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# A low-temperature solid-state bonding method based on copper bump coated with nickel microcones and silver buffer

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ABSTRACT

A low temperature solid state bonding between Cu bump coated with Nickel microcone arrays (Ni MCAs) and Ag layer is put forward. Ag, as an excellent electrical and thermal conductivity material, is used as a bonding medium between Cu substrate and Cu bumps. The bonding process is conducted under low temperature and flat surface because of the presence of nano dimension of Ni MCAs and deformation of Ag. The best bonding quality is obtained under the bonding pressure of 180 MPa, time of 20 min and temperature of 250 °C in ambient air. No molten phase is involved in the bonding process. Scanning Electron Microscopy showed that the Ni MCAs have been effectively embedded into Ag layer without voids and intermetallic compounds (IMC). Thus, reliability is enhanced. Transmission Electron Microscopy results demonstrated a sufficient insertion and atomic scale bonding between Ni MCAs and Ag. This work is expected for extensive practical application.



## 1. Introduction

In recent years, 3D integration technology has attracted much attention since it provides higher bandwidth, heterogeneous integration, smaller form factor, shorter interconnection length, and lower cost [1]. There are a variety of ways to accomplish 3D integrated circuit stacking, such as eutectic bonding [2], surface activation bonding [3], nano-rod array bonding [4], and metal diffusion bonding [5]. Among these different bonding technologies, metal-to-metal bonding is preferred as it allows simultaneous formation of electrical, mechanical, and hermetic bonds [6]. Although solder-based materials are widely used in the industry for the electrical connections, it suffers from poor physical properties, scalability, and reliability, which are closely related to formation of IMC in eutectic bonding [7,8]. Furthermore, the IMC does not deform as the soft solder does to accommodate the coefficient of thermal expansion (CTE) mismatch between semiconductor chips and Cu substrates. Soft solders also tend to get fatigued under long-term thermal cycling conditions [9,10].

To solve the IMC and large CTE mismatch between semiconductor chips and Cu substrates, We chose Ag as an alternative bonding medium. As known, Ag has been considered as an excellent candidate for 3D integration due to its highest electrical conductivity ($63 \times 10^6$/m Ω) and the highest thermal conductivity (429 W/m K). It also has superior ductile properties and low yield strength. Ag thus can help to accommodate large mismatch in the coefficient of thermal expansion between Si ($2.7 \times 10^{-6}$ °C$^{-1}$) and Cu($17 \times 10^{-6}$ °C$^{-1}$). Lee [11,12] conducted continuous researches on pure Ag foil as the bonding medium in the application of low-temperature solid-state bonding. However, an annealing process at 450 °C is needed to make Ag ductile by increasing its grain size, and make the subsequent solid state bonding possible. Besides, a high vacuum environment is needed to prevent oxidation of Cu during the bonding, which limits its applications.

Including nanoscale structures and materials into the bonding process, an alternative approach was put forward to reduce bonding temperature [13]. In previous work, Chen [14] reported insertion bonding technology with Ni MCAs and the bonding temperature can be reduced to 160 °C, which was much lower than melting temperature of solder. The mechanisms of mechanical interlock and solid state diffusion were also explored. In this research, we reported a low temperature insertion bonding method between Cu bump coated with Ni MCAs and Ag without solder and flux, and mechanism of such bonds is discussed. Compared with other Cu-Ag bonding methods, the bonding mate is conducted under a low operation temperature and flat surface because of the nano dimension of Ni MCAs and deformation of Ag.

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## 2. Materials and methods

### 2.1. Synthesis of Ni MCAs and Ag layer

In this experiment, copper alloy (Cu-2.3Fe-0.12Zn-0.03P wt%) was pretreated by electrochemically degreasing, 10% $H_2SO_4$ cleaning, and deionized water cleaning. After that, Ag layer was electrodeposited on the Cu plate at 20 °C and 0.02 $Adm^{-2}$ for 15 min in an electro bath. On the other side, photoresist was patterned with 121 holes with 100 μm diameter, 60 μm height, and 300 μm pitch on Cr/Cu seeded Si chips as shown in Fig. 1(c). The Cu pillar plating [14] and subsequent Ni MCAs plating [15] were performed at 5 $Adm^{-2}$ for 15 min and 1 $Adm^{-2}$ for 20 min respectively, as shown in Fig. 1(d). As shown in Fig. 1(b), this results in the deposition of Ni MCAs with an average height of 800–1000 nm on 35 μm tall pillar bumps.

### 2.2. Bonding test

A Rhesca PTR-1101 Tester modified with a hot plate and a highly flat loader has been used to perform the bonding process [14]. First, Cu substrate with Ag layer has been put on the substrate. After placing the bonding couple face-to-face, hot plate heated the couple to 250 °C in 13 min. Then the loader started to apply vertical pressure with a loading rate of 1.2 mm $min^{-1}$ until the predetermined bonding pressure was reached. Bonding process lasted for 20 min at 250 °C and the pressure of 140–200 MPa. Fig. 1(a) is the schematic diagram of the bonding process. The entire bonding process was performed in ambient atmosphere air.

After bonding, the interfacial morphologies of cross section were observed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

## 3. Results and discussions

### 3.1. Bonding interfacial morphologies

Cross-sectional SEM images of the bonding interface are shown in Fig. 2. After cooling, the bonding couples are easily separated as adhesion between Cu bump and Cr/Cu seed layer are weak without the existence of under bump metallization (UBM), making it possible to test the bonding strength of individual bumps, which made the bump array disbanded to the opposite Cu substrate with the cones embedded as exhibited in Fig. 2(a) and (b). As shown in Fig. 2(c) and (d), tips of the Ni MCAs are embedded into the soft Ag layer, and some voids appear along the bond interface under the bonding conditions of 230 °C and 180 MPa for 20 min. When the temperature was increased to 250 °C, the Ni MCAs are completely embedded into the Ag layer and show no voids in the interface. This indicates that an excellent bonding interface can be obtained under the bonding condition of 250 °C and 180 MPa for 20 min. Compared with Fig. 2(d) and (f) shows larger insertion bonding and less voids. This result may be caused by the sufficient mechanical interlock at high bonding temperature. Considering the special morphology of the Ni MCAs, Ni cone could easily insert into the soft Ag layer due to its sharp tip under the hot-pressure bonding temperature.

### 3.2. Bonding mechanisms

Fig. 3 shows the result of TEM observation and analysis on the cross-sectional lamination of a sample bonded at 250 °C and 180 MPa for 20 min. Fig. 3(a) shows the low magnification image of several Ni MCAs on top of bottom Ag filling the valley between cones. It's clear that the Ni cones were inserted into the Ag layer on other side. The bonding interface is very compact and almost

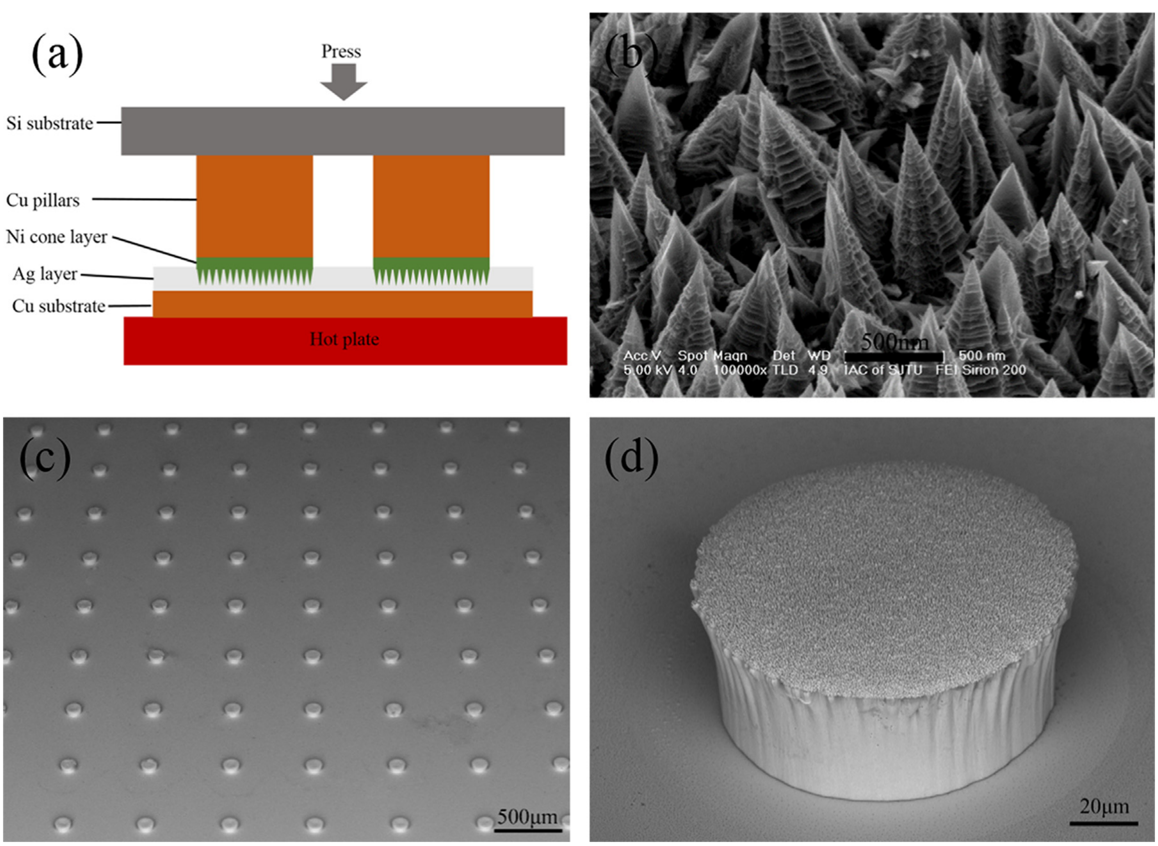


**Fig. 1.** (a) Schematic diagram of the bonding method. (b) Electrodeposited Ni MCAs. (c, d) 300 μm pitch bump arrays coated with Ni MCAs.