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Techniques for dynamic analysis of bonding wire

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ABSTRACT

This study describes new experimental techniques for dynamic analysis of bonding wire. The techniques employ a laser Doppler vibrometer (LDV) for non-contact measurement of wire response to transient, impact, and steady-state (harmonic) excitations. The first technique determines the transients and response time of the wire to current pulse excitations. The second technique, employs impacts delivered by a solenoid actuator to perform modal analysis on bonding wire and obtain their natural frequencies. Steady-state experimental techniques are also developed to obtain the mode shapes, nodal points, and frequency-response curves of bonding wire under thermal (current) excitation.

These techniques are deployed to study the response of 300μm diameter Aluminum and Aluminum coated Copper bonding wires to DC and AC currents. The experimental results are interpreted and verified by comparing them to numerical results obtained from finite element analysis. This study experimentally measures and reports, for the first time, the second and fourth in-plane and the second out-of-plane bending mode shapes of bonding wire.

1. Introduction

Demand for bonding wires continues to increase despite the availability of other alternatives [1]. More than 4 trillion wire bonds are made annually [2]. Many of these use thick bonding wire, 100–500μm in diameter, predominantly used in Insulated Gate Bipolar Transistors (IGBT) modules, which require transfer of high power from one chip to another. The high current involved in energy transfer generate heat, through Joule heating, and lead to various failure mechanisms, such as heel crack and lift-off [3]. Thin bonding wires, 25–100μm in diameter, are increasingly being used for interconnects in MEMS modules.

The prediction of wire life time is critical to safe operation of electronic modules. Investigators have taken into account thermal [4], mechanical [5], and power (current) cycling [6] loads. These are all time varying, fatigue inducing, load cycles that jointly determine wire life time. Merkle et al. [5] found that high aspect ratio thick bonding wires can withstand a higher number of load cycles to failure. On the other hand, Barber et al. [7] reported that thin bonding wires failed within a few minutes under low current, power cycling when it driven at primary resonance with AC currents with a frequency close to their natural frequency. Their results demonstrate the importance of identifying the natural frequencies of bonding wire and avoiding resonance inducing currents.

Investigators also analyzed the dynamic response of bonding wires, curved beams and circular rings. Wang et al. [8] proposed an analytical method to determine the natural frequencies and mode shapes of bending modes in the wire plane (in-plane) assuming a circular ring wire shape. Irie et al. [9] used Timoshenko beam theory to determine the natural frequencies of bending modes out of the wire plane (out-of-plane) assuming a circular ring wire shape and taking rotary inertia into account. Laura et al. [10] used Rayleigh-Ritz method to obtain the natural frequencies of the first two in-plane bending modes for hinged and clamped arches with linearly varying thickness.

Czerny et al. [11] experimentally measured the in-plane displacement of bonding wire under currents with amplitudes of 4 A and 10 A and frequencies in the operational range for IGBT modules, 200–1000 Hz. They obtained the time-response of the wire displacement using a laser Doppler vibrometer (LDV). Barber et al. [7] presented an approach to experimentally determine the natural frequencies of bonding wires with 12% standard deviation using back e.m.f.

This paper develops experimental techniques to carry out full dynamic analysis of bonding wires, including transient, steady-state, and modal analyses. All techniques employ non-contact measurement of the wire displacement and velocity in response to thermal and external impact excitations. The measured natural frequencies and modes shapes of 300μm diameter Aluminum (Al) and Aluminum coated Copper (CucorAl) bonding wires are verified and interpreted by comparison to numerically obtained results from an analytical model and finite element analysis (FEA).

2. Methods

2.1. Specimen preparation

Wires were bonded to identical Direct Copper bonded (DCB) substrate, Fig. 1 providing direct contact to copper. The DCB substrate is

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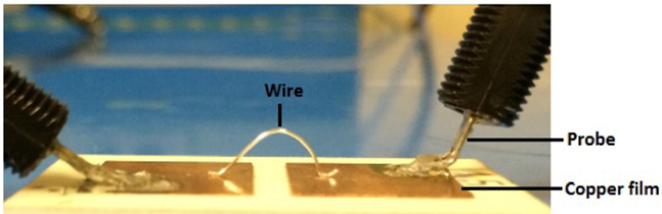

Fig. 1. CucorAl wire on DCB substrate during testing.

Table 1
Material properties and dimensions.

Material	Al	CucorAl
λ (W/mK)	230	-
ρ (kg/m ^{3})	2700	7082
d (μm)	300	300
L (mm)	11	10
H (mm)	4	4
E (GPa)	69	100
ρ_r ($\mu\Omega$.cm)	2.8	-
$\alpha(\times 10^{-6})$/K	25.3	-

made of two copper film, 300 μm thick, fused to a ceramic substrate at high temperature [12]. The bonding process employs ultrasonic bonding [13].

Two wire materials were tested: Al wires traditionally used in power modules and a recently introduced alternative, CucorAl wires. The dimensions and material properties [13] of the specimen are listed in Table 1, where λ is thermal conductivity, ρ is density, d is wire diameter, E is young modulus, ν is Passion's ratio, ρ_r is electrical resistivity, and α is the thermal expansion coefficient. The wire dimensions are illustrated in Fig. 2. A SEM picture of an etched CucorAl wire, Fig. 3, show that the Al coat is 25μm thick.

2.2. Transient analysis

The displacement-response of the wires was obtained by applying the current pulse train defined in Fig. 4 to the wires. A probe was soldered to each of the copper patches on the DCB substrate, Fig. 1, and used to pass the current through the bonding wire. The displacement of the wire peak point was measured as a function of time using the LDV. The pulse width was set to PW= 2–3 s while the pulse amplitude was varied. This experiment was developed to determine the thermal time constant (rise and fall times) of the wire, their transient response to step excitation, and their static displacement under DC current.

2.3. Modal analysis

An impact experiment was designed to obtain the modal response of bonding wires. An Al block was attached to one end of the DCB substrate. The substrate and a solenoid actuator were attached to the stage of a probe station, Fig. 5, such that the block and the solenoid plunger were aligned. A schematic of the experimental setup is shown in Fig. 6. The actuator was used to deliver low-frequency impacts to the block, thereby delivering an impact (pulse) train to the bonding wire. The period of the impact train is set large enough to allow the ring down oscillations subsequent to the falling edge of the pulse to dissipate and the wire to settle down to its static equilibrium position. A function generator was used to drive the solenoid actuator and command the frequency f_p and duty cycle D of the impact pulse train.

Fig. 7 shows the time-history of CucorAl wire peak point velocity in response to a pulse impact. The ring down oscillations settle down in less than 0.1 s well before the rising edge of the next pulse impact.

The velocity of the wire peak point $v(t)$ was measured using a LDV. The Fast Fourier Transform (FFT) of the velocity signal $v(t)$ was obtained for the response time-history measured subsequent to the falling edge of one pulse. The peaks in the FFT, corresponding to the natural frequencies of the wire, were identified. This technique can be used

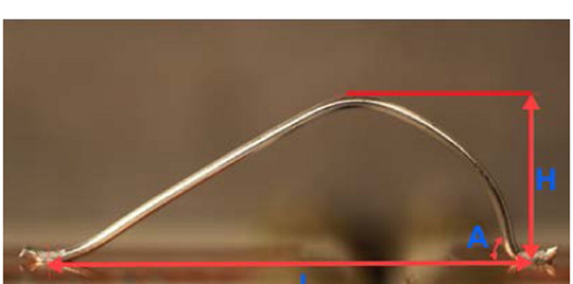

Fig. 2. Picture of Cu bonding wire.

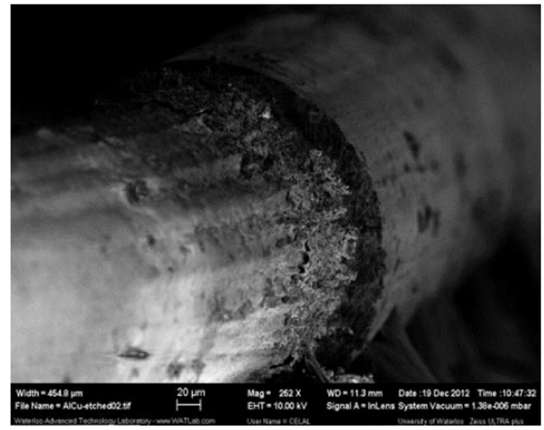

Fig. 3. SEM picture of CucorAl wire after etching.

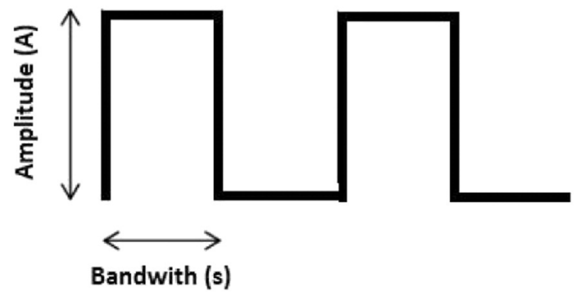

Fig. 4. A schematic of the current pulse train.

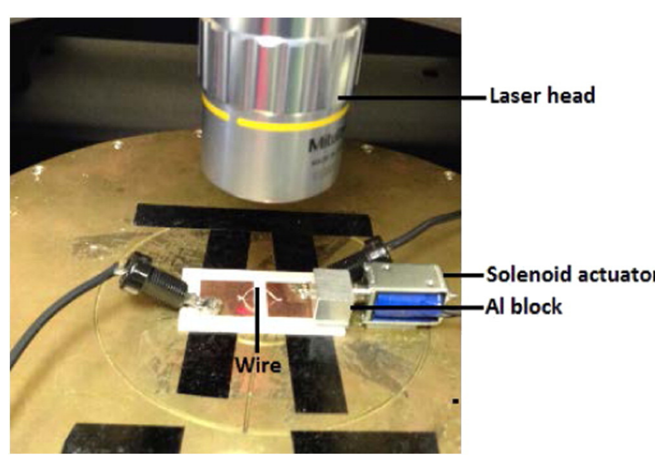

Fig. 5. The experimental setup for modal analysis.

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