3D Imaging of Electrical-Thermal-Mechanical Deformation on Bonding Wire Loops using Phase-Sensitive Line-field Optical Coherence Tomography

Zhiyi Zhao, Zijian Zhang, Xingyu Yang, Yihua Hu, Ju Xu, Yaochun Shen
Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool L69 3GJ, UK
Department of Electronic Engineering, University of York, YO10 5DD York, UK
Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China
Author e-mail address: ycshen@liverpool.ac.uk

Abstract: The repetitive electrical-thermal-mechanical deformation causes bonding wires failures that can damage whole power electronic modules. The LF-OCT can measure electrical-thermal-mechanical deformation on a bonding wire's loop, which can help the reliability analysis of bonding wires. © 2022 The Author(s)

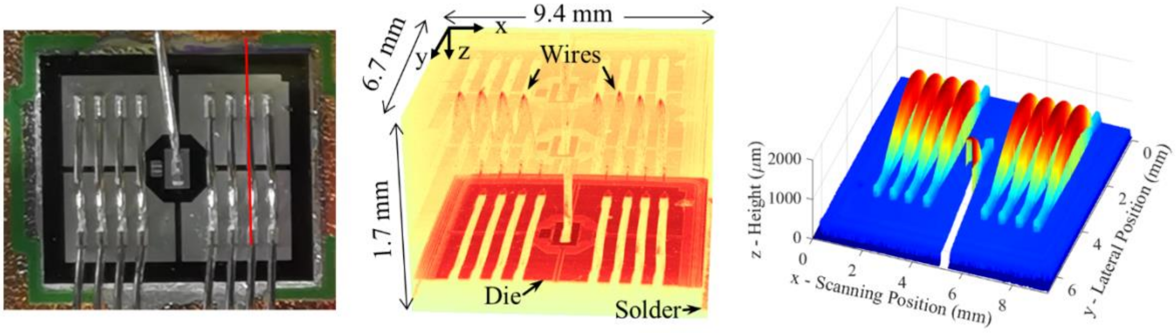
1. Introduction

Insulated gate bipolar transistor (IGBT) modules are widely employed as switching semiconductor devices in power converters/inverters that establish the connection between different power components. The failures of IGBT modules can cause catastrophic faults in the whole power conversion system. The bonding wires are the most fragile components in IGBT modules due to the repetitive electrical-thermal-mechanical (ETM) deformations in use. The ETM deformation-induced bonding wires failures, such as wire lift-off and heel cracks, affect the reliability and reduce the lifetime of IGBT modules. Therefore, there is an urgent need for analytical techniques to characterise the bonding wire deformation behaviour.

Several methods, including the laser Doppler vibrometer (LDV) [1], the laser displacement sensor [2], and the confocal monochromatic sensor [3], have been used to study the ETM deformation behaviour in power modules. However, these methods cannot simultaneously measure the displacements of different points on a bonding wire in real-time; e.g., the ETM displacement distribution on a wire loop cannot be obtained. More recently, line-field optical coherence tomography (LF-OCT), which can acquire cross-sectional images in a single shot, was proposed for characterising bonding wire deformation [4]. In this work, we report the imaging of the displacement distribution on a bonding wire loop by using our in-house built phase-sensitive LF-OCT system with nanometre displacement sensitivity.

2. 3D Imaging of IGBT sample

The IGBT sample used in this study is shown in Fig. 1 (a). Eight parallel-connected heavy bonding wires (emitter wires) provide interconnections between the IGBT die's emitter side and the DBC substrate. The wire bonded at the centre of the die (gate wire) is used for switching control of the IGBT. The IGBT sample was placed on a motorised translational stage, and the volumetric data were acquired at a frame rate of 10 B-scan images per second when the stage was moving at a speed of 0.1mm/s along the x-direction. Each B-scan image covers an area of 6.7mm (y-direction) x 1.7mm (z-direction). Fig.1 (b) shows the resultant volumetric OCT data where the bonding wires, IGBT die, and solders are visible.Fig.1 (c) shows the surface topograph of the IGBT sample which was obtained by finding the peaks of A-scan waveforms of the 3D volumetric OCT data.



(a) (b) (c)

Fig. 1 IGBT sample. (a) Photograph of IGBT sample; (b) Acquired volumetric data; (c) Surface topograph of the IGBT sample, and the colour represents different heights.

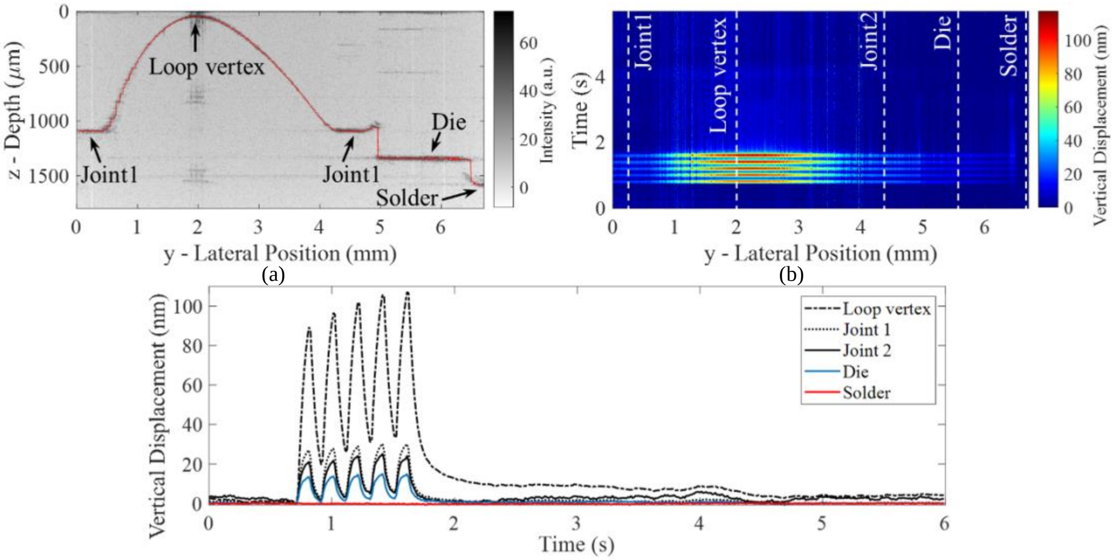
3. Time-dependent Displacement Distribution on a Bonding Wire Loop

In order to study the time-dependent displacement distribution of a bonding wire, the vertical displacement of a bonding wire was imaged when a load current (4 A, 5 Hz, 1 second, 50% duty cycle) was applied to the IGBT device where 8 bonding wires share the load current. The measurement position is marked as the red-solid line in Fig. 1 (a). Fig. 2(a) shows a typical B-scan image where the bonding wire loop is on the left, and the IGBT die and solder surface are on the right. The red curve on the B-scan indicates the detected surface. Fig. 2(b) shows the time-dependent vertical displacement map, and Fig. 2(c) shows the vertical displacements extracted at different positions over a measurement duration of 6 seconds. The vertical displacements Δz are calculated by Equation (1) [5].

$$\Delta z = \varphi / (2nk_o) \tag{1}$$

φ denotes the phase angle calculated from the complex OCT depth profile, n is the refractive index ($n=1$ when measuring bare IGBT sample), and k_o is the centre wavenumber of the light source. The results show that different parts of the sample exhibit significant differences in the amplitude of the vertical displacement. For example, the vertical displacements of the wire bond joints and die are smaller than that of the centre of the bonding wire, namely the loop vertex. The most prominent vertical displacement is observed a the loop vertex, while insignificant displacement is observed at the solder. In addition, the bonding wire shows rapid changes during the presence of the load current. The wire returns to its original position within a few seconds after the load current was turned off.

In conclusion, we experimentally measured the displacement distribution on a bonding wire loop for the first time. The experimental results can provide useful data to assist bonding wire loop geometry design and reliability analysis, and validate the simulation results.



(a) (b)

(c)

Fig. 2 Vertical displacement on a bonding wire loop (a) B-scan of the bonding wire loop. Red curve denotes the detected surface of the sample; (b) Time-dependent vertical displacement map; (c) Vertical displacements acquired from different points indicated by white dash lines.

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