Abstract

This paper presents a combined surface activated bonding (SAB) technique for Cu/SiO₂ hybrid bonding at 200 °C. The combined SAB technique involves combinations of surface activation by using surface bombardment by neutralized Ar ion beam containing Si atoms and prebonding attach-detach prior to wafer bonding in vacuum. Bonding experiments of SiO₂-SiO₂ and Cu-Cu bonding were conducted using the same process. Bonding strength close to the Si bulk fracture energy was achieved for both bonding pairs. This technique is promising for 3D integration through Cu/SiO₂ hybrid bonding at sub-200 °C.

1 Introduction

Low-temperature silicon direct wafer bonding with high strength and void-less interface is important for manufacturing silicon-on-insulator (SOI), micro-electromechanical systems (MEMS), and three-dimensional (3D) integrated systems.[1] Among many other bonding schemes, Cu/SiO₂ hybrid bonding is considered the most promising approach to realized seamless interface with metal electrical bonding and enhanced mechanical bonding.

Hydrophilic bonding approaches with wet chemical or plasma activation have been widely studied for SiO₂-SiO₂ bonding.[2] Typically, the hydrophilic bonding is performed in humid air after surface activation. However, interfacial bubbles and voids due to trapped air and contaminants can be formed. Furthermore, excess water trapped at the interface causes generation of annealing voids and limits the bonding strength.[3][4] Wafer bonding in vacuum is one promising way to minimize trapped species, particularly water molecules, at the bonding interface. Furthermore, bonding in vacuum is also desired for Cu-Cu bonding to prevent Cu oxidation by trapped Oₐ and H₂O.

However, bonding in vacuum usually yields very low bonding strength of SiO₂-SiO₂ pairs. For instance, by using the in situ plasma activated wafer bonding, which is conducted in the plasma chamber after plasma activation without breaking vacuum, the resulted strength of SiO₂-SiO₂ bonding is significant lower than Si-SiO₂ and Si-Si bonding. At 200 °C, the SiO₂-SiO₂ bonding even yields around 80% lower bonding strength compared to bonding in air.[5] It was suggested that SiO₂-SiO₂ wafer bonding should be conducted with RH greater than 15% in order to form more than one monolayer of water molecules on the bonding surfaces.[6] The conventional surface activated bonding (SAB) method using Ar beam bombardment has successfully realized high-strength Si-Si bonding in ultrahigh vacuum, however, it has been shown ineffective for SiO₂-SiO₂ bonding. SiO₂-SiO₂ and Cu/SiO₂ hybrid bonding in vacuum remains challenging and needs a detailed study.

In this study, a combined surface activated bonding (SAB) technique combining Si-containing Ar beam irradiation and prebonding attach-detach is developed for SiO₂-SiO₂ bonding and Cu/SiO₂ hybrid bonding at 200 °C.

2 Experiments

4-inch Si wafers with a 100-nm thermally grown SiO₂ layer and 50/300-nm sputtered Ti/Cu layers were used for the SiO₂-SiO₂ and Cu-Cu bonding experiments, respectively. Fig. 1 shows the general bonding process steps. Si-containing Ar beam at power of 1.0 kV×100 mA is used to irradiate the wafers in ultrahigh vacuum of 5×10⁻⁶ Pa. Then the wafers are unloaded from the vacuum chamber after humid N₂ purge. The wafers are prebonding attached, i.e., brought into contact, in air at room temperature. After storage in air for more than 10 min, the attached pair is transported into a vacuum bonding chamber, detached and bonded in vacuum of 10⁻² Pa. The SiO₂-SiO₂ pair is bonded at room temperature for 5 min, followed by postbonding annealing in air at 200 °C. The Cu-Cu pair is bonded at 200 °C for 30 min, without any postbonding annealing.

Bonding strength was measured by the crack opening method in air and at room temperature.[7] The bonding strength was estimated to close to the Si bulk fracture energy (2.5 J/m²) if the wafer fractured during blade insertion. X-ray photoelectron spectroscopy (XPS) was used to detect the presence/absence of Si species on the Cu wafer after surface irradiation by Si-containing Ar beam.
Fig. 1. Process flow of the combined SAB technique: (a) wafer surface irradiation by Si-containing Ar beam, (b) humid N₂ purge, (c) prebonding attach in air, (d) wafer transport into vacuum chamber, (e) prebonding detach and bonding in vacuum, (f) postbonding annealing at 200 °C in air.

3 Results and Discussion

Fig. 2 and Fig. 3 show the photos of SiO₂-SiO₂ and Cu-Cu bonded wafers, respectively, with fractures occurred during blade insertion. The fractures imply a very high bonding strength close to 2.5 J/m².

XPS analysis was used to confirm the presence/absence of Si impurities on Cu surface induced by the Si-containing Ar beam irradiation. The results of wide scan and narrow scan are shown in Fig. 4 (a) and (b), respectively. The C and O peaks were from contaminants adsorbed on the surfaces and no significant peaks corresponding to Si were observed, indicating little Si introduced onto the Cu surface by the Si-containing Ar beam irradiation.

Fig. 2. Image of SiO₂-SiO₂ bonded pair.

Fig. 3. Image of Cu-Cu bonded pair.

Fig. 4. XPS profiles of Cu surface treated by Si-containing Ar beam: (a) wide scan (1 eV step) and (b) narrow scan (0.1 eV step) of Si 2p region.

Fig. 2. Image of SiO₂-SiO₂ bonded pair.
can be prevented. The Si-OH groups are transformed to strong covalent Si-O-Si bonds after post-bonding annealing, while the generated water diffuses outside along the interface. Cu-Cu bonding is achieved by conversion of Cu-OH into Cu-O-Cu bonds and Cu/O interdiffusion at the interface.

4 Conclusions

In this work, we report a combined SAB technique for low-temperature Cu/SiO\textsubscript{2} hybrid bonding at 200 °C. Bonding strength close to the Si bulk fracture strength (2.5 J/m\textsuperscript{2}) were achieved in both Cu-Cu and SiO\textsubscript{2}-SiO\textsubscript{2} bonding. This combined SAB technique is useful for the development of novel void-free low-temperature wafer bonding approaches with a high bonding energy.

References


