Advancements in Copper Ball-Wedge Wire Bonding: A Cost-Effective Alternative to Gold in Semiconductor Manufacturing

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Title: Development and Status of Cu Ball/Wedge Bonding in 2012

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Equipment Used:

The referenced studies use K&S iConn, ESEC COWI-2, Maxum Ultra, ASM AB339

Samples Used

Substrates such as nickel/palladium (Ni/Pd) over copper (Cu), electroless nickel/electroless palladium (ENEP) finishes

Number of samples:

Not explicitly stated, but a variety of samples were used for different metallizations and tests

Tests Performed

Pull tests, shear tests, high-temperature storage tests, thermal cycling, humidity testing

Analyzing methods

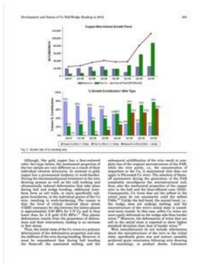
Optical microscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic emission spectroscopy (AES)

Figures & Facts

Pages: 38

40 figures including tables and graphs displaying test results, 8 detailed images of bond interfaces and failure modes



Executive Summary

The literature review examines advancements in copper (Cu) ball-wedge bonding, a technique utilized to establish connections between wires in electronic devices. Historically, gold (Au) was the material of choice due to its resistance to corrosion. However, the increasing costs associated with gold have prompted the exploration of alternative materials, such as copper. Copper offers superior electrical performance, but it also presents challenges such as oxidation (rusting) and increased hardness, which complicate the bonding process.

The study presents potential solutions, including the use of protective gas environments and palladium-coated copper wires, to prevent oxidation. Furthermore, the study underscores the significance of testing methodologies, such as pull and shear tests, in guaranteeing the durability and reliability of the bonds.

In conclusion, the literature indicates that with enhanced equipment and methodologies, copper bonding may emerge as a cost-effective alternative to gold in the context of electronics manufacturing.

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Main Focus

The literature study focuses on the emerging field of copper (Cu) ball-wedge (B/W) bonding, which has been identified as a cost-effective alternative to traditional gold (Au) bonding in the context of electronic packaging. This review examines recent advancements in Cu bonding technology, its reliability in high-temperature environments, and solutions for overcoming challenges such as oxidation and hardness. Furthermore, it examines the various equipment and methodologies employed to guarantee the structural integrity and long-term reliability of Cu bonds.

Background and Motivation

Gold has historically been the primary material utilized in wire bonding of semiconductor devices, largely due to its corrosion resistance, ease of bonding, and high reliability. However, the increasing cost of gold has prompted research into alternative materials, with copper emerging as the most promising candidate due to its superior electrical and thermal properties. The higher hardness of copper and tendency to oxidize present significant challenges, particularly during the bonding process and in long-term reliability under operational conditions.

The objective of this study is to evaluate the potential of Cu B/W bonding as a substitute for Au in a range of electronic applications, particularly in consumer electronics and high-end industrial applications. The review examines how recent technological advancements in bonding techniques, protective coatings, and process controls have addressed the earlier limitations of Cu bonding.

Methodology

The literature review synthesizes a comprehensive range of scientific publications from 2000 to 2012, with a particular focus on experimental studies that evaluate the mechanical and chemical behavior of Cu bonding under diverse conditions. The reviewed studies investigate the following:

- Various copper wire qualities (3 N to 5 N purity, Pd-coated Cu wire).
- Protective atmospheres (N_2 + 5% H_2 forming gas) used during the flame-off process.
- Bonding parameters (ultrasonic power, bonding force, temperature control).
- Reliability testing methodologies such as pull tests, shear tests, thermal aging, and humidity resistance.
- Detailed analysis of microstructural changes using scanning electron microscopy (SEM) and atomic emission spectroscopy (AES) to assess intermetallic phase formation and potential failure mechanisms in Cu-Al bonds.

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Key Findings

Copper Wire Properties: The study indicates that copper wires (in particular those with 4N and 5N purity) exhibit greater hardness and strength than gold, which presents a challenge in forming reliable bonds without damaging the underlying semiconductor. The use of Pd-coated Cu wire represents a partial solution, as it reduces oxidation and enables more stable bond formation.

Protective Atmosphere and Oxidation Control: The utilization of forming gas (N_2 + 5% H_2) has been demonstrated to be of paramount importance in the prevention of oxidation during the electronic flame-off (EFO) process. The use of forming gas facilitates the formation of nearly oxide-free free air balls (FABs), which in turn contributes to the generation of more stable and reliable first bonds. The application of Pd coatings serves to further mitigate the risk of oxidation, thereby enabling the storage of wires for extended periods and facilitating enhanced performance in applications that demand high reliability.

Equipment Advancements: Bonding machines such as the ESEC COWI-2 and K&S iConn have been optimized for Cu bonding through the provision of enhanced control over ultrasonic power, bonding force, and gas flow. Additionally, these machines facilitate the processing of fine-pitch Cu wires, which are of paramount importance in modern high-density semiconductor packages.

Testing and Reliability: The study underscores the significance of pull and shear tests in evaluating the strength and durability of Cu bonds. Shear testing is of particular importance in ensuring the integrity of the bond, given the higher hardness of Cu. Moreover, thermal cycling and humidity testing are essential for assessing the long-term reliability of the material, particularly in applications that are subjected to high temperatures or corrosive environments.

Intermetallic Phase Formation: A substantial emphasis is placed on the formation of intermetallic compounds (IMCs) at the Cu-Al interface. The lower diffusion coefficient of Cu in comparison to Au results in the formation of thinner intermetallic compounds (IMCs), which enhances the reliability of the bond under conditions of high-temperature aging. Nevertheless, the study indicates that the current research on IMC growth mechanisms in Cu-Al bonds remains incomplete, thereby allowing for further investigation.

Implications for Future Research and Industry

The results of the study indicate that Cu bonding is on the verge of becoming a widely adopted industrial practice, particularly in light of the continued increase in Au prices. The reduced cost and enhanced performance of Cu bonds in high-power and high-frequency applications render them highly attractive for both consumer and industrial electronics. Nevertheless, further research is required to address specific challenges, including:

Optimization of Microstructure: Further studies are required to investigate the control of grain size in Cu wires and the impact of thermomechanical processing on bond quality.

Reliability in Harsh Environments: Further comprehensive long-term testing under real-world conditions, particularly in environments with high humidity and corrosive agents, is required.

Alternative Coatings: Further investigation of novel protective coatings that exhibit enhanced oxidation resistance and reliability compared to Pd-coated Cu wires.

In industry, the findings imply that the transition to Cu bonding will depend heavily on manufacturers' ability to implement advanced bonding equipment and develop more robust quality control processes. The increased adoption of Pd-coated Cu wires may facilitate a reduction in costs while simultaneously enhancing long-term reliability, thereby enabling Cu bonding to be deployed in a broader range of applications, including automotive electronics and high-reliability aerospace components.

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Limitations

There is a lack of comprehensive understanding of the processes involved in IMC formation. Although the lower diffusion rates of Cu at the Cu-Al interface are regarded as advantageous, the precise metallurgical interactions between Cu and Al in diverse environmental contexts (such as humidity or halide exposure) remain inadequately understood.

A limited number of studies have been conducted on the long-term durability of this subject. While the study encompasses a range of reliability tests (e.g., high-temperature aging, humidity resistance), there is a dearth of long-term empirical data on Cu bond performance in highly demanding environments, particularly under dynamic stress and vibration.

The effects of capillary wear and ultrasonic power control on the durability of the bond must be considered. The enhanced hardness of Cu necessitates more sophisticated capillary designs and elevated bonding forces, which may diminish the equipment's operational lifespan. The study mentions the use of advanced capillaries with tailored geometries, but suggests that further optimization is required to improve bonding performance in ultra-fine-pitch applications.

The effects of oxidation and storage constraints on the material in question must also be considered. Despite the notable enhancements offered by Pd coatings, Cu bonding continues to encounter obstacles pertaining to oxidation during storage and processing, particularly in the context of large-scale manufacturing environments.

By addressing these limitations through future research, copper bonding could become a more widely adopted technology in high-end applications, potentially shifting the industry standard away from gold and toward more cost-effective and robust copper bonding technologies.

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