Power MOSFET | Metallization Degradation | Active Power Cycling | Thermo-Mechanical Simulation | Reliability Testing

Can Copper Clips Solve the Reliability Problem in Power Electronics? A Look into Metallization Failures and Degradation

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THE SOURCE OF THIS SUMMARY IS THE FOLLOWING SCIENTIFIC PUBLICATION

Title: Failure Mechanisms in Chip-Metallization in Power Applications

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Equipment Used:

Heat sink for mounting MOSFETs

Power cycling equipment with adjustable load currents (200A to 600A)

Samples Used

Power MOSFET chips with a copper clip design

Aluminum and copper (clip), with solder layers

Number of samples:

Not explicitly stated, but tests involved several MOSFET modules

Tests Performed

Active Power Cycling (APC)

Electrical characterization (leak currents, resistance, thermal impedance)

Metallographic analysis post-failure

Analyzing methods

Optical microscopy

Scanning Electron Microscopy (SEM)

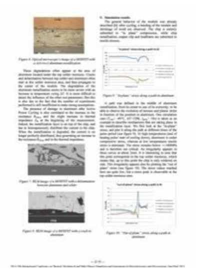
Finite Element Analysis (FEA) with a 2D axisymmetric model

Figures & Facts

Pages: 5

Multiple diagrams (e.g., stress and strain plots). Several tables with parameter ranges and results. At least 3 pictures showcasing different failure modes.





Executive Summary

The publication's primary focus is on the reliability and failure mechanisms of the aluminum metallization layer utilized in power electronics. Power electronics, including the MOSFET (a type of transistor), are integral components in a multitude of devices, such as automobiles. Power cycling tests are typically conducted to observe the behavior of materials under conditions of elevated temperature and mechanical stress. Over time, these tests simulate the effects of real-world conditions on the chip, including temperature changes, which can cause wear and tear on the aluminum layer. This study examines the impact of switching from traditional aluminum wire bonds to copper clips on the performance and reliability of the module.

The researchers conducted tests and simulations to investigate the impact of stress and strain on the aluminum layer, with a particular focus on the solder connections that attach the copper clips to the chip. The researchers discovered that when the aluminum layer is subjected to repeated heating and cooling cycles, it can develop cracks and deformations, which may eventually result in a complete failure. Their findings indicate that temperature fluctuations play a pivotal role in these failures. The study contributes to our knowledge of how to design more reliable power modules by enhancing the metallization and soldering techniques, which may extend the lifespan of these electronic components.

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Main Focus

This study examines the degradation mechanisms of the aluminum metallization layer in power MOSFETs under active power cycling (APC). The research project focuses on an innovative packaging design that employs copper clips in lieu of conventional aluminum wire bonds, which are susceptible to fatigue-related failures. The primary objective is to comprehend the influence of thermo-mechanical stresses on the metallization and their contribution to failure mechanisms, with a particular emphasis on the critical region situated beneath the top solder meniscus. The study combines experimental APC tests with thermo-mechanical simulations using a two-dimensional finite element model (FEM) to identify stress, strain, and plastic deformation in the metallization.

Background and Motivation

In the context of power electronic applications, the reliability of metallization layers is a well-documented concern, largely due to the detrimental effects of temperature gradients and mechanical stress caused by power cycling. These temperature fluctuations induce stress due to the discrepancy in the coefficient of thermal expansion (CTE) between materials such as silicon and aluminum.

Over time, these stresses result in plastic deformation, cracking, and eventual failure of the aluminum metallization. Previous studies have focused on wire bond fatigue and solder degradation; however, less attention has been given to the metallization itself, particularly with newer package designs that use copper clips. This research aims to address this gap by exploring the behavior of aluminum metallization under APC in such configurations.

Methodology

- **Experimental Setup**:An active power cycling test was conducted on MOSFETs with copper clips. A series of load currents, spanning a range from 200A to 600A, were applied in conjunction with temperature swings that ranged from 60K to 120K. To emulate real-world operational scenarios, the modules were affixed to heat sinks. The temperature and stress data were collected during the cycling process, and the thermal and electrical characterizations were conducted before and after the tests. The resistance (RDSon) and thermal impedance (Zth) were monitored as key parameters. A metallographic analysis was conducted on the failed samples in order to investigate the degradation patterns observed in the aluminum layer.
- **Numerical Simulation**: A two-dimensional finite element model (FEM) of a metal–oxide–semiconductor field-effect transistor (MOSFET) was developed on the assumption of axisymmetry, thus facilitating a simplified yet accurate thermal and mechanical analysis. The thermo-mechanical analysis incorporated temperature-dependent material properties, employing a bilinear kinematic hardening model for aluminum to simulate plastic deformation. The simulations concentrated on three cycles, with the objective of studying the evolution of stress and strain in the aluminum metallization. In particular, critical regions, most notably those situated beneath the top solder meniscus, were subjected to meticulous scrutiny with a view to identifying any accumulation of stress and evidence of plastic strain. A sensitivity analysis was conducted to ascertain the impact of varying parameters, including the initial temperature (Tstart), temperature swing (ΔT), and pulse width.

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Key Findings

- **Critical Stress Zones**: The region situated beneath the top solder meniscus was identified as the area exhibiting the greatest propensity for stress accumulation. During the power cycling process, this zone was subjected to considerable "in-plane" compressive and tensile stresses, particularly at elevated temperatures and during significant temperature fluctuations.
- **Plastic Strain and Crack Propagation**: It was determined that plastic strain accumulates in the aluminum layer, particularly under conditions of significant temperature differential (ΔT) and low starting temperature (Tstart). Cracks and delamination were observed in this critical region, which propagated toward the center of the chip as the cycling continued. Additionally, shorter pulse widths were found to contribute to a greater accumulation of plastic strain.
- **Failure Mechanisms**: A number of metallization degradation mechanisms were identified, including warping and the migration of the aluminum layer into the solder. The phenomenon of delamination or separation between the aluminum metallization and the solder layer was observed. Cracks within the aluminum layer typically originate from the solder meniscus area and propagate due to thermal fatigue. These failures were found to be correlated with an increase in electrical resistance (RDSon) and thermal impedance (Zth), which indicated a loss of metallization integrity.
- **Simulation Validation**: The simulation results exhibited a high degree of correlation with the experimental data, particularly in identifying the regions of maximum stress and plastic strain. The study demonstrated that high ΔT, low Tstart, and short pulse widths were the primary factors contributing to the degradation of the metal substrate.

Implications for Future Research and Industry

Design Optimization: The findings indicate that the optimization of temperature management and cycling parameters may enhance the durability of power MOSFETs. It would be beneficial for industry designs to prioritize the minimization of temperature fluctuations and the adjustment of operational parameters with the objective of reducing stress on the metallization layer.

Material Innovation: Further research could investigate alternative metallization materials or coatings that offer enhanced thermal and mechanical performance compared to aluminum, particularly under high cycling conditions. The implementation of novel soldering techniques and alternative metallization layouts may prove an effective means of further mitigating the stress concentrations observed in this study.

Advanced Modeling Techniques: The integration of fracture mechanics into thermo-mechanical simulations would facilitate more accurate predictions of crack initiation and propagation, which could be pivotal for enhancing the reliability of power modules in practical applications.

Reliability Testing Protocols: The study underscores the necessity for standardized testing protocols that accommodate fluctuations in temperature, pulse width, and initial temperature settings. Further comprehensive long-term testing could facilitate a more detailed comprehension of the underlying failure mechanisms in response to diverse operational conditions.

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Limitations

The study was constrained by a relatively small number of experimental samples, which limits the ability to make statistically robust conclusions about the influence of all test parameters (e.g., pulse width). Although the research provides valuable insights into aluminum metallization degradation, it does not extensively explore other metallization materials that could potentially offer enhanced reliability under APC conditions. Further research could concentrate on a more extensive range of materials. The 2D axisymmetric model simplifies the package design, which may result in the omission of some three-dimensional effects that could influence the behavior of the metallization.

Future simulations should incorporate three-dimensional modeling to capture more complex stress distributions. Overall, the research provides critical insights into the thermo-mechanical behavior of power MOSFETs under APC, with practical implications for improving the reliability of power electronic devices. However, the findings also highlight the need for further investigations into material alternatives and more comprehensive experimental testing.

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