Low-Temperature Nanocrystalline Cu/polymer Hybrid Bonding with Tailored CMP Process

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***Abstract*—The fine-pitch hybrid bonding technique allows for high integration density in advanced packaging. This paper demonstrates the nanocrystalline copper (nc-Cu)/polymer hybrid structure for both wafer-to-wafer as well as die to wafer hybrid bonding process. The nc-Cu material can be filled in photosensitive polymer material, with an average grain size of approximately 80 nm. Moreover, chemical mechanical polishing with tailed method attributes good interface for the nc-Cu and polymer layers bonding performance, achieving a roughness Ra of 0.26 nm and tailored dishing of 7 nm. The hybrid bonding process was completed by using a 10 µm fine-pitch nc-Cu/polymer with hybrid structure, can be bonding with pronouncedly reduced temperature of 150 ºC. Both nc-Cu/polymer with distinctive properties have shown promising candidate toward hybrid bonding and interconnections in foreseeable future. In summary, this study have focus on the nc-Cu/polymer with tailored CMP. Such extraordinary interconnection technology with low temperature hybrid bonding can be achieved and shown great potential candidates in advanced packaging.**

Keywords—nanocrystalline copper, 3DIC, CMP, Cu Pad, low-temperature bonding, polymer hybrid bonding

I. Introduction

Heterogeneous integration is the core package technology for several applications including mobile, wearable devices, HPCs and AI. In particular, AI applications are attractive in practice with numerous novel technologies as well as mathematical methods emerging in the foreseeable future. Generally, AI system-on chip (SoC) consists of GPU, logic IC, neural engine, and energy-efficient memory for chip configuration [1-4]. For such complex integrated chip configurations, strategies with solderless packaging technologies have been developed toward advanced packaging with numerous interposers as well as RDL [5]. Accordingly, it is necessary for hybrid bonding to be developed to further provide higher I/O and lower power consumption for advanced packaging in AI applications.

The nanostructures materials are attractive in different domains due to their distinctive properties including high surface area with many grain boundaries as well as great electrical tunneling though interconnections and electric contacts [6-7]. In view of our previous study [8], it was reported that the nanocrystalline copper (nc-Cu) and SiO_2 were successfully hybrid bonded at a low temperature of 200°C within wafer on-wafer process. More recently, we have reported that the distinctive photosensitive polymeric bonding material can be bonded using polymer to polymer hybrid bonding process performed at room temperature [9]. For the first time, we have herein reported distinctive hybrid bonding by using a nc-Cu/polymer hybrid structure with a pronouncedly reduced bonding temperature of 150°C for die-to-wafer hybrid bonding. More importantly, the nc-Cu/polymer surface topography is well controlled by a tailored CMP process in which the moderate dishing of nc-Cu can be controlled within a few nanometers. CMP mechanism with corresponding coplanarization of nc-Cu and polymer surface mediation with a tailored method is also discussed within this paper. For the demand of high-performance SOC, this nc-Cu/polymer novel hybrid structure has shown potential towards AI applications with parallel connective paths and interconnections of electric characteristics.

II. Experimental

A. Wafer fabrication for hybrid bonding

Fig. 1 shows a simplified process flow for this manufacturing process. In the wafer-level process, the wafer is initially coated with a photosensitive polymeric material. Upon photo exposure by using a stepper, polymeric patterned wafers with bonding pads sized to the critical dimension of 10 µm in full array are formed. Subsequently, polymeric patterned wafers are filled with nc-Cu with an average grain size of 80 nm. For the demand of polymer and nc-Cu hybrid structure, a tailored CMP process was conducted with suitable downforce and low rotation followed integrated within one recipe was developed. Thus, this hybrid structure has well-controlled roughness with the entire wafer flattened by CMP. The fabrication of recessed nc-Cu on the bonding surface is planarized using specialized nc-Cu CMP slurry and CMP disk for the demand of controlling dishing and achieving arithmetic average roughness of 0.26 nm with moderate dishing from 0-10 nm on nc-Cu. The CMP corresponding coplanarization mechanism has successfully achieved remarkable surface roughness as well as a perfect

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interface of nc-Cu and polymer. The specialized nc-Cu slurry has removed not only nc-Cu but also planarized the polymer surface topography. After bonding, nc-Cu/polymer hybrid structure was bonded successfully with a significantly reduced bonding temperature of 150°C with a pre-bond force of 2 MPa and gang-bond of 40 MPa. The high density of grain boundaries of nanocrystalline Cu structure could enhance atomic diffusion at the interface of the bonded Cu film to achieve low temperature bonding. Due to the distinctive property of nc-Cu with diffusion at low temperature, the polymer can be bonded regardless of the large CTE, indicating the process window within both materials can be enlarged. The morphology and structure of the nc-Cu/polymer hybrid bonding wafers were analyzed using FIB-SEM and TEM to investigate the cross-sectional bonding interfacial dynamics.

Subsequently, the post-bond wafer with 10.0 mm x 10.0 mm chips were further conducted with thermal shock and shear test to evaluate the mechanical properties of bonding strength and reliability. The temperature of thermal shock ranged from -55°C to 125°C, with a dwell time of 5 minutes, and the transfer time was less than 1 minute and further carried out with 250 and 500 cycles of thermal shock in the reliability test. No fracture occurred by scanning acoustic tomography, revealing a strong interface between nc-Cu and polymer.

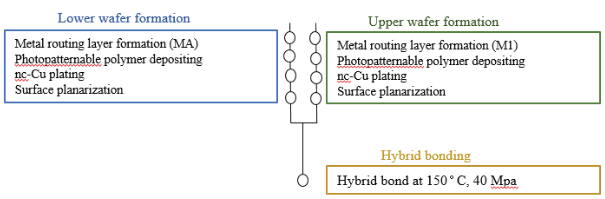

Fig. 1. Schematic of upper and lower wafer process flow.

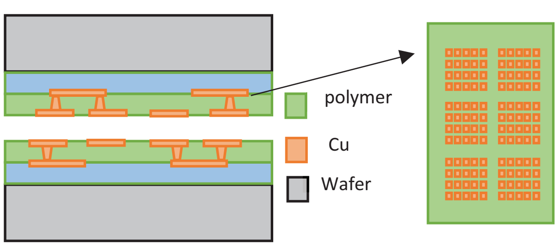

Fig. 2. Schematic of upper and lower wafer architecture.

II. Results and Discussions

For achieving and ensure the interface of nc-Cu/polymer hybrid bonding, the morphology and structure of both top and bottom wafers was analyzed to confirm the nc-Cu and polymer interdiffusion dynamics. To further analyzed the interface of nc-Cu and polymer, the roughness of the bonding surface was also evaluated by using the AFM. FIB-SEM and TEM was conduct to evaluate the interface of nc-Cu and polymer for further bonding.

A. Patternable polymer with microstructure and structure analysis

Table I summarizes the material characteristics of an i-line sensitive, photopatternable polymeric bonding material. Due to its low dielectric constant, low dissipation factor, high thermal stability, and previously demonstrated ability to be bonded at room temperature, this polymer material was deemed suitable for the organic dielectric component of the hybrid bonding interface in this study. The polymer material was patterned using previously optimized conditions consisting of 100-mJ/cm^2 exposure energy and a three-puddle developing process, which achieved 10μm vias with minimal footing or scum observed via optical microscope (Fig.3).

Material properties of the polymeric bonding material	
Item	Result
Thermal Stability (2% wt. loss in N_2)	350 ºC
Glass-transition temperature (Tg)	85 ºC
Young's Modulus	171.4 MPa
Tensile Strength	12.39 MPa
Elongation	112.30%
Relative Permittivity (10 GHz)	2.5
Loss Tangent (10 GHz)	0.0016

TABLE I Material properties of the polymeric bonding material

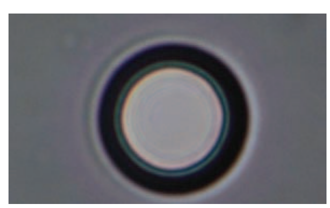

Fig 3. OM observation of patterned polymeric bonding material on test wafer.

B. *nc-Cu/polymer with tailored CMP process and interface morphologies*

To achieve a good interface of the nc-Cu/polymer interface, tailored CMP process were conduct to achieved the great interface and tailored dishing performance of nc-Cu/polymer. During the CMP polishing, the chemical composition of the slurry dominates the polishing process, thus, specialized slurry is necessary to develop to remove the topography for nc-Cu. Additionally, to overcome the dishing phenomenon, critical component of specialized slurry with dimension of 60 nm abrasive is necessary to control the and ensure a suitable selectivity of 20:1 between nc-Cu and polymer during the CMP. Fig. 4 shows the schematic diagram with mechanism of nc-Cu/polymer co-planarization. As shown in the diagram, specialized slurry with fixed flow-rate can ensure the uniform abrasive with isotropic flowing dynamics, resulting a well-controlled surface.

For such complex CMP removing process, variety of dishing performance can be achieved for sequential bonding process. Table II has shown the CMP parameters with corresponding dishing performance ranging from few nanometers to 1 micrometer. It is worth note that dishing performance of 7 nm is chosen for relative bonding condition due to the mismatch CTE of nc-cu and polymer material. To further analyzed the surface topography of Cu/polymer, AFM analysis is used accordingly. Fig.5 displayed the surface topography of dishing performance within tailored CMP. Based on the AFM analysis, tailored CMP with nc-Cu dishing with 7 nm can be achieved and chosen for good interface of nc-Cu and polymer, leading to a highly effective hybrid bonding interface with well achieved roughness of Ra 0.26 nm. It is well-known that hybrid bonding requires uniform interface as well as nano-scale roughness. Fig.6 displayed the cross-sectional view of FIB-SEM images of post-CMP wafer. Well-Controlled interface of nc-Cu/polymer has shown good interface for further bonding interface. Thus, suitable downforce and tailored CMP slurry for nc-Cu and polymer are crucial for well-controlled interface. Fig. 7 displayed the TEM images showing that the microstructure of nc-Cu has successfully filled in the via of polymer and well-controlled surface after CMP process.

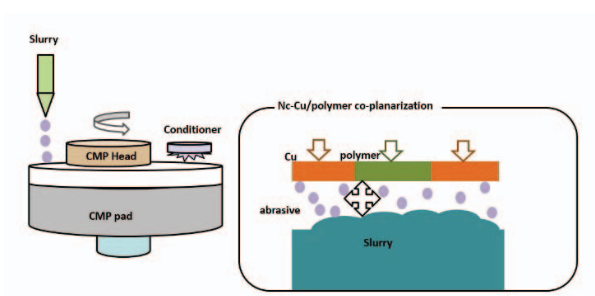

Fig. 4. Schematic of the mechanism of nc-Cu/polymer CMP co-planarization.

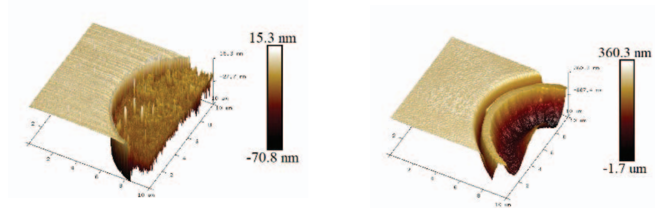

Fig. 5. The tilted-view of AFM images on a post-CMP wafer for (a) dishing 7 nm and (b) dishing 1 um, respectively.

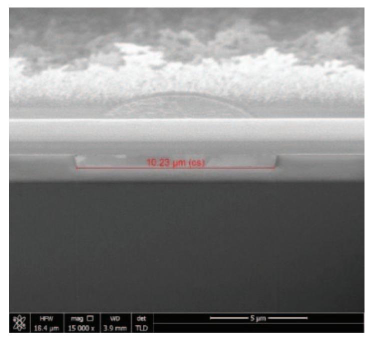

Fig. 6. Typical cross-sectional view of SEM images on a post-CMP wafer.

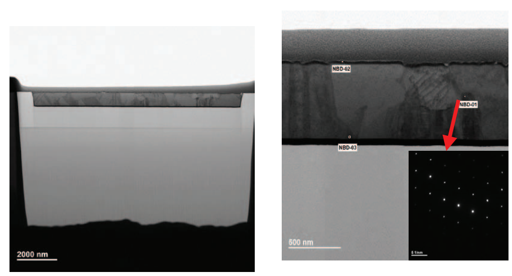

Fig. 7. The cross-sectional the tilted-view of TEM images on a post-CMP wafer.

Table II. AFM results corresponding to CMP parameters

AFM results corresponding to CMP parameters		
Slurry	Conditions	Dishing
Slurry C	Low pressure	7 nm
Slurry C	High pressure	14 nm
Slurry A	High pressure	1 um

C. *Characterization of nc-Cu/polymer hybrid bonding*

To achieved low temperature hybrid bonding, both nc-Cu and polymer are selected with distinctive properties. In our previous studies, nc-Cu contained substantially massive amount of tiny grains rather than a single huge crystalline when solidification, forming numerous tiny grains with grain boundaries [10]. Polymer on the other hand, can be bonded at room temperature due to its unique properties of low Young's modulus and low glass transition temperature Tg. During pre-bond process with accurate alignment at 150 ^{o}C, polymer and polymer can be bonded at the initial stage, which the polymer entanglement chain loop can be first bonded and subsequently interdiffusion, this lead to the Van der Wal force to be covalent bonded with strong bonded. Further, while the external pressure of 40 Mpa is applied, these nanocrystals cu started to grow and well jointed with each other. Numerous grain boundaries also provide surface energy in which nc-Cu may be able to form interdiffusion of Cu, thereby the nc-Cu/polymer hybrid bonding is achieved.

The post-wafer bonding sample was ion-milled with FIB to further analyzed the bonding interface with cross-sectional SEM image. Fig 8 displays the FIB-SEM for nc-Cu/hybrid bonding. As presented in Fig 8 , the enlarged SEM has shown the well bonded nc-Cu and good interface of polymer with misalignment of 1.82 nm.

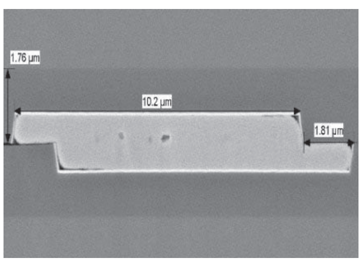

Fig. 8. The enlarged view with SEM images of nc-Cu/polymer hybrid bonding showing the hybrid interface.

D. *Mechanical and reliability test*

To ensure the reliability of the nc-Cu/polymer, post-bonded samples were conducted to a thermal shock test in an oven upon exposed to the ambient air from -55°C to 125°C. To conduct with this test, 2 samples were sent to the chamber for reliability test and further analyzed with conditions of 250 and 500 cycles respectively. After the reliability test with 250 and 500 cycles, no visible cracks were observed on the chips with subsequent C-SAT analysis, as seen in Fig 9. More importantly, there was no apparent void on the bonding interface for all tested chips, indicating the good bonding interface.

Furthermore, the bonding strength is further analyzed with shear test to observe the creep when applied with constant load of 500g with test speed of 1000 um/s with parallel. The corresponding shear strength is 10 Mpa with 150°C bonding, indicating the well bonding after the thermal shock cycling without cracking or delamination. Fig 10 displays the shear-test method and corresponding bonding strength.

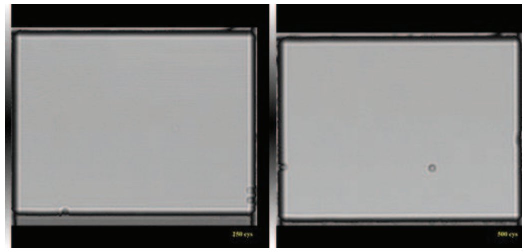

Fig 9. Nc-cu/polymer hybrid bonding with 150°C was achieved with SAT images showing well bonding wafer pair after TCT cycle with 250 cycles and 500 cycles.

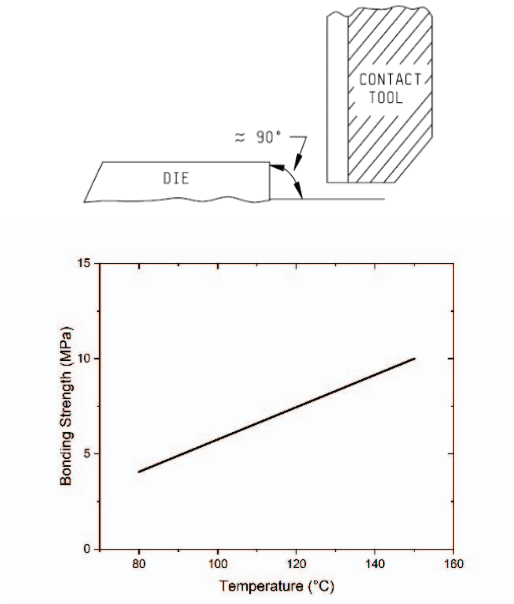

Fig 10. (a) Schematic diagram of shear test and (b) Bonding strength with relative bonding temperature.

CONCLUSIONS

Hybrid bonding of nc-Cu/polymer was successfully bonded with 150°C for 60 min. The tailored CMP method with specialized slurry and dishing with few nanometers can achieved great interface of nc-Cu/polymer for further hybrid bonding. Interface morphology were analyzed by AFM, SEM and TEM subsequently to further indicate good interface with roughness Ra of 0.26 nm and tailored dishing of 7 nm accordingly.

In conclusion, these material have proved to be reliable and with shear strength of 10 Mpa. Both nc-Cu/polymer with distinctive properties have shown promising candidate toward hybrid bonding and interconnections in foreseeable future. Further electric characteristics will be carrier out for the applications of interconnections and advanced packages.

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