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Enhanced Cu pillar design to reduce thermomechanical stress induced during flip chip assembly

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ABSTRACT

In this work a Cu pillar design that combines a stiff metal pedestal with a soft polymer as buffer layer has been integrated in a dedicated test vehicle to investigate the thermo mechanical stress induced during flip chip assembly. In-situ electrical measurements of dedicated stress sensors during a Bump Assisted BEOL Stability Indentation (BABSI) test were performed to assess the strength of the bump designs. Furthermore, the package induced stress was monitored in different regions of the test chips by measuring and comparing the I_{ON} current of the stress sensors before and after packaging. By combining in-situ electrical measurements and finite element modeling it was possible to quantify the stress level induced in the Si die after packaging. Additionally, the package out of plane deformation has been measured after flip chip to laminate and after molding. The results show that the use of a stiff pedestal is very efficient to mitigate packaging induced stress. It has also been shown that the out of plane deformation is independent of the Cu pillar design.

1. Introduction

The constant demands of the electronic industry for miniaturization, performance and reliability of innovative chip designs, require the development of new materials, processes and packaging strategies [1–4]. The high density and more robust Cu pillar interconnect aligned with highly porous material integrated in the back end of line (BEOL) improve the electrical performance of the circuit, however they decrease the mechanical stability of the chips [5–9].

Thermo mechanical strain and stress induced during 3D IC's assembly and packaging is becoming an important issue to enable 3D technology [10–14]. During assembly the rigid Cu pillar interconnect is subjected to a large bending moment caused by the coefficient of thermal expansion (CTE) mismatch between Si die and the organic laminate. The bending of the rigid Cu pillar induces high stress that is directly transferred to the BEOL causing cracks and delamination failures. One way to mitigate this stress is to increase the stiffness of the base of the Cu pillar. By making the base larger than the Cu pillar diameter and increasing its thickness it becomes stiffer. This will distribute the stress over a large area avoiding stress concentration in the base of the Cu pillar. Another option to minimize the stresses caused by the Cu pillar bending moment is to introduce a softer material between the pillar and the BEOL. This soft material will act as buffer accommodating part of the deformation and avoiding that the stress is directly transferred to the BEOL [15, 16]. In this work we will investigate some Cu pillar designs that use a combination of stiff and soft material in order to reduce thermo mechanical stress induced during flip chip assembly.

A dedicated test vehicle integrated with stress sensors was used to verify the efficiency of Cu pillar designs. It is used to perform in-situ Bump Assisted BEOL Stability Indentation (BABSI) test. After a first assessment of the strength of the Cu pillar design the test chips were packaged in a fcBGA configuration. The flip chip assembly was made by mass reflow in combination with capillarity underfill followed by molding. The stress sensors were measured before the flip chip is assembled to the laminate, before and after molding. Also, a 3D Finite Element Model (FEM) has been used to quantify the stress and the full packaging process was simulated.

2. Test vehicle

In order to study the mechanical stress induced during packaging a special test chip has been designed and manufactured in 65 nm technology. The test chip contains different test structures in FEOL and BEOL which are used as electrically measurable sensor [11, 13]. The FEOL sensors available on the test chip are differently oriented n- and p-field effect transistors (FETs) which are used as stress sensor due to their significant piezoelectric response. The FET channel dimensions are 4 µm × 4 µm and they are grouped in the 7 × 8 arrays as shown in Fig. 1. The FETs are used to measure local stress or its variations near

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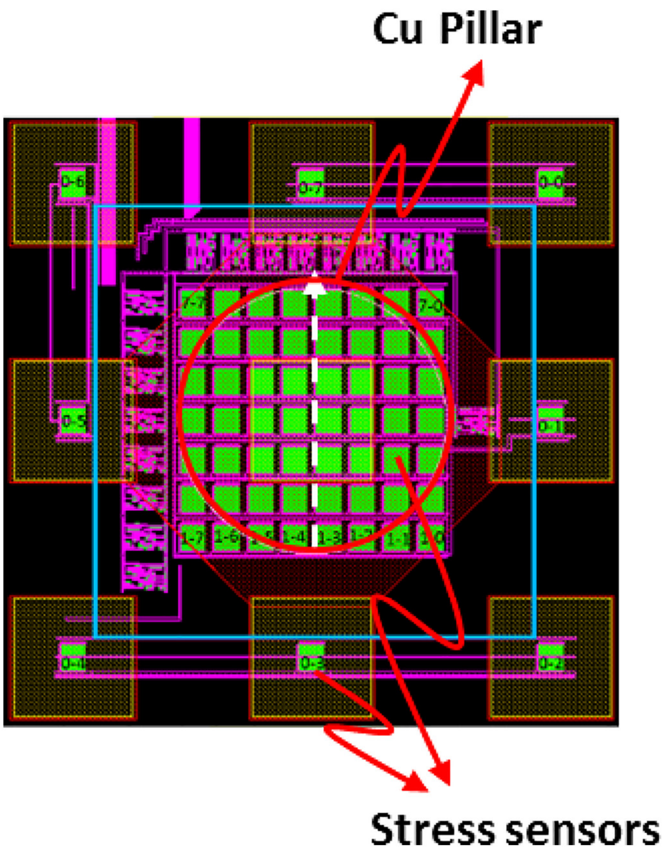

Fig. 1. Arrangement of the FEOL stress sensors around the copper pillar. The green squares indicate the positions of the n-FET stress sensors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the Cu pillars. After calibration these sensors allow quantitative analysis of mechanical stresses induced during packaging.

The saturation currents of the sensors (I_{ON}) were measured at different locations in the die. The minimal current measured between the arrays is used as reference. The relative change of the saturation currents (ΔI_{ON}) is calculated as:

$$\Delta I_{ON}\,(\%) = \frac{I_{ON} - I_{ON,ref}}{I_{ON,ref}} \times 100 \tag{1}$$

The test chip has been integrated with different under bump mentalizations in order to mitigate the mechanical stress transferred to the Si die during assembly. Fig. 2 shows the Cu pillar designs considered in this work. The first design Fig. 2(a) presents a thick Al pad, 2.8 µm that differs from the baseline that presents a standard Al pad of 500 nm. The designs from Fig. 2(b) to (e) have the standard thin Al pad, 500 nm, with additional 10 µm thick Cu pedestal integrated together with a 5 µm thick soft polymer. The polymers have different openings, Fig. 2(b) 20 µm, (c) 30 µm, (d) 40 µm and (e) 60 µm. For all designs a 20 µm height Cu pillar and 16 µm thick Sn have been integrated to enable the assembly with the laminate.

The dimension of the Cu pedestal is 70 µm × 70 µm. The variation of polymer opening falls within the FET's array area, Fig. 3, except in the case of 60 µm opening. It is expected that the effect of different polymer openings will be detected by sensors located at different positions within the FET area.

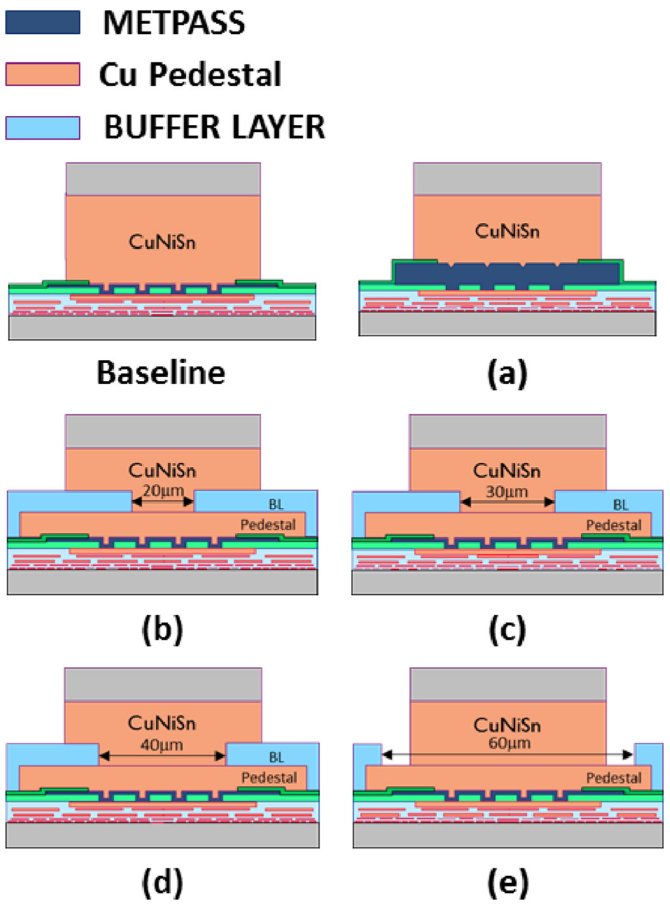

Fig. 2. Cu pillar design configurations: (a) Thick Al, (b) Cu pedestal with 20 µm polymer opening, (c) Cu pedestal with 30 µm polymer opening, (d) Cu pedestal with 40 µm polymer opening and (e) Cu pedestal with 60 µm polymer opening.

3. BABSI test

During flip chip assembly the Cu pillars are subjected to a large bending moment, mainly during the mass reflow step on which no underfill is present. In order to understand the impact of the bending moment on the stress and verify the efficiency of Cu pillar designs, the dedicated test chip with integrated stress sensor was used to perform in-situ Bump Assisted BEOL Stability Indentation (BABSI) test [17, 18]. A conical indenter tip with a flat end of 10 µm in diameter was used on a commercial nanoindenter system (MTS Systems Corporation), which allows very sensitive force and displacement detection. During this test, a normal load of 350 mN is applied to a single Cu pillar of 50 µm diameter, after which a lateral movement of the tip is performed at a velocity of 10 nm/s. This low speed was chosen to allow the electrical read of the stress sensors. The Fig. 4(a) shows the position of the stress sensor and the direction of the BABSI test. It has been measured 7 sensors in the diagonal of the Cu pillar shown in Fig. 4(b). Fig. 4(c) shows the response of the n-FET transistors at the diagonal of Cu pillar for the design case with 60 µm polymer opening during the BABSI test.

During the testing time, some sensors show a gradually increase in ΔI_{ON} while the sensors in the opposite side show a decrease in ΔI_{ON}. The sensors located to the opposite side of the indenter tip direction show a negative ΔI_{ON} while opposite sensors detect a positive ΔI_{ON}. This