

Comparative Analysis of Wedge Bonding Methods and Factors Affecting the Quality of Contact Interconnections in Microelectronics

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Abstract: The paper presents a comparative analysis of wedge bonding methods used for forming contact interconnections in microelectronics and hybrid electronic modules, considering the principles of energy input, bonding configuration, wire materials, and technological conditions. The analysis identifies the main advantages and limitations of ultrasonic, thermosonic, thermal, and auxiliary-energy-assisted wedge bonding and establishes that contact quality is determined by the combined influence of ultrasonic energy, temperature, bonding force, bonding time, wire properties, contact surface condition, and joint geometry, providing a basis for further optimization and digital modeling of the bonding process.

Keywords: wedge bonding, microelectronics, hybrid electronic modules, ultrasonic bonding, thermosonic bonding, contact joint quality, bonding parameters, wire bonding.

I. INTRODUCTION

The modern development of microelectronics and the manufacturing of hybrid electronic modules is accompanied by continuously increasing requirements for the reliability, stability, and quality of contact interconnections, which largely determine the operational performance of finished electronic devices. One of the widely used techniques for forming such interconnections is thin-wire wedge bonding, the effectiveness of which depends both on the characteristics of the bonding method employed and on a combination of technological parameters, material properties, and contact formation conditions. Variations in bonding force, ultrasonic energy, bonding time, temperature conditions, and the geometrical characteristics of the joint can significantly affect its mechanical strength, stability, and the probability of technological defects. Therefore, a comparative analysis of existing wedge bonding methods and the identification of the main factors affecting the formation of high-quality contact interconnections in microelectronics are of considerable relevance. The results of such a study provide a basis for the justified selection of technological parameters, improvement of quality control techniques, and further development of models of the wedge bonding technological process.

II. COMPARATIVE ANALYSIS OF WEDGE BONDING METHODS

To develop a scientifically substantiated approach to the selection of wedge bonding technology, it is appropriate to conduct a comparative analysis of existing methods, taking into account the principle of joint formation, the type of energy input, the bonding wire material, and the

characteristics of the contact surfaces. Systematization of these approaches makes it possible to identify their distinctive features and provides a basis for further investigation of the factors affecting the quality and reliability of contact interconnections in microelectronics and hybrid electronic modules. A generalized classification of wedge bonding methods is presented in Figure 1.

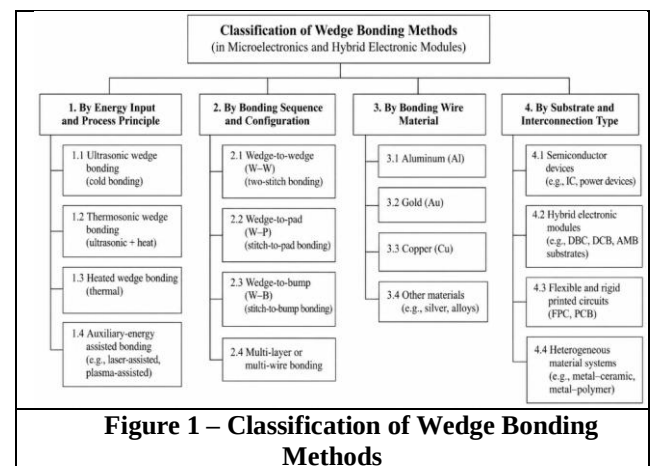


Figure 1 – Classification of Wedge Bonding Methods

Ultrasonic Wedge Bonding is one of the most widely used methods for forming wire contact interconnections in microelectronics, in which the bond is formed through the simultaneous application of bonding force and high-frequency mechanical vibrations of the wedge tool. Ultrasonic action promotes the disruption of surface oxide and contamination layers, increases the actual contact area, and induces plastic deformation of the wire material, resulting in the formation of a metallic bond without the need for significant external heating. The method is widely used for thin aluminum wire and is particularly suitable for temperature-sensitive components. Its main advantages include a relatively low process temperature, high bonding speed, the possibility of automation, and suitability for mass production. The disadvantages include a strong dependence of bond quality on the proper selection of ultrasonic power, bonding force, and bonding time, while excessive ultrasonic energy or force may cause excessive wire deformation, damage to the bonding pad, and reduced mechanical strength of the joint.

Thermosonic Wedge Bonding is based on the simultaneous application of ultrasonic vibrations, mechanical bonding force, and additional thermal energy.

Heating of the contact area increases material plasticity and facilitates the formation of a metallic bond, thereby allowing the required ultrasonic energy to be reduced compared with cold ultrasonic bonding. This approach can be applied to materials and contact systems for which the formation of a stable bond solely by ultrasonic action is difficult. The advantages of the method include the ability to obtain stable bonds under less intensive mechanical and ultrasonic loading, a wider range of bondable materials, and improved conditions for interfacial contact formation. At the same time, the need for heating increases the complexity of the technological equipment and process control, increases the number of parameters requiring optimization, and may impose additional technological limitations on temperature-sensitive semiconductor structures and substrates.

Heated Wedge Bonding involves the formation of a contact joint primarily through a combination of mechanical pressure and thermal energy. Increasing the temperature reduces the material's resistance to plastic deformation and facilitates the formation of the required contact area between the wire and the metallized pad. An advantage of this approach is the absence or substantial reduction of intensive ultrasonic loading on the components being bonded, which may be important for sensitive structures under certain technological conditions. However, the method places increased demands on temperature conditions, dwell time, and heat-transfer stability, while heating may adversely affect temperature-sensitive materials, induce thermal stresses, and increase the duration of the technological cycle. Therefore, its application requires careful coordination of temperature, bonding force, and the properties of the particular material system.

Auxiliary-Energy Assisted Bonding involves supplementing conventional mechanical, ultrasonic, or thermal action with other physical methods of contact-surface activation, such as laser or plasma treatment. Additional energy can be used for localized heating, cleaning, or activation of surfaces to create more favorable conditions for bond formation. The advantage of this approach is the ability to localize the energy input, broaden the process window, and work with complex material combinations. Its main disadvantages are increased equipment complexity, the need to synchronize several energy sources, a greater number of controllable technological parameters, and higher implementation costs. Furthermore, improper selection of auxiliary-energy parameters may result in localized overheating or surface damage.

In terms of bond configuration, Wedge-to-Wedge Bonding is a conventional configuration in which both the first and second bonds are formed using a wedge tool, with a wire loop of a specified geometry created between them. This configuration ensures technological uniformity of the two bonds and is well suited to the automated interconnection of bonding pads on integrated circuits, substrates, and packages. Its advantages include reproducibility of the technological cycle, the ability to accurately form low-profile wire loops, and compatibility with thin aluminum wire. A disadvantage is the dependence of the process on the orientation of the wedge tool relative

to the wire routing direction, which may restrict the formation of complex trajectories and places higher demands on the positioning system.

The Wedge-to-Pad configuration involves forming a wedge bond directly on a metallized bonding pad, whose characteristics significantly affect the final bond quality. In this case, the wedge geometry, wire diameter, pad dimensions, and permissible deformation of the contact area must be properly matched. The advantage of this configuration is the ability to create compact interconnections with high positioning accuracy and to use bonding pads of various electronic components. Its disadvantages include high sensitivity to the condition of the pad surface, metallization quality, contamination, oxide layers, and positioning errors, since these factors directly affect the actual contact area and mechanical strength of the bond.

Wedge-to-Bump Bonding involves forming a wedge bond to a preformed metallic protrusion or bump contact. The presence of such an element makes it possible to adapt the process to more complex contact structures and may improve compatibility between the wire and the bonding-pad surface. Its advantages include suitability for miniaturized structures and the ability to form a bond on a specially prepared surface, whereas its disadvantages include the need for an additional bump-formation operation, increased complexity of the technological route, and additional sources of variability associated with the geometry, material, and quality of the preformed contact.

Multi-Layer or Multi-Wire Bonding is used in structures requiring multiple wire interconnections or a multilevel interconnection system. This approach is particularly relevant to power and hybrid electronic modules, where the parallel use of several conductors may be necessary to provide the required current-carrying capacity and to implement complex electrical interconnection topologies. Its advantage is the ability to realize complex interconnection schemes and distribute the electrical load among several conductors. At the same time, increasing the number of wires complicates the planning of the bonding sequence, control of loop geometry, and prevention of mechanical contact between wires, while also imposing higher accuracy requirements on the automated positioning system.

Wire material is another determining factor in the selection of wedge bonding technology. Aluminum wire is widely used because of its plasticity, suitability for ultrasonic bonding, relatively low cost, and compatibility with many types of metallization. At the same time, an oxide layer rapidly forms on the aluminum surface, and its disruption is an important part of the process of forming a high-quality bond. Gold wire is characterized by high corrosion resistance and favorable properties for forming reliable interconnections; however, its high cost represents a significant economic disadvantage. Copper wire has high electrical and thermal conductivity and may be more economically attractive than gold, but its greater hardness increases the mechanical load on the bonding pad, while its susceptibility to surface oxidation complicates the technological process. The use of silver and specialized metal alloys makes it possible to adapt interconnection

properties to specific operating conditions; however, it requires separate determination of the process window for each particular combination of wire, metallization, and substrate.

Thus, the comparative analysis demonstrates that the selection of a wedge bonding method cannot be determined solely by the method of energy input, since the quality of the contact joint is formed through the complex interaction of ultrasonic energy, temperature, bonding force, bonding time, wire properties, contact-surface condition, and the geometrical parameters of the joint. Ultrasonic bonding is technologically attractive for low-temperature contact formation, thermosonic bonding expands process-control capabilities through additional thermal input, while auxiliary-energy-assisted methods provide opportunities for working with more complex material systems but simultaneously increase equipment complexity and the number of process-control parameters. Therefore, further research should focus on establishing relationships between controllable technological parameters and the quality indicators of the resulting bonds, which will make it possible to determine rational wedge bonding conditions and provide a basis for mathematical modeling and digital representation of the technological process.

IV. CONCLUSION

As a result of the conducted study, a comparative analysis of wedge bonding methods was performed, and it was established that the quality of contact interconnections in microelectronics is determined by the complex interaction of the energy input method, ultrasonic energy, temperature, bonding force, process duration, wire material properties, contact surface condition, and joint geometry. It was established that ultrasonic wedge bonding provides effective low-temperature contact formation, thermosonic bonding broadens the process window through additional thermal input, while the use of auxiliary energy sources enhances the capability to work with complex material combinations but simultaneously increases the complexity of technological process control. The obtained results substantiate the need for further determination of quantitative relationships between controllable wedge bonding parameters and contact quality indicators as a basis for optimizing technological conditions, mathematical modeling, and developing a digital representation of the process.

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