a power semiconductor device. The second experiment is to study whether TDR can detect and respond when there is a wire sweep failure in the power semiconductor device. The last experiment is to characterize the response of the TDR curve with a statistical data analysis method and establish modelling with regression equations that can be used to predict the gap between the two wire sweeps. Lastly, a case study is performed to confirm that the proposed TDR methodology can detect the wire sweep defects and the gap for the wire sweep can be estimated using the regression equation model. By performing TDR measurement using Single-Pin Grounded method at the affected pin of the power semiconductor having a wire sweep defect and calculating the area under the TDR curve with a 4pSec time-range, the TDR curve shifts statistical significantly (p-value ≤ 0.05) to lower impedance in comparison to a good reference curve. This demonstrates that the proposed method using TDR can detect and respond to both types of wire-wire (WW) sweep and wire-lead (WL) sweep defects. By fitting the value for the area under the TDR curve into the regression equation established, the estimated gap between the wire sweep is within +/-10% tolerance in comparison to the actual gap. From this research, it is demonstrated TDR can detect both wire sweep defects in nearly short conditions on a power semiconductor device bonded with thin aluminium wire; and can overcome the limitation of conventional methods using AOI, X-ray and ATE electrical test. The area under the TDR curve together with the regression equation model can be used to predict the gap between wire sweep which is useful since it is a non-destructive method.

PEMBANGUNAN KAEDAH PEMANTULAN DOMAIN MASA UNTUK MENGESAN KECACATAN SAPUAN WAYAR DALAM KEADAAN HAMPIR LITAR PINTAS

ABSTRAK

Sapuan wayar merupakan kecacatan biasa dalam pembuatan peranti semikonduktor kuasa terutamanya apabila menggunakan wayar aluminium yang halus (< 100µm). Kaedah konvensional yang digunakan untuk mengesan kecacatan sapuan wayar adalah dengan menggunakan Pemeriksaan Optik Automatik (AOI), Sinaran-X dan Peralatan Ujian Automatik (ATE). Namun, ketiga-tiga kaedah tersebut mempunyai kelemahan dalam mengesan kecacatan sapuan wayar terutama dalam keadaan hampir litar pintas. Objektif penyelidikan ini adalah untuk mencari kaedah alternatif baru bagi mengesan kecacatan sapuan wayar dengan menggunakan Pemantulan Domain Masa (TDR). Fokus jenis kecacatan sapuan wayar adalah pada sapuan wayar-wayar dan sapuan wayar-pin. Penyelidikan ini menggunakan peranti semikonduktor kuasa yang diikat dengan wayar aluminium halus 75µm sebagai sampel ujian dan mempunyai tiga fasa penyiasatan dan satu kajian kes. Penyelidikan pertama adalah untuk menentukan teknik pengukuran TDR terbaik yang boleh digunakan untuk mengesan kegagalan berkaitan wayar di dalam peranti semikonduktor kuasa. Penyelidikan kedua adalah melakukan kajian untuk mengetahui sama ada TDR dapat mengesan dan bertindak balas apabila terdapat kecacatan sapuan wayar dalam peranti semikonduktor kuasa. Penyelidikan terakhir adalah untuk mencirikan tindak balas TDR dengan cara menganalisa data secara statistik dan mewujudkan persamaan regresi yang dapat digunakan untuk meramalkan jarak di antara sapuan wayar. Akhir sekali, kajian kes dilakukan untuk mengesahkan sama ada TDR dapat mengesan dan menganggarkan jurang sapuan wayar. Pengukuran TDR dilaksanakan dengan menggunakan kaedah Pembumian Pin Tunggal pada pin yang mempunyai kecacatan sapuan wayar, dan menghitung kawasan keluasan di bawah graf TDR dengan tempoh 4pSec. Didapati graf TDR beralih secara signifikan (nilai $p \leq 0.05$) ke impedan yang lebih rendah jika dibandingkan dengan sampel yang baik. Ini menunjukkan bahawa kaedah pengesanan yang dicadangkan dengan menggunakan TDR mampu mengesan kedua-dua jenis kecacatan sapuan wayar. Dengan memasukkan nilai untuk keluasan di bawah graf TDR ke dalam persamaan regresi, didapati ia dapat menganggarkan jurang sapuan wayar dengan toleransi sebanyak +/- 10%. Dari penyelidikan ini, jelas ditunjukkan bahawa TDR dapat mengesan kecacatan sapuan wayar pada peranti semikonduktor kuasa yang diikat dengan wayar aluminium halus dan dalam keadaan hampir litar pintas. Dengan ini, TDR dapat mengatasi kelemahan kaedah konvensional menggunakan AOI, sinaran-X dan ATE. Selain itu, kawasan di bawah graf TDR bersama dengan persamaan regresi dapat digunakan untuk meramalkan jurang antara sapuan wayar secara tidak merosakkan peranti semikonduktor kuasa.

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LIST OF ABBREVIATIONS

AELB - Atomic Energy Licensing Board
Al - Aluminium
AOI - Automatic Optical Inspection
ATE - Automatic Test Equipment
Au - Gold
BE - Backend
BGA - Ball Grid Array
CAGR - Compound Annual Growth Rate
CMOS - Complementary Metal-Oxide-Semiconductor
Cu - Copper
DB-FIB - Dual-Beam Focused Ion Beam
EBGA - Thermally Enhanced Ball Grid Array
fcBGA - Flip Chip Ball Grid Array
FE - Frontend
FEA - Finite Element Analysis
GaN - Gallium Nitride
GR&R - Gage Repeatability and Reproducibility
GTO - Gate Turn-Off Thyristor
IC - Integrated Circuit
IGBT - Insulated-Gate Bipolar Transistor
Laser - Light Amplification by Stimulated Emission of Radiation
LFBGA - Low-profile Fine-pitch Ball Grid Array
MCM - Multi-Chip Module
Mg - Magnesium
MOSFET - Metal-Oxide-Silicon Field Effect Transistor
NDA - Non-Destructive Analysis
OEF - Open-End Fixture
PCB - Printed Circuit Board

QFP - Quad Flat Package
RF - Radio Frequency
SAM - Scanning Acoustic Microscopy
SCR - Silicon Controlled Rectifier
SEM - Scanning Electron Microscopy
Si - Silicon
SiC - Silicon Carbide
SiO2 - Silicon Dioxide
SQUID - Superconducting Quantum Interference Device
TDR - Time Domain Reflectometry
UV - Ultraviolet

LIST OF SYMBOLS

Z_O - Characteristic Impedance
^{o} C - Degree Celsius
d - Distance
GHz - Giga Hertz
Z_L - Load Impedance
μm - Micrometre
mm - Millimetre
Nm - Nanometre
nSec - Nanosecond
Ω - Ohm
% - Percentage
pSec - Picosecond
ρ - Reflection coefficient
S/m - Siemens per meter
Td - Time delay
Vp - Velocity of Propagation

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LIST OF PUBLICATIONS

Journal

Ng, K.K. and Soo, Y.G.**,** 2022. Comparison Study of Time Domain Reflectometry (TDR) Measurement Methods for Detecting Wire Interconnect Related Open-Contact and Short-Contact Failures in Power Semiconductor. *Trends in Sciences*, 19(11), pp.4207-4207.
(Published: May 16, 2022)

Ng, K.K. and Soo, Y. G., 2021, New Method of Wire sweep Detection in Plastic Moulded Semiconductor Component Using Time Domain Reflectometry (TDR). *Solid State Technology*, 64(2), pp 2304 – 2314.
(Published: February 12, 2021)

CHAPTER 1

INTRODUCTION

1.1 Background

Figure 1.1 is showing the typical manufacturing flow in producing semiconductor devices with wire bonding as one of the important processes (Bard et al., 2015; Park et al.; Ye N., 2020). The purpose of wire bonding is to provide electrical connections in microelectronics as shown in Figure 1.2 (Harman, 2010). During wire bonding, the wire is attached to a bond pad or lead post by applying large amounts of heat or ultrasonic vibration (depending on wire bonding types), pressure and high force over a limited period on the wire (Shannon, 2019). Nowadays, wire bonding is performed with the wire bonder machine to achieve good bonding quality and high throughput (Levine, 2016).

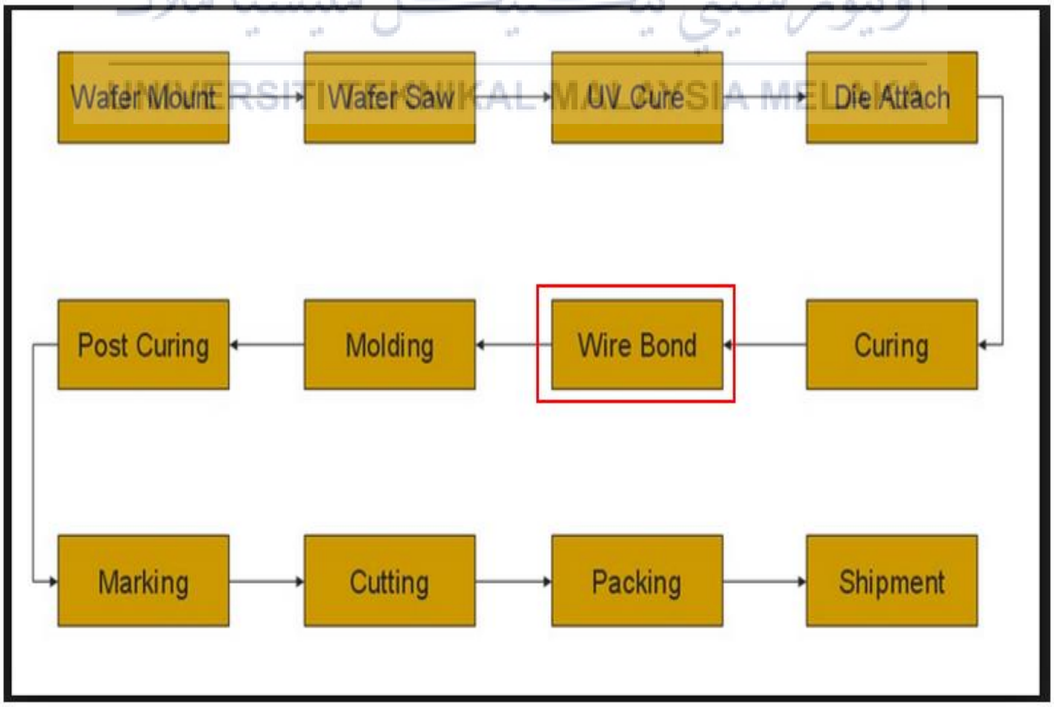

Figure 1.1 Typical semiconductor device manufacturing flow

There are three main types of wires used for wire bonding, namely: gold (Au) wire, copper (Cu) wire and aluminium (Al) wire (Harman, 2010; Lee, H. et al., 2019). Aluminium wire is widely used for wire bonding in power semiconductor devices because of its advantages over gold and copper wires (Pecht et al., 2017). With the shrinkage in size and increased integration density of semiconductor IC (integrated circuit), the pitch between bond pads is becoming closer and there is a need to use thinner wire during the wire bonding (van Driel, 2009). A thin wire is known to have a lower wire sweep resistance (Teh, S.S et al., 2010). Lower wire sweep resistance means the wires prone to shift during the manufacturing processes; before the semiconductor IC is being covered and protected with the plastic moulding compound. This is leading to one of the critical defects in the wire bonding process that is known as the wire sweep defect and is shown in Figure 1.3 (Liu, P. et al., 2012). If the wire sweeps and comes into contact with other wires, it will cause the device electrically to malfunction and fail at the final electrical test (Chen, H.S et al., 2008). However, if the wire only sweeps in proximity to neighbouring wires (known as a nearly short condition), this defective device may not always be able to remove during the final electrical test (Ming et al., 2015). As a result, it ends up with reliability failure where the defective semiconductor device failed later in the field applications (Tummala et al., 2013; Qu, F. et al., 2021). The worst-case scenario is the defective semiconductor device with a wire sweep defect failed in the field application and leads to the casualty of human life (Yun, G et al., 2018). For example, the malfunction of a semiconductor device used in automotive applications such as anti-lock braking systems (ABS) can cause serious car accidents. Therefore, the detection of a defective semiconductor device with a wire sweep defect in the nearly short condition is important.

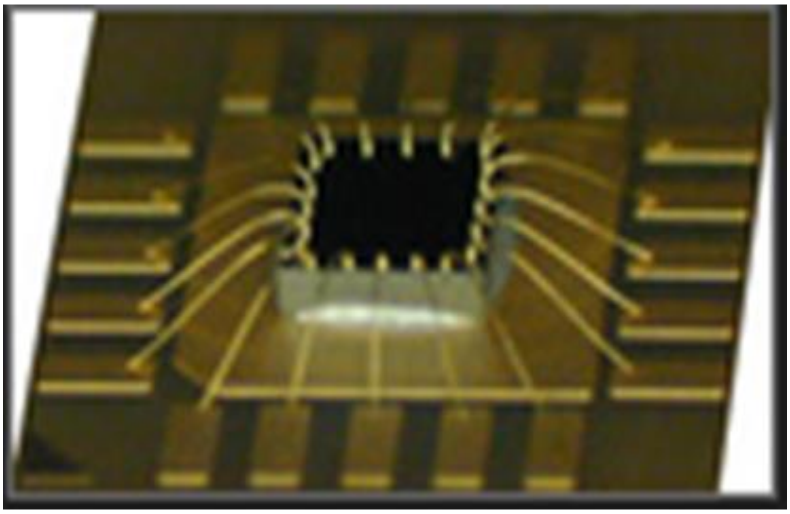

Figure 1.2 Semiconductor device bonded with wire bonding

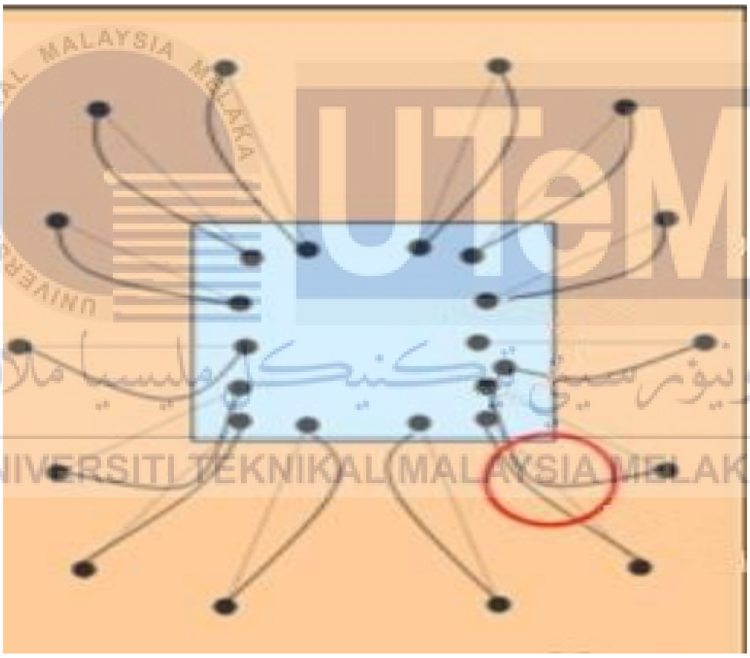

Figure 1.3 Semiconductor device with wire sweep defect

1.2 Problem Statement

There are three common methods used for detecting the wire sweep defect in a semiconductor device during the manufacturing process. These methods are by using Automatic Optical Inspection (AOI), Real-Time X-ray and Automatic Test Equipment