

Inspection, Design, and Improvement of Hybrid Bonding in 3D IC Fabrication Using In-situ Heating Atomic Force Microscopy

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Abstract

Cu/SiO₂ hybrid bonding serves as an important process for vertical chip stacking in 3D IC fabrication, which provides electrical interconnection and isolation in the same process. However, its unique bonding mechanism brings manufacture challenges. In hybrid bonding Cu pads are initially polished slightly below the surrounding SiO₂ surface by chemical-mechanical planarization (CMP). Subsequently, dielectric-to-dielectric bonding is conducted at room temperature after proper surface activation. Finally, during annealing, Cu pads expand and reach Cu pads on the opposite side, forming Cu joints. Since the expansion of Cu pads is only a few tens of nanometers or even less, Cu recess control by CMP becomes extremely rigorous. If Cu pads are overpolished during CMP, insufficient Cu expansion would lead to bonding failure. Thus, estimating Cu expansion at high temperatures is critical for designing relevant processes of hybrid bonding. Although many studies obtained Cu expansion using simulation, direct measurement is still insufficient.

In this study, we developed an effective method to measure actual Cu expansion at elevated temperatures using in-situ heating atomic force microscopy (AFM). The nanometer scale expansion of Cu pads was captured, and the transition of Cu pads from recess to protrusion was observed. This is the first time a study has observed the behavior of hybrid bonding mechanism. We also investigated the dimensional effect on Cu expansion, providing information for further downscaling hybrid bonding development. Additionally, by grain-boundary engineering, we enhanced the expansion of Cu pads using nanocrystalline Cu (NC-Cu). The results showed that the expansion of NC-Cu was more than two times larger than that of regular-Cu, showing the potential of NC-Cu for fine-pitch hybrid bonding.

Keywords - 3D IC packaging, Hybrid bonding, Thermal expansion, NC-Cu