Electroless Nickel/Copper Plating as a New Bump Metallization

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***Abstract*—An electroless bumping method was developed both for flip chip and TAB applications. Electroless Ni/Cu plating is a maskless low-cost approach to bumping directly on aluminum bondpads. An immersion tin layer for coating and soldering is plated on the copper. Due to the high alkalinity (pH $>$ 12) of electroless Cu baths, a thick Ni layer of about 7 μm is required on the aluminum for sealing. A shear strength of 180 cN and a contact resistance of less than 2 mΩ for the bumps were obtained. Because of the high hardness of nickel, conventional gang bonding techniques are not applicable. The hardness of electroless copper is about 200 mHV_{25}, and after annealing in the range of 130–150 mHV_{25}. Thermocompression gang bonding of Au plated tape to the Ni/Cu/Sn metallization was carried out. The average pull strength was 50 cN. The influences of the size and electroless solder plating of the deposited copper are also investigated.**

I. Introduction

THE INCREASING number of I/O's on integrated circuits has forced significant increases in packaging density and the need for methods of chip interconnection with high conductivity and low capacitance. At the same time the interest in MCM packaging is being driven by demand for more efficient and high-performance manufacturing processes.

MCM packaging technologies require bare chips interconnected on a common supporting substrate. Connecting techniques such as flip chip and TAB offer advantageously high lead count at a fine pitch, high performance, and the ability to collectively bond all I/O's with one operation. However, the conventional bumping process involves many complex steps, such as sputtering, photolithography and plating. To resolve this problem, some authors have shown that electroless nickel plating is a suitable method for bumping [1]–[3]. This selective metallization technique has the advantage of a hermetic aluminum seal with a maskless low-cost process.

During the gang bonding process a certain plastic deformation only at the bond interface is of great importance. This deformation will be used to compensate for the nonplanarity of the thermode and bump height and is required to avoid cracks in the passivation. Due to the hardness of the nickel bumps this is only possible by using alternative metallization or bonding methods [1].

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In this context we have developed the possibility of a new bumping method based on electroless nickel and electroless copper plating. As an alternative to the electroless Ni bumps, the use of Ni/Cu bumps was investigated. The mechanical properties of copper deposits and the kinetics of electroless copper plating were analyzed for various types of baths. Selective copper plating introduces some new problems in general, like the compatibility with integrated circuits materials. There are also some particular problems that are associated with the technique, which are described here.

II. Deposition Process

The detailed steps of the electroless Ni process have been described before in the literature [4]. The electroless copper deposition reaction is based on the reduction of positive copper ions in an alkaline solution, which is the result of the reaction between formaldehyde and the hydroxyl ions [5], [6]. The overall reaction can be described by the following equations:

anodic reaction

$$2HCHO + 4OH^- \rightarrow 2HCOO^- + 2H_2O + H_2$$

cathodic reaction

$$Cu^{++} + 2e^- \rightarrow Cu \downarrow$$

The reduction reaction requires a high pH value typically in the range of 11.5–13 at a plating temperature which is between 40°C and 70°C.

Electroless copper plating can be carried out selectively since deposition is autocatalytic and requires a catalytic surface to start [5]. The deposition then continues, providing that the metal ion and reducing agent are replenished. For example, the deposition process is highly favorable at chemically active surfaces such as gold and nickel, as opposed to chemically inert dielectric surfaces such as polyimide and silicon dioxide.

1) Electrolytes: Table I lists the commercial solutions which were investigated for electroless copper plating. It is important to distinguish between two types of solutions: nondecomposable EDTA and environmentally friendly tartrate. The difference between the two can be seen in the separate ways in which they react with complexing agents. The sodium potassium tartrate complexing agent is of great practical importance because it is biologically decomposable and therefore fulfills the legal conditions for waste water treatment. We investigated two EDTA baths and three tartrate baths which were further selected for pH value, plating temperature and plating rate.

TABLE I
VARIOUS COPPER ELECTROLYTES USED FOR BUMPING

EDTA:	E1:	pH = 13, 60°C, 4μm/h Atotech, Printoganth ML
	E2:	pH = 12.8, 46°C, 5μm/h Shipley, Cuposit 251
Tartrat:	T1:	pH = 12.5, 44°C, 5μm/h Doduco, Doduprint 540
	T2:	pH = 13, 43°C, 6μm/h Shipley, Cuposit CP-78
	T3:	pH = 12.9, 40°C, 4μm/h Blasberg, Metalyt Cu 40

2) Bump Formation Process: The characteristic feature of copper baths, a high pH value with a low plating rate, requires long exposure times and therefore corrosion of the basic material. As a result of a substitution reaction, there is copper deposition on nonoxidized silicon surfaces. A direct copper deposition on the aluminum bondpads is not possible, because of the high alkaline content of the solution. Therefore, before copper plating is carried out, a sufficiently thick nickel layer is deposited on the pads to protect them.

The schematic bumping process is shown in Fig. 1. In preparing the chips for Ni/Cu bumps the first step (after cleaning) is the activation of bondpads [7]. To do this, the native oxide on the aluminum surface is removed and a layer which can initiate electroless nickel deposition is formed. We use a commercially modified alloy zincate solution for this pretreatment. The quality of this nucleation depends strongly on the past history of the aluminum bondpad. The electroless nickel hypophosphite bath was operated at 90°C with a pH value of 4.5. The plating rate is 25 μm/h under these conditions.

Approximately 7 μm of nickel is necessary to seal and protect the aluminum bondpad from the high alkaline copper bath. Nickel and copper plating is isotropic, hence bumps grow laterally and overlap the passivation.

When the nickel layer is too thin, OH^- ions can move between the passivation and the nickel, reaching the aluminum and damaging it. No corrosion was observed with nickel layers thicker than 7 μm.

For coating and soldering, a thin layer (about 1 μm) of tin was deposited on the copper from an immersion tin plating bath. A cross section of a Ni/Cu/Sn bump is given in Fig. 2.

The shear strength of nickel copper bumps deposited on 100 $\mu m^2 \times 100\ \mu m^2$ aluminum pads was measured with a shear tester. The average value of the shear force was measured at 180 cN. The measurements of the contact resistances of bumps (size: 100 $\mu m^2 \times 100\ \mu m^2$) were better than 2 m$\Omega$.

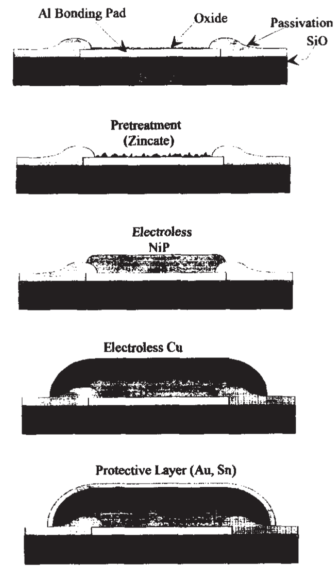

Fig. 1. Schematic of the electroless bumping process.

Fig. 2. Metallographic cross section of a nickel/copper/tin bump. The bump height is 25 μm with 12 μm copper and a layer of 2 μm tin on top.

III. INFLUENCE OF PLATING RATE

The plating rate of the copper bath mainly depends on the bath temperature, the amount of copper present, and the concentration of the reducing agent. If this concentration is increased, a higher plating rate results; unfortunately, the reduced stability of the bath also results. For this reason special stabilization compounds are used to increase the plating rate of copper baths, so that despite rates of 5 μm per hour the bath stability is maintained.

Less stable baths have a higher plating rate, but tend toward nonselective deposition and spontaneous decomposition. Highly stabilized baths have a longer lifetime, but lower plating rates. The influence of the plating rate during electroless bumping can be seen in Fig. 3.

In this case the plating was carried out for a period of one h with a constant loading at constant bath temperature. Thereby the concentration of the bath ingredients is reduced. In this way, the plating rate can be well adjusted.

A strong nonselectivity is clearly recognized in conjunction with high plating rates. In extreme cases this leads to a short circuit and to irregular bump surfaces. Lower plating rates have a slower start and long exposure periods.

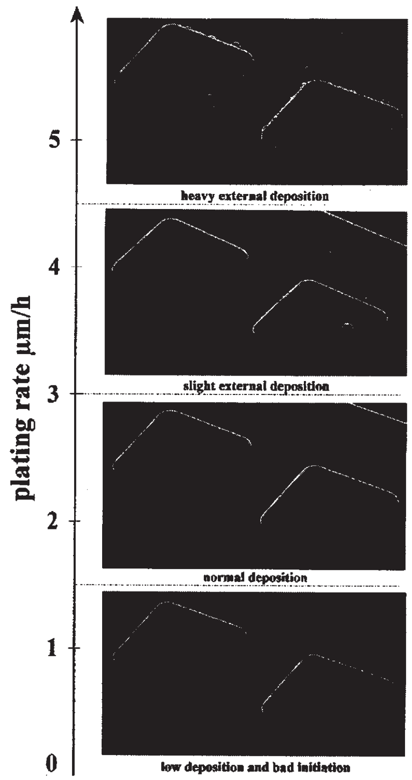

Fig. 3. Influence of the plating rate on the growth condition.

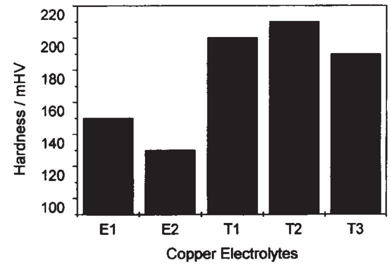

Fig. 4. Hardness of copper bumps for investigated copper electrolytes.

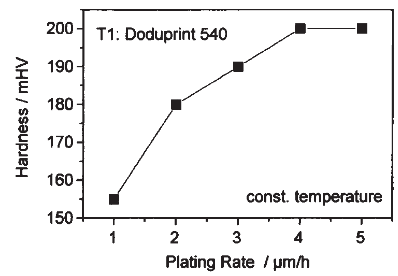

Fig. 5. Effect of plating rate on hardness.

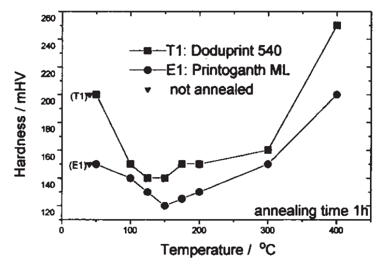

Fig. 6. Annealing behavior for solutions with tartrate and EDTA as complexing agent.

Electroless copper solutions with tartrate as the complexing agent produced the best results. Ideal growth conditions for this type of bath are in the range of 1.5–3.5 μm/h. In this range a copper layer of 10 μm can be plated in 3 h without external deposition and with no degradation of the integrated circuit.

IV. Hardness

The hardness of the copper bumps was measured at the top of the bump with a Vicker identer. The hardness results reported here are the average of 10 readings. A comparison for all investigated electrolytes is presented in Fig. 4. It can be seen that the tartrate solutions have higher hardness values than the EDTA solutions at the same plating rate.

As seen in Fig. 5 the hardness depends on the plating rate. Indeed, at lower plating rate, atoms can more easily occupy a relatively stress-free configuration with fewer structural defects.

Fig. 6 shows the hardness as a function of the annealing temperature in nitrogen atmosphere for two investigated copper baths. Typical annealing times are about one h.

The initial value differs between 200 mHV25 for the tartrate bath and 150 mHV25 for the EDTA bath. The lowest values after annealing are in the range of 130–150 mHV25 at a temperature of 150°C. The effect of high temperature annealing on the hardness of the plate is conspicuous. The hardness of electroless copper deposits increases when increasing the annealing temperature beyond the minimal point. Measurements were taken at cross sections in order to be able to exclude a surface oxidation at the annealing time. The results at the top of the bump were the same as before.

The detrimental effect of higher hardness can perhaps be explained by the presence of stabilizing additives and organic by products. These inclusions lead to an internal stress of the deposit at high annealing temperatures and thereby to an increasing of the hardness.

V. Bonding

The bonding investigations were performed with a test die of 328 I/O's, an inner lead pitch of 100 μm, and two different bump metallurgies.

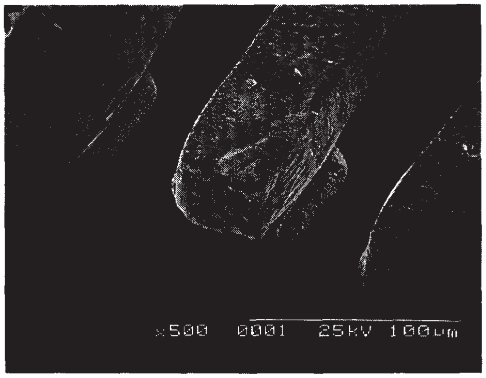

Fig. 7. Inner lead bonded Ni/Cu bumps.

Inner lead bonding was carried out by gang bonding. Fig. 7 shows the test sample bonded to a gold tape with Ni/Cu/Sn bumps. Destructive pull tests were performed with the bonded devices. An average pull strength of 50 cN could be achieved. The mean failure mode was lead lift and lead break.

During gang bonding of conventional Au bumps the plastic deformation at the bondpad can cause cracks in the passivation and in the sputtered barrier layer [8]. Baggermann *et al.* [9] introduced an additional Ni layer to avoid the deformation at the bondpad. The hard Ni layer reduces the stress and the plastic strain in the bondpad. The Ni/Cu process already has this advantage. The Cu/Sn metallization compensates for the nonplanarity of the thermode and absorbs the distortion energy during inner lead bonding.

VI. Further Investigations

For flip chip applications the availability of an electroless Pb/Sn electrolyte would be of great interest. An electroless Pb/Sn coating of adequate thickness can be plated on a copper metallization. Despite the potential applications of electroless solder coating, only a few electrolytes are available [10] because of instability problems and critical parameters. For the future we intend to evaluate the possibility of electroless solder plating for bumping technology.

A second point of interest is the observed effect of a critical size for the isolated catalytic pads. For small sizes an electroless metal deposition does not start. This difficulty and the nonselectivity become essential when plating sub micron structures in VLSI applications [11]–[13]. The reason for all the interest in copper is the very low resistance and projected reliability. Therefore it is an obvious choice for long and narrow interconnections

VII. Summary

A selective electroless copper bumping technique was developed. The copper metallization has in comparison to nickel the advantage of a high ductility which enables gang bonding. Due to the high pH value of electroless copper baths a basic nickel layer of about 7 μm is required to protect the aluminum. The relationship between kinetics and growth conditions of Cu have been investigated for various electroless copper solutions. As a result, the best growth conditions were achieved with the more environmentally friendly complexing agent. Using this type of solution a copper layer of 10 μm can be plated in 3 h. With the appropriate bath conditions a selective metallization can be achieved without nonselective deposition. An immersion tin layer for coating and soldering can be plated on the copper. Using this bumping method a die with 328 I/O's was successfully gang bonded.

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