A STUDY OF Sn-Ag-Cu SOLDER INTERCONNECTION BEHAVIOUR UNDER GAMMA RADIATION EXPOSURE

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Thesis submitted to the Centre for Graduate Studies, Universiti Pertahanan Nasional Malaysia, in fulfilment of the requirements for the Degree of Master of Science (Physics)

ABSTRACT

The resilience of microelectronic packaging to gamma radiation is a crucial factor in solder joint evaluation due to its impact on the reliability of electronics within radiation-prone environments. This study focused on tin-silver copper (Sn96.5Ag3.0Cu0.5; SAC305) solder joints durability due to extreme gamma radiation environment. The SAC305 solder were exposed to gamma radiation with doses ranging from 5 to 50000 Gy. The evolution of the microstructure, intermetallic compound layer growth, crystallographic structure of solder alloy and behaviour of micromechanical properties of SAC305 solder joint due to gamma radiation exposure was investigated. The microstructure and IMC layer images were captured using optical microscope and then analysed by using ImageJ software. The micromechanical properties of solder joint such as the hardness, reduced modulus and creep behaviour was determined using nanoindentation testing and analysed using Oliver-Pharr Method. As the gamma radiation dose increased, the IMC layer thickness increases due to heat-induced coarsening behaviour. The XRD results show the presence of the β-Sn, Cu_6Sn_5 and Ag_3Sn phases. Micromechanical properties obtained from nanoindentation test indicated that the occurrence of wavy-pattern on the load-depth (*P*-*h*) curve. As radiation dose increased, the SAC305 solder transition from elastic to plastic. For the 0 Gy of SAC305 solder, the hardness and reduced modulus values were determined to be 0.26 GPa and 66.5 GPa, respectively. Prolonged exposure to gamma radiation leads to the coarsening of Ag_3Sn, diminishing the strengthening effect of the compound and increasing dislocation mobility. The eutectic phase area showed a parallel trend to the hardness value obtained. Overall, gamma radiation significantly

impacts microstructure, mechanical properties, and solder joint performance. Consideration of gamma radiation effects is essential in electronic package design for reliable operation in radiation-prone environments.

ABSTRAK

Ketahanan pempakejan mikroelektronik terhadap sinaran gama adalah faktor penting dalam penilaian sambungan pateri kerana kesannya terhadap kebolehharapan elektronik dalam persekitaran yang cenderung kepada sinaran. Kajian ini memberi tumpuan kepada ketahanan sambungan pateri timah-perak-kuprum (Sn96.5Ag3.0Cu0.5; SAC305) terhadap persekitaran gama yang ekstrem. Sambungan pateri SAC305 telah terdedah kepada sinar gama dengan dos dari 5 hingga 50000 Gy. Evolusi mikrostruktur, pertumbuhan lapisan sebatian antara logam (IMC), struktur kristalografi aloi, dan tingkah laku sifat-sifat mikromekanikal sambungan pateri SAC305 disebabkan pendedahan kepada sinar gama telah diselidiki. Mikrostruktur dan imej lapisan IMC dicerap menggunakan mikroskop optik dan kemudian dianalisis dengan menggunakan perisian ImageJ. Sifat-sifat mikromekanikal sambungan pateri seperti kekerasan, modulus terkurang, dan rayapan ditentukan menggunakan ujian pelekukan nano dan dianalisis menggunakan kaedah Oliver-Pharr. Dengan peningkatan dos sinar gama, ketebalan lapisan IMC meningkat disebabkan oleh kelakuan pelembutan akibat haba. Keputusan XRD menunjukkan kehadiran fasa β-Sn, Cu_6Sn_5, dan Ag_3Sn. Sifat-sifat mikromekanikal yang diperoleh daripada ujian pelekukan nano menunjukkan kehadiran corak bergelombang pada lengkung beban-kedalaman (*P*-*h*). Dengan peningkatan dos radiasi, sambungan pateri SAC305 berubah dari keadaan elastik kepada plastik. Bagi sambungan pateri SAC305 kawalan, nilai kekerasan dan modulus terkurang ditentukan masing-masing adalah 0.26 GPa dan 66.5 GPa. Pendedahan yang berpanjangan kepada sinar gama menyebabkan pelembutan Ag_3Sn, mengurangkan kesan penguatannya dan meningkatkan mobiliti kehelan.

Kawasan fasa eutektik menunjukkan trend yang selari dengan nilai kekerasan yang diperoleh. Secara keseluruhan, sinaran gama secara signifikan mempengaruhi mikrostruktur, sifat-sifat mekanikal, dan prestasi sambungan pateri. Pertimbangan kesan sinar gama adalah penting dalam reka bentuk pembungkusan elektronik untuk operasi yang boleh dipercayai dalam persekitaran cenderung radiasi.

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APPROVAL

The Examination Committee has met on **12 July 2024** to conduct the final examination of **Muhammad Nur Hisyam Bin Rosman** on his degree thesis entitled **'A Study Of Solder Interconnection Behaviour Under Gamma Radiation Exposure.'.**

The committee recommends that the student be awarded the of Master of Science (Physics).

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Academic session	: 2024/2025

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LIST OF ABBREVIATIONS

Ag	-	Argentum
Au	-	Gold
Au-Sn	-	Gold-Tin
BGA	-	Ball Grid Array
Bi	-	Bismuth
Cd	-	Cadmium
Cu	-	Copper
Co-60	-	Cobalt-60
DSC	-	Differential Scanning Calorimetry
EDS	-	Energy Dispersive X-ray Spectroscopy
EMR	-	Electromagnetic Radiation
FESEM	-	Field Emission Scanning Electron Microscopy
FIB	-	Focussed Ion Beam
Ge	-	Germanium
HCl	-	Hydrochloric acid
hrs	-	hours
HRTEM	-	High-resolution Transmission Electron Microscopy
IMC	-	Intermetallic Compound
In	-	Indium
IPC	-	Institute for Printed Circuits
min	-	minute
PCB	-	Printed Circuit Board
P-h	-	Load-depth
PTH	-	Plated through-hole
Pu	-	Plutonium
Ra	-	Radium
RoHS	-	Restriction of Hazardous Substances
s	-	second

Sb	-	Antimony
SiC	-	Silicon Carbide
SMT	-	Surface Mount Technology
Sn-Ag-Cu, SAC	-	Tin-Silver-Copper
Sn-Cu	-	Tin-Copper
Sn-Pb	-	Tin-Lead
SVPC	-	Solder Value Product Council
TGA	-	Thermogravimetric Analysis
Th	-	Thorium
U	-	Uranium
WEE	-	Waste Electrical and Electronic Equipment Directive
XRD	-	X-Ray Diffraction

LIST OF SYMBOLS

A	-	dose rate
A_c	-	projected contact area
A_o	-	initial activity
α	-	alpha
β	-	Beta
c	-	speed of light
$^\circ C$	-	Celsius
d	-	d-spacing
dh	-	change of displacement
dP	-	change of load
E	-	reduced modulus
E_i	-	reduced elastic modulus
E_r	-	initial elastic reduced modulus
e	-	indenter geometry
$e+$	-	Proton
$e-$	-	Electron
H	-	Hardness
h	-	depth
h_c	-	contact depth
h_f	-	final displacement
h_s	-	Stiffness displacement
h_{max}	-	maximum depth
hv	-	energy of directional photon
hv'	-	energy of scattering photon
m_0c^2	-	rest mass of electron
n	-	poisson’s ratio
P	-	Load
P_{max}	-	contact depth
S	-	Stiffness

s	-	Second
T	-	Temperature
t	-	Time
$t_{1/2}$	-	half life
v	-	Velocity
v_i	-	poisson's ratio for indenter
γ	-	gamma radiation
λ	-	Wavelength
θ	-	Angle
$^\circ$	-	Degree

CHAPTER 1

INTRODUCTION

1.1 Background

The durability and reliability of interconnection in electronic packaging is very important especially when it is applied to satellites, spacecraft, biomedical or nuclear power devices since this equipment ordinarily interacts with ionizing radiation such as high energy cosmic, neutron and gamma rays. Ionizing radiation has enough energy to alter the properties of the material by breaking its chemical bond will cause degradation and displacement damage. Therefore, the assessment of its mechanical, and physical properties and microstructural study at the atomic level such as dislocation movements and solder interconnection behaviour are vital to prevent the failure in electronic packaging.

Application of microelectronics packages covers almost all areas of application including radiation-related industries such as radiography used in medical and health sciences; and non-destructive testing. According to Arshak *et. al.,* (2004), exposure to ionizing radiation can occur in various occupational environments such as educational institutes, research establishments and medical institutions. Gamma radiation, a form of ionizing radiation, is denoted by γ. This electromagnetic radiation consists of packets of photons, which are massless particles with very high frequencies and very short wavelengths. Yannakopoulos *et. al.,* (2008) mentioned that the effects of radiation on matter could be grouped into atomic displacement, production of impurities and ionization. Ray (2023) reported that electronic solid-state devices experience displacement damage of solder after exposed to radiation. Some of these radiation effects may lead to changes in terms of the physical and chemical properties of the substance. Irradiation on electronic material may degrade the device's performance (Arshak *et. al.*, 2004) and also alter the internal structure of the materials and therefore their mechanical and chemical properties (Stiegler *et. al.*, 1979). Previous studies showed that package material can be affected by gamma radiation (Jalar *et. al.*, 2014; Yusoff *et. al.*, 2011). In satellite sensor applications, microelectronic packages are embedded in sensor devices. These devices may be exposed to high levels of gamma radiation. Sensors may be affected by prolonged exposure to ionizing radiation such as gamma rays. The results from these studies may lead to improvement in material selection and the design of microelectronic packages. Earlier studies have investigated the effects of radiation on the solder joint, microelectronic packages and devices (Wen *et. al.*, 2020; Wang *et. al.,* 2018; Gong *et. al.,* 2017; Arutt *et. al.*, 2016; Jalar *et. al.,* 2012). Yusoff *et. al.,* (2014) found that exposure to Co-60 gamma radiation-induced dislocation of atomic arrangement on gold ball bond. According to Abdul Amir *et. al.,* (2009), the occurrence of atomic displacement on the silicon metal oxide semiconductor due to ionizing radiation has decreased the reliability of the sample. The subthreshold irradiation plays an important role in the microstructure evolution and defects migration on irradiated ceramics (Zinkle and Kinoshita 1997). However, the study on the durability and reliability of interconnect materials especially solder joints (for extraordinary applications) such as