All-Copper Pillar Interconnects

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Abstract:

As modern electronics decrease in size, one of the major problems which arises is the signal delay between the transistor and substrate through the current tin-based solder sphere connections. The focus of this project is to replace solder spheres with all-copper pillar interconnects. The pillars are to be grown from a copper (Cu) seed area on each chip or wafer via Cu electroplating, and then bonded together via electroless Cu plating, as seen in Figure 1.

Further stabilization of the bond results from polymer collars and optimization of the Cu electroplating and Cu electroless plating conditions. Various electroplating bath conditions were tested to form flat-ended Cu pillars. Similarly, various electroless plating bath conditions were tested to achieve the greatest all-Cu bond strength. These experiments took place on both processed wafers and on actual microchips.

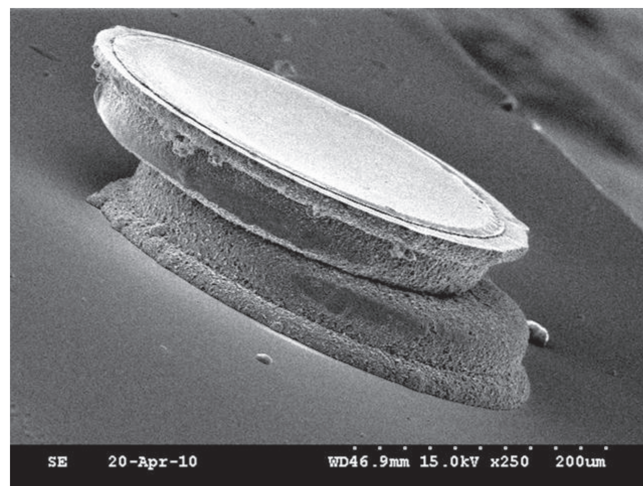

Figure 1: Side view of electroless-bonded copper pillars.

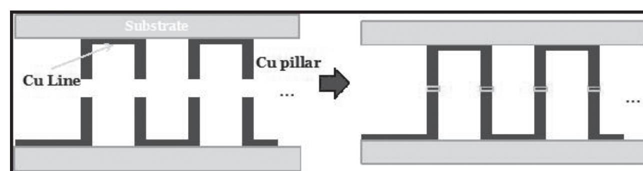

Figure 2: Schematic of "daisy-chain" structure.

Experimental Procedure:

In order to experimentally electroplate Cu pillars, we processed 4″ silicon (Si) wafers to resemble the Cu lines of microchips where electrical connections to the substrate are made. We grew a 1 μm silicon dioxide (SiO_2) layer on each wafer, and then sputtered chrome (Cr), Cu, and titanium (Ti) layers in respective thicknesses of 30, 300, and 20 nm. The Cr layer ensured adhesion of the Cu layer to the wafer, while the Ti layer protected the Cu from oxidation when the second SiO_2 layer was grown, 1.5 μm thick. The purpose of this SiO_2 layer was to insulate the unexposed Cu from the electrolytic plating solutions.

Next, SC 1813 photoresist was spun and baked onto the wafer. We then exposed the photoresist to 365 nm wavelength light under a patterned mask, developed it, and cleaned away residual photoresist with reactive ion etching to expose the SiO_2 layer in a pattern. Buffered oxide etchant was used to wet etch through the SiO_2 and Ti layers to fully expose the Cu seed area. After stripping off this photoresist, we spun and baked on an Aquatrel™ polymer layer. As with the photoresist, we then exposed, developed, and cleaned this layer to form our polymer collars for each pillar hole. For future electrical characterization and bond yield measurement experimentation, we used an alternative patterned mask, which resulted in the formation of a "daisy-chain" pillar structure, seen in Figure 2.

We used Cu electroplating to grow Cu pillars with heights of 50 μm and diameters of 150 μm. Electroplating is a process where in-solution cations of a desired material are reduced onto the surface of another conductive material. The electrical current supplied to our Cu metal anode oxidizes the Cu atoms, the ions of which are reduced at the cathode, a processed wafer, to plate Cu metal onto the surface (Figure 3).

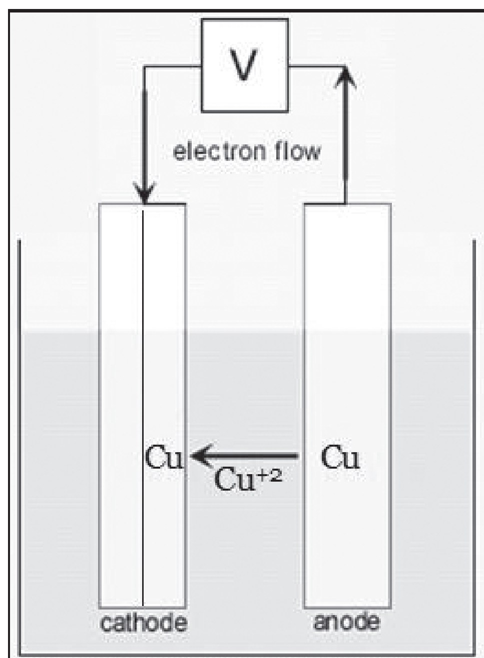

Figure 3: Electroplating system schematic.

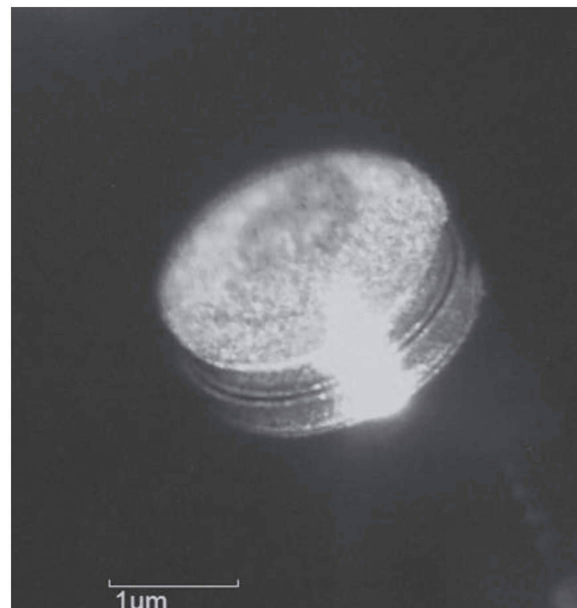

Figure 4: A flat-ended copper pillar.

Electroplating on the processed wafers resulted in the precise growing of Cu pillars from the Cu seed areas of the wafer. The electroplating bath was an acidic solution of copper sulfate ($CuSO_4$), sulfuric acid (H_2SO_4), the surfactant polyethylene glycol (PEG, MW: 4000 g/mol), and sodium chloride (NaCl) dissolved in deionized water. This research focused partly on studying the pillar surfaces in order to optimize the electroplating bath solution, and the results of this will be discussed later.

We also sought to design an optimal electroless plating bath in which to bond the Cu pillars. While electroless plating serves the same purpose as electroplating, it uses the following chemical reaction: Cu^{+2} + 2 HCHO + 4 OH- → Cu + $2HCOO^-$ + $2H_20$ + H_2, instead of external electrical power, to drive the Cu redox reaction. Our bath consisted of 3.6 grams (g) Cu sulfate, 9.6 g EDTA, 9.87 g KOH, approximately 20 mg potassium ferrocyanide, 0.2 mL of HCl, 1.79 g of paraformaldehyde, and other experimental additives dissolved in 200 mL of DI water. With heating and stirring, Cu^{+2} ions were complexed to EDTA in solution before they were reduced at the electroplated Cu pillar surface. Simultaneously, formaldehyde (HCHO) molecules were oxidized to formic acid.

Results and Conclusions:

Our best electroplating results came from a bath designed for a high current density maximum and low conductivity, with the corrosion inhibitor benzotriazole (BTA) as the optimizing additive. To achieve these conditions, we used 30 g of $CuSO_4$ and 24 mL H_2SO_4 in 300 mL of deionized water. This bath composition, which also included 0.18 g of PEG, 0.03 g NaCl, 0.6 mL SPS, and 0.03 g of BTA, resulted in the even electroplating of flat-ended Cu pillars (Figure 4).

Flat-ended pillars are an improvement over the concave-ended pillars grown previously, because they reduce the possibility of voids becoming trapped in the subsequent electroless bond. These voids, which result from a long solution transfer length over the concave top of the pillar, weaken both the physical structure and electrical conductivity of the electroless bonds pillars.

In optimizing the electroless plating bath, we found that the additives 2,2'-dipyridyl and PEG in the respective concentrations of 20 mg/L and 7.5 mg/L produced the most uniform and crystalline electroless plated Cu structure in comparison to other electroless plating experiments. Thus, these additives will help reduce trapping of voids resultant from evolved hydrogen gas bubbles and improve the strength and conductivity of electroless bonds.

Future Work:

In the future, we would like to continue optimizing the electroless bath conditions and develop dome-ended pillars. We would also like to refine the "daisy chain" structure with an adhesion promoter between the polymer and SiO2 layer, and begin electrical characterization and bond yield testing.

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