Power Cycling and Wire Bond Reliability: The Critical Role of Wire Material and Diameter in Extending Lifetime

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Title: Influence of wire material and diameter on the reliability of Al-H11, Al-CR, Al-R and AlX heavy wire bonds during power cycling

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Equipment Used:

IR-thermography

Al-thick wire bonder

Shear tester

Samples Used

Ag-sintered DCB substrates, MOSFETs with 5 µm AlSiCu0.5 metallization on Al_2O_3 substrates; wire diameters of 125 µm, 300 µm, and 400 µm

Number of samples:

Not explicitly mentioned, but testing across multiple temperature swings (75 K, 85 K, 95 K, and 105 K) implies several experimental iterations

Tests Performed

Active power cycling, shear testing, electron backscatter diffraction (EBSD), IR-thermography

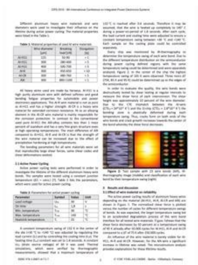
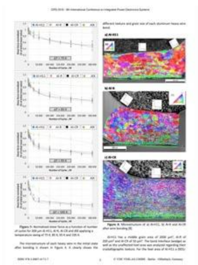
Analyzing methods

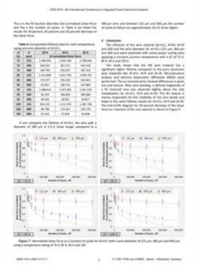
Shear force measurements, microstructural analysis (EBSD), crack propagation analysis

Figures & Facts

Pages: 6

9 diagrams (including shear force and end-of-life diagrams), 6 images (including cross sectional images of wire bonds)




Executive Summary

This research project examines the reliability of various types of aluminum heavy wire bonds utilized in power electronics, with a particular focus on their performance in MOSFET modules. Wire bonding is a common method used to connect electronic components, but the reliability of these bonds is of critical importance for long-term performance. The study examines the impact of varying aluminum wire materials and diameters on the durability of these wire bonds during power cycling, a process whereby the system is repeatedly turned on and off, resulting in temperature fluctuations. The research involved the testing of a number of aluminum wire types. The wire materials tested were Al-H11, Al-CR, Al-R, and AlX. The specimens were subjected to a series of temperature fluctuations in order to ascertain the durability of the bonds under these conditions. The study revealed that smaller diameter wires exhibited superior performance, with the AlX wire type demonstrating the greatest durability compared to the other wire types. The findings highlight the crucial role of both the material and the thickness of the wire in determining the reliability of the bonds. This research contributes to the optimization of the wire bonding process, offering insights into how the lifespan of power modules can be extended by selecting the appropriate wire material and diameter.

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Main Focus

This study examines the influence of aluminum wire material composition and diameter on the reliability and lifetime of heavy wire bonds under power cycling conditions. The objective is to evaluate the performance of various aluminum alloys (Al-H11, Al-CR, Al-R, and AlX) and wire diameters (125 µm, 300 µm, and 400 µm) in order to ascertain which combinations are most effective in enhancing the durability of wire bonds in power modules, particularly MOSFET devices.

Background and Motivation

Heavy wire bonding represents a pivotal technology in the field of power electronics, serving as the primary method for interconnecting semiconductors with their substrates. It is crucial for ensuring the longevity and reliability of power modules, particularly in applications that are subjected to thermal and mechanical stresses, such as those found in automotive and renewable energy systems. Prior research has predominantly concentrated on pure aluminum wires and copper bonding, with comparatively limited investigation of alloyed aluminum wires.

The principal failure mechanism in heavy wire bonds is thermal fatigue, which is caused by a discrepancy in the coefficients of thermal expansion (CTE) between the wire material and the silicon (Si) die. This research addresses the existing gap in knowledge by testing a range of aluminum alloys under a variety of power cycling conditions and temperatures. The objective of this study is to gain insight into the impact of wire material and diameter on the longevity of wire bonds, as well as to ascertain whether alloying or wire size modifications can enhance reliability.

Methodology

The study employed MOSFET power modules comprising Al_2O_3 ceramic-based direct copper bonded (DCB) substrates and a 5 µm AlSiCu0.5 topside MOSFET metallization. Wires derived from four distinct aluminum materials (Al-H11, Al-R, Al-CR, and AlX) and three wire diameters (125 µm, 300 µm, and 400 µm) were bonded onto the aforementioned MOSFETs. Power cycling tests were conducted with temperature swings (ΔT) of 75 K, 85 K, 95 K, and 105 K, in order to simulate operational conditions. A load voltage of 30 V, a heating time of 1.8 seconds, and maximum and minimum junction temperatures of 140°C and 30°C, respectively, were maintained throughout the experiment. The bonds were subjected to destructive shear testing at designated intervals to assess the extent of degradation. A microstructural analysis, including electron backscatter diffraction (EBSD), was conducted to evaluate changes in grain structure and orientation across different stages of power cycling. Furthermore, infrared thermography was employed to monitor the temperature distribution and ensure the maintenance of controlled heating across the samples.

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Key Findings

- **Wire Material Performance**: The AIX wire demonstrated markedly enhanced reliability in comparison to Al-H11, Al-R, and Al-CR. The degradation patterns exhibited by Al-H11, Al-R, and Al-CR were found to be similar due to their comparable rotated cube (RC) texture formation during ultrasonic bonding. The superior performance of AIX can be attributed to its scandium (Sc) content, which provides precipitation hardening at temperatures between 200°C and 300°C, preventing the grain coarsening and softening that are typical of other aluminum alloys.
- **Wire Diameter Influence**: The results demonstrated that wire diameters of 125 µm exhibited significantly enhanced reliability during power cycling in comparison to larger diameters of 300 µm and 400 µm. Wires with a diameter of 125 µm exhibited a cycle life that was 10 to 15 times greater than that of wires with a diameter of 300 µm under comparable conditions. A lifetime model, utilising an exponential decay and linear regression fit function, corroborated the hypothesis that smaller diameters exhibited superior resistance to fatigue-induced shear force degradation, particularly in the context of higher temperature swings.
- **Microstructural Insights**: The results of the EBSD analysis indicated that for the Al-H11, Al-R, and Al-CR samples, a district (101)-A1 texture was observed to have formed above the chip metallization post-bonding. This texture, which exhibits a rotated cube (RC) orientation, was identified as the underlying cause of the comparable lifetimes observed in these wires. In contrast, the AIX wire bonds exhibited a more refined grain structure, accompanied by the presence of Sc precipitates at the grain boundaries. These precipitates were observed to play a stabilizing role under elevated temperatures. Crack propagation analysis demonstrated that in Al-H11 bonds, cracks developed at a depth of 10-20 µm above the chip metallization. In contrast, in AIX bonds, cracks propagated in a different manner, forming within the chip metallization itself, which contributed to its longer lifespan.
- **Temperature Dependence**: It was observed that elevated temperature fluctuations resulted in accelerated deterioration across all wire materials. At a temperature differential of 95 K, Al-H11, Al-R, and Al-CR exhibited a 50% reduction in shear force after 50,000 cycles, whereas AIX demonstrated durability beyond 500,000 cycles at comparable temperature conditions.

Implications for Future Research and Industry

The findings indicate that AIX wire material, with its exceptional resistance to thermal fatigue, presents a substantial opportunity to extend the operational lifetime of power modules, particularly in high-temperature environments such as those encountered in automotive and renewable energy applications. The potential for industry adoption of AIX is that it could reduce the frequency of module replacements and improve system reliability.

Furthermore, the research highlights the significance of wire diameter optimization for specific applications, with smaller diameters being more suitable for environments subjected to extensive thermal cycling. Future research could investigate additional alloy modifications, such as combining elements like Sc with other materials to enhance wire performance. Additionally, an investigation into alternative bonding techniques, such as ultrasonic or thermocompression bonding with these new materials, could offer further reliability gains.

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Limitations

A significant limitation of this study is its focus on aluminum-based alloys, which excludes other potential materials, such as copper alloys, that are known for their high electrical and thermal conductivity. Furthermore, the testing was constrained to a specific set of power cycling conditions with a defined range of temperature fluctuations, which may not fully encompass the spectrum of operational environments.

Further research into other alloy compositions, alternative bonding surfaces, and the impact of different types of metallization (such as Ni or Ag) on wire bond longevity could enhance the current understanding. Furthermore, the study did not investigate long-term aging effects beyond the power cycling experiments. For instance, the impact of continuous thermal stress without cycling could reveal additional failure mechanisms.

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