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Effect of ENEPIG metallization for solid-state gold-gold diffusion bonds

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ABSTRACT

Gold-gold (Au—Au) diffusion bonding behavior of different tri-layer thicknesses of Electroless Ni/Electroless Pd/Immersion Au (ENEPIG) plating on a high-density system on a flex (SOF) package was examined. Plating thickness has a significant effect on surface roughness and void formation at the Au—Au bonding interface, which exhibits degraded bond strength with an affected failure mode. It is seen that relatively smooth surface roughness (Ra < 100 nm) of thicker Ni(P) plating samples facilitates the shrinkage of voids and significantly increases bonding strength. Higher surface roughness in the low Ni(P) sample has a poor surface profile, which results in large lenticular shape voids and requires more energy to shrink by diffusion and a creep process. Enhancing bonding parameters constitutes an essential feature to compensate the physical and mechanical properties of ENEPIG plating. Based on this study, the authors recommend a suitable ENEPIG plating thickness for a high quality metallurgical bond, which passes different reliability tests.

1. Introduction

In recent years, flexible electronic systems on flex (SOF) packages have gained increasing attention from scientific communities due to their potential to create new classes of applications, such as information displays, medical diagnostics, X-ray imagers, implantable medical devices, health monitors and other systems, as shown in Fig. 1, that lie outside of conventional wafer-based electronics. Au—Au diffusion bonding is frequently used for both MEMS structures and for silicon integration of a combination of different device structures, including III-V and Si integration [1–3]. It also constitutes an attractive solution for many advanced packaging applications, including high performance SOF packages [4–7], while producing high die attachment accuracy, good electrical conductivity, and hermeticity with a lack of problematic native oxides. Recently, ENEPIG surface finishes have gained popularity in electronics industries due to the electroless plating process, low cost, and high reliability in both wire bonding and soldering applications [8]. However, the Au—Au solid state bonding performance of the ENEPIG surface finish and electroplated Au bump interconnection has not yet been sufficiently studied. Au—Au diffusion bonding is a simple process based on atomics diffusion of elements at the joining interface. In general, the diffusion rate, in terms of diffusion coefficient D, is defined as [9,10]:

$$D = Do\exp(-Q/RT), \quad (1)$$

where Do is the frequency factor; Q is the activation energy; R is the gas constant; and T is the temperature in Kelvin. The diffusion coefficient (D) is independent of concentration. As the temperature is raised, the rate of diffusion increases exponentially. Diffusion of atoms is a thermodynamic process, in which temperature and diffusibility of the material are considerable parameters, and the creep mechanism allows a material flow to produce full intimate contact at the joint interface, as required for diffusion bonding. Therefore, surface finish on the substrate plays a vital role to enhance diffusion bonding, particularly at high-density interconnections. It is obvious that knowledge of the bonding mechanism is also essential in order to determine the necessary amount of energy for diffusion bonding of ENEPIG. The dominant mechanisms for bond formation are creep deformation and void elimination from the bonding zone, which is related to the sintering mechanism [10]. Normally, bonded surfaces are not flat. A bond is formed only when a new grain appears at the zone of the interface with voids remaining at the joint line. The rate-controlling step in diffusion bonding is the removal of interfacial voids due to surface roughness [11]. Somekawa et al. [12] reported that finer grain reduces the diffusion bonding temperature. Therefore, different ENEPIG plating thicknesses with different surface roughness are selected for diffusion bonding.

For the present study, the role of bonding parameters during diffusion bonding of different thicknesses of ENEPIG plating is evaluated. The key is to establish the major factors influencing diffusion bonding: 1) optimize the Au—Au bonding parameters for high density interconnections; 2) determine the effect of surface roughness on diffusion bonding; 3) quantitatively measure bond strength with different experimental plating thicknesses; and 4) determine whether the high density Au—Au bonds are metallurgically stable after a reliability test.

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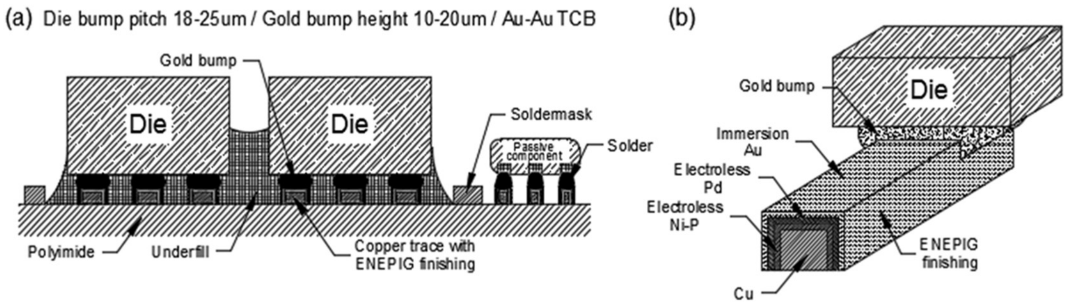

Fig. 1. SOF package. (a) Au—Au diffusion bonding in SOF, and (b) TCB with ENEPIG surface finish on fine trace.

2. Experimental procedure

A SOF package with 23 μm of inner lead bonding (ILB) pitch, having different Au, Pd and Ni(P) thicknesses, was used as a test vehicle. The ENEPIG plating thicknesses are measured by XRF (Fischercope X-ray, Model: XDVM-*u*SD), and the isotropic elastic-plastic properties of the ENEPIG plating material are presented in Tables 1 and 2 respectively. XPS surface analysis (Physical Electronics 5600 multi-technique system) is performed after ENEPIG plating and after being subjected to isothermal aging of 150 °C for 24 h.

A Toray FC3000 bonder with alignment accuracy of ±2 μm was used for diffusion bonding. The number of gold bumps in the die is 532, with an I/O count of 526. The die bump size is 15 μm × 80 μm, and the total die bonding area is 0.608 mm^2. The conventional electrolytic Ni/Au plating sample C is employed as a control, with average Ni and Au plating thicknesses of 2 μm and 0.5 μm, respectively. A total of nine experimental legs and 50 samples per leg were prepared for this study.

During bonding, the chip is picked up and aligned face-down to bumps on a heated substrate. After alignment, the chip is pressed down on the bumps at an optimized pressure and temperature for certain time. Therefore, optimization of bonding temperature, pressure, and time plays a critical role to establish a reliable Au—Au metallurgical bonding between the flip chip and flexible substrate.

For optimization of bonding temperature, different bonding temperatures were used. The actual bond line temperatures between the die bump and flex substrate interface were measured by NR-500 series, which are 180 °C, 220 °C, 260 °C, 300 °C, 320 °C, and 340 °C. Fig. 2 graphically illustrates the actual bonding temperature profile.

Die-attached samples were inspected by using an X-ray machine to determine any bond misalignment, and other visual anomalies in the bonded samples prior to die shear and reliability tests. A die shear tester, Dage Series 4000, was utilized to determine the bonding strength, and failure analyses were performed by using an optical microscope and SEM. FIB analysis was conducted to check the quality of the Au—Au diffusion bonds.

A die pull off test (Method 2031.1) was performed. Fig. 3 presents the schematic diagram of the die pull test method. A pull-off rod is connected on the top surface of the die by using die attach epoxy material, which covers approximately 75% of the die surface. The rod is connected to the pull test machine. The die pull strength result is quantitatively measured by the pull test machine.

For reliability, test samples were prepared with optimized diffusion bonding parameters, followed by a standard underfill encapsulation. Resistances of the samples (10 points per sample and 25 samples per leg) were measured before the reliability tests. After validation by electrical tests, samples were subjected to reliability tests, such as a temperature and humidity tests (THT) and a thermal shock test (TST). For the THT, a temperature of 60 °C and 60% relative humidity were used for 1000 h. For the air to air TST, −40 °C to +125 °C temperature, for 15 min at each temperature extreme and a 10 s transition time were used for 1000 cycles. The samples were tested again to determine if they were functional after every 250 cycles, for a total 1000 cycles. The samples were than inspected by using SEM microstructural analysis.

3. Results and discussion

3.1. Effect of aging on ENEPIG plating surface

The XPS analysis result of different ENEPIG plating samples with different sputtering depths (2 nm, 4 nm, and 6 nm) are presented in Table 3. The elemental analyses of the bonding surface are mainly Au with a trace amount of Pd, and O and C signal peaks.

Fig. 4 shows the intensity of photoelectrons with respect to binding energy. The elemental analysis on the bonding surface was further determined from the XPS spectrum [16,17]. The peak binding energy of the Pd 3d3/2 was found to be 340.2 eV (Fig. 4a). This value is very close to that of Pd (340.3 eV), but not to PdO which has a binding energy of 342.5 eV [16,17]. Therefore, it can be concluded that a small amount of Pd exists as a pure metallic form in the plating surface, which has no effect on diffusion bonding. In addition, the peak binding energy of the O1s was found to be 531.7 eV (Fig. 4b). For metal oxide, the range of binding energy was 528.1–531.1 eV, indicating that the bonding surface had no metal oxidation effects [16,17]. Based on the XPS results, it can be concluded that the O found in the sample is associated with an organic compound.

3.2. Effect of plating thickness on surface roughness

Fig. 5 shows a fine grain (<5 μm) structure in all samples. A relatively rough and uneven surface was observed in the low Ni(P) plating (1 μm)

Table 1
ENEPIG surface finish with different Ni(P), Pd, and Au thicknesses.

Plating	Average plating thickness				Remarks
	Ni(P)		Pd	Au	
	Low 1 μm	Medium 3 μm	μm	μm	
ENEPIG	A	J	0.05	0.04	Low Au/low Pd
	B	K	0.05	0.07	Medium Au/low Pd
	E	N	0.2	0.07	Medium Au/medium Pd
	G	P	0.4	0.04	Low Au/high Pd
Ni/Au	C medium-2 μm			0.5	High Au

Table 2
Isotropic elastic-plastic properties of the materials [7,13–15].

Materials	Cu	Ni(P)	Au	Pd
Elastic (GPa)	117	70	79	120
Poisson's ratio	0.33	0.31	0.44	0.39
Initial yield stress (MPa)	172.38	140	100	200
Tangent modulus (MPa)	1034.2	86,666	200	13,043.5
CTE (ppm/K)	17	12	14	11.8
Hardness (HV)	~350	~500	~200	~400