論文の内容の要旨

論文題目: Surface Activated Bonding of Micro-Bumps
at Low-Temperature and in Ambient Air

(表面活性化によるマイクロバンプの大気中・低温接合)

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1. Introduction

Focused on the bottleneck problem of the thermal expansion mismatch in the development of flip-chip interconnection using conventional bonding methods at high temperatures, surface activated bonding (SAB) method is concerned with reducing the bonding temperature. Since using activated surfaces is the basic concept of SAB, high vacuum is regarded as a necessary condition to achieve and maintain cleaned surfaces. With this common wisdom, no work has previously been attempted to check the possibility of treating surfaces under low vacuum and performing the bonding in ambient air except with Au. Bonding in ambient air has the advantages of low cost and short fabrication time. If it is possible, low-temperature bonding in ambient air would be highly prospected.

However, the residue gases under low vacuum might influence the cleanliness of Ar-plasma pretreatment. Moreover, typically the electrodes of environmentally-friendly Sn-based alloys are easily oxidized in ambient air. Therefore, the key problem of bonding in ambient air is surface contamination on the activated surfaces. However, less information is available regarding the characterization of surface contamination before bonding and their influence on bonding of lead-free micro-bumps. Furthermore, if the surface contamination could be dispersed by chemical reaction and mechanical contact deformation, the bonding might be achieved in some bonding boundaries, which can be controlled by the process parameters of bonding pressure, temperature and time and influenced by material properties and geometrical factors. However, little studies have addressed these issues, and their influence on the bonding of micro-bumps is not well understood. Numerous experimental data and a theory model are necessary to establish the relationship of such factors to find suitable process windows enabling bonding of micro-bumps in ambient air.

The purpose of this research is to realize the bonding of micro-bumps below 200°C in ambient air by the SAB method by approaching the study of the characterization of surface contamination and the influencing factors to achieve suitable process parameters. The achieved bonding boundaries and the determined relationships of the influencing factors are prospected to apply in the bonding of micro-bumps between different substrates.

2. Experimental Models and Methods

Typical electrodes, the hardly-oxidized Au, and easily-oxidized Sn and Sn-Ag or Sn-Ag-Cu are selected is this the study. X-ray photoelectron spectrometer (XPS) was selected for analysis the surface contamination of Au, Sn, and Sn-2.0Ag (wt%) alloy films. A submicron flip-chip bonder and various Au, Au/Sn and Sn-Ag-Cu micro-bumps were used for investigating the functions of the influencing factors. Some evaluation methods were carried out for understanding the surface conditions, electrical characteristics, and mechanical characteristics of the interconnections, including atomic force microscopy (AFM), contact angle measuring, surface profiling, electrical resistance test, die shear test, tensile test, scanning electron microscopy (SEM), and electron probe micro-analysis (EPMA).

3. Characterization of Surface Contamination and Its Influence on Bonding

Few effects of the annealing and flattening processes and the addition of 2.0wt% Ag composition were detected on the initial thickness of surface contamination. The initial thickness of carbon contaminants is around 2 nm on Au, Sn, or Sn-2.0Ag surfaces, and the initial thickness of oxides of Sn or Sn-2.0Ag is around 5-11 nm. The growth of contamination of Sn follows a logarithmic rate law.

The influence of the vacuum background is not sensitive to Au. Carbon contaminants are removed from the surfaces regardless of whether the background is high or low vacuum. In the case of Sn, carbon contaminants are removed from the surfaces, whereas Ar-etched Sn is oxidized at the same time due to the residual air in the low vacuum conditions, and the contamination ratio is seldom reduced. Compared with that pretreated under the high-vacuum background, the water droplet contact angles proved the cleanliness in terms of carbon contaminants of activated surfaces pretreated under the low-vacuum background. Regardless of the vacuum background, Ar-plasma pretreatment improves the bondability of Sn-Ag-Cu micro-bumps at low temperatures in ambient air. The status of carbon contaminants is a critical factor in the low-temperature bonding of ambient air. The low-vacuum background of Ar-plasma pretreatment is available for the low-temperature bonding of Sn-based micro-bumps in ambient air, even though the thickness of the oxides is not obviously reduced.

In the low-temperature bonding of micro-bumps in ambient air, the critical values of the Ar-plasma pretreatment time and the air exposure time are related to the thickness of carbon contaminants, material properties, and bonding parameters. To achieve a high bond quality, 2-nm-thick carbon contaminants should be removed by Ar-plasma pretreatment. Deformation and diffusion is effective on the bonding of micro-bumps. The critical time of Ar-plasma pretreatment and air exposure is changed depending on the material property and process parameters of bonding pressure and temperature. The shear strength on the bonding of Au micro-bumps at room temperature under 300 MPa increased more than 8 times by Ar-plasma pretreatment, whereas the shear strength on the bonding of Sn-Ag-Cu micro-bumps at 100°C under the bonding pressure of 250 MPa reached more than 20 MPa without Ar-plasma pretreatment, and there is no critical time of Ar-plasma pretreatment and air exposure in this case. The Ar-plasma pretreatment time and air exposure time should be controlled according to the material properties and bonding parameters and was determined as follows to study other influencing facotrs:

- Ar-plasma pretreatment time: 30 s for Au and 120 s for Sn or Sn-Ag-Cu under a low vacuum background of 5-7 Pa;
- Air exposure time: 3-30 min.

4. Influencing Factors on Micro-Bump Bonding

Quick diffusion between bonding couples may accelerate the surface contact at low-temperature bonding in ambient air. The diffusion accelerates the shrinking process of gaps between the contact surfaces. With a large diffusion rate of Au and Sn, the required bonding pressure in the bonding of Au and Sn is smaller than that of Au and Au at 150°C. The oxides on the bond interface of Au and Sn were found to be dispersed quickly with the help of diffusion. The intermetallic compounds formed in the bonded interfaces is assumed to be AuSn on the Au pads side, and $AuSn_2$ and $AuSn_4$ on the Au/Sn bump side at 100 and 150°C. One phase, $AuSn_5$, emerges between the AuSn phase and Au at 200°C. The diffusion rate becomes increases with the temperature increase.

In the bonding of Au/Sn bumps to Au pads, surface roughness is not critical, whereas the key point is for a certain thick Sn layer to remain on top of the Au/Sn bumps for deformation and diffusion. In the bonding of Au micro-bumps, a smooth surface increases the actual contact area, and therefore increases the bonding strength and bond yield, and reduces the required bonding pressure and temperature. With a lower hardness of Sn than that of Au, a sufficient contact area of Au-Sn was achieved more easily than that of Au-Au, even though the Au/Sn bumps had rougher surfaces than the Au bumps. Through annealing to lower the hardness of Au, the required bonding pressure of Au micro-bumps was reduced more than 30% at room temperature. Since the self-diffusion rates are low, the contact deformation is the dominant function of the bonding of Au and Sn-Ag-Cu micro-bumps at low temperatures. A high bump profile (h/w) lowers the required bonding pressure.

The bonding parallelism between chip and substrate influences the bond yield. When the bump size and pattern were determined, a smaller bonding pressure was required to achieve a high bond yield and strength due to a smaller planarity angle. The planarity angle used in this study was controlled at around 0.005°.

The relationship between bonding strength and bonding time of Au and Sn-Ag-Cu micro-bumps follows a logarithmic law. Bonding time is assumed to have a minor influence in these cases, whereas it has a significant influence on the bonding of Au-Sn due to the contribution of diffusion. The actual contact area of micro-bumps was strongly dependent on the bonding pressure and temperature. A suitable bonding boundary was selected depending on the material properties and geometric factors by controlling the bonding pressure and temperature. A model of the relationship with bonding pressure, temperature and bump profile was given.

5. Applications

The SAB method was successfully applied to connect various substrates in bonding chip-on-board, with non-conductive film, and surface acoustic wave components at 25-150°C using bonding boundaries and the relationship of the bump profile, bonding temperature and pressure achieved. The critical problem of thermal mismatch in conventional methods due to the large difference of the coefficient of thermal expansion of each substrate is overcome.

6. Conclusions

In this research, the bonding of micro-bumps of Au and Sn as well as Sn-Ag and Sn-Ag-Cu is realized in the temperature range below 200°C by the SAB method using Ar-plasma activation under low vacuum background and contact in ambient air. Suitable process parameters were determined for low temperature micro-bonding in ambient air, such as pretreatment time and air exposure time for surface activation process, and parallelism, bonding temperature, bonding pressure, and bonding time for bonding process, depending on the materials, hardness, surface roughness, and bump profile. It demonstrates that the successful application of SAB to connect various substrates at low temperatures, and therefore overcome the critical problem of the thermal mismatch in conventional methods. It contributes to the microelectronic industry a systemically fundamental and applicable guide of the low-temperature flip-chip bonding technology.