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Influence of Free Radical Surface Activation on Si/SiC Heterogeneous Integration by Direct Wafer Bonding

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***Abstract*— In this study, a surface activated bonding method using remote plasma is applied to realize the direct wafer bonding of Si and SiC. A comparison of different surface treatments is reported. Hydrophilic and hydrophobic wafers have been exposed to *in-situ* argon and nitrogen radicals generated by remote plasma for surface activation before bonding. A comparison of the bonding yield and surface condition has been conducted and analyzed as a function of the surface treatments. It has been shown that N_2 plasma leads to the highest yield of > 97 %, strongest bond of > 360 N and interfacial layer (IL) thickness of ~1.5 nm.**

Keywords-direct wafer bonding; free radical surface activation; heterogenious integration; Si; SiC

I. Introduction

Silicon Carbide (SiC) is a wide bandgap semiconductor material with a thermal conductivity three times that of Silicon (Si). This minimizes the self-heating effects as power is dissipated in this material in Si-on-SiC devices [1]. Furthermore, SiC is a material traditionally used for its mechanical properties; i.e., it can be thinned down to a thickness as low as 50 µm and remain freestanding. This is another major boost to the thermal performance of Si-on-SiC devices providing a short path to the heat sink.

The large lattice mismatch between Si and SiC results in a polycrystalline Si film containing a large density of defects and dislocations originated from the material interface [2]. An alternative promising approach to circumvent the problems of epitaxy for hybrid integration is direct wafer bonding (DWB) resulting in defect-free layers at both sides of the bonded pair [3]. DWB is accomplished by activating the surfaces of separated wafers by wet chemistry, direct or remote plasma exposure, or ultraviolet exposure, before physically pressing them together. In this study, we have investigated the use of argon and nitrogen free radicals formed by remote plasma for Si/SiC wafer bonding with attenuated electron and ion concentrations.

II. Experiment

Commercial 4-inch semi-insulating SiC wafers were bonded to 4-inch [100]-oriented Si wafers. Both wafers were cleaned using Standard Cleaning 1 and Standard Cleaning 2 solutions. Wafers were then further cleaned using an EVG wafer cleaning tool equipped with DI megasonic nozzle. For the hydrophobic bonding, the wafers were dipped in diluted HF solution for 60 s prior to the bonding. The wafers were then loaded in a bonder fitted with an *in-situ* remote plasma source. The bonded pairs were then diced into 1 × 1 cm^2 dies and the Si substrate was ground to ~10 µm for TEM analysis.

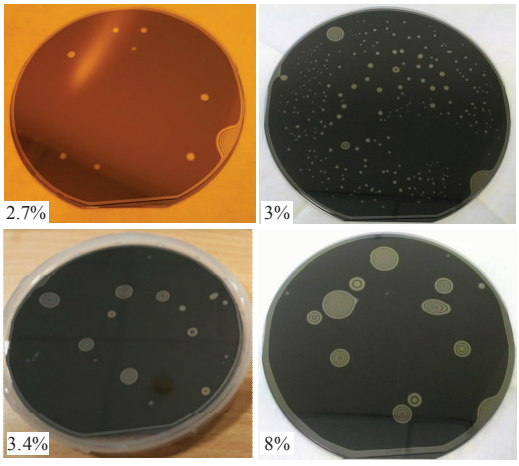

Figure 1. Optical images of the bonded wafers (SiC on top) showing the voided area percentage. Left column: N_2 plasma surface activation. Right colomn: Ar plasma surface activatin. Top row: Hydrophilic bonding. Bottom row: Hydrophobic bonding.

III. Results and Discussions

SiC wafers are transparent in visible range and some voids with interference fringes can be observed at the interface, as shown in Fig. 1. The voided area percentage (Fig.1), number of voids and their distribution should be considered to evaluate the quality of the bonding.

TEM images of the bonded interfaces are shown in Figs. 2(a) and 2(b) for the N_2/hydrophobic and N_2/hydrophilic, respectively. All interfaces have an amorphous interfacial layer (IL) between 0.65 nm - 1.6 nm thick.

The average tensile strength of the Si/SiC bonded pairs is obtained by pulling tests, results of which are summarized in Table I. As can be seen, the bond strength varies depending on surface treatment and for the N_2 plasma it is at least equal to bulk Si strength, as the fractures always occurred in the bulk of the Si wafer.

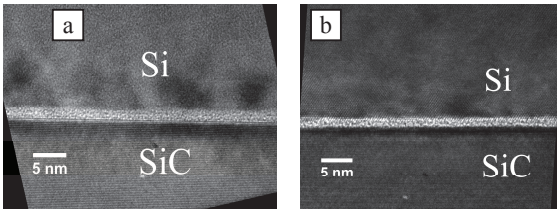

Figure 2. Cross-sectional TEM image of (a) N_2/hydrophobic, and (b) N_2/hydrophilic bonded interface.

TABLE I. Bond strength of the Si/SiC bonded pairs.

Plasma/surface	Bond strength (N)
N_2/hydrophilic	> 360 (no delamination)
N_2/hydrophobic	> 360 (no delamination)
Ar/hydrophilic	285
Ar/hydrophobic	118

All samples were de-bonded in air, near the XPS UHV chamber, resulting in an exposure to air for less than 10 s prior to inserting into the XPS spectrometer. The Si samples displayed broadly similar surface chemistries as shown in the Si *2p* overlay in Fig. 3(a). The Si *2p* core-level data shows a primary peak at approximately 99 eV, which is indicative of elemental, non-oxidized Si. A secondary peak present at approximately 103 eV may be attributed to the presence of SiO_2 formed by oxidation of the pristine Si surface. Interestingly, Ar/hydrophobic sample contained the largest amount of SiO_2 with a concentration of approximately 18 at.% while N_2/hydrophobic sample contained trace amounts of SiO_2 at ~2 at.%. High-resolution core-level data for the SiC samples is shown in Fig. 3(b). The Si *2p* spectrum for Ar/hydrophobic and N_2/hydrophobic could be fitted by two components: SiC at ~101 eV and SiO_xC_y/SiO_2 at ~102 eV. This would indicate the presence of surface contamination and partial oxidation of the SiC surface.

After de-bonding the samples, both SiC and Si dies were analyzed by AFM. Sub-nanometer values of the rms roughness over a scanned area of 2 × 2 μm^2 indicate that no significant degradation of the surface is detectable

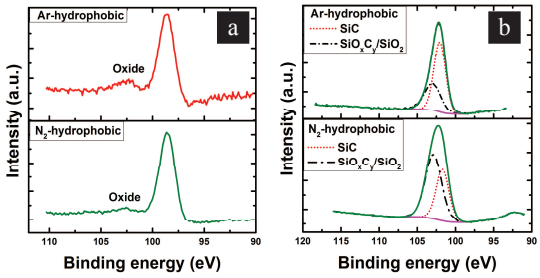

Figure 3. Si *2p* core-level data acquired on (a) Si, and (b) SiC.

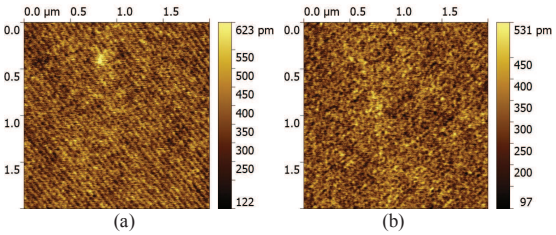

Figure 4. AFM images of (a) SiC, and (b) Si surfaces (N_2/hydrophobic).

after radical exposure. All samples show parallel stripes whose widths match in the SiC and Si scans when de-bonded from the same die, but vary for different plasma exposures. Even though the difference in height from tops and valleys of the stripes is very small and close to the resolution limit of the equipment, their movement with physical rotations of the scanned dies confirms that they are real and not due to any form of artifact.

IV. Conclusions

Remote plasma surface pre-bonding treatment has been presented as a promising solution to increase the surface chemical reaction for high yield and high bond strength integration of Si/SiC by direct wafer bonding. An amorphous interfacial layer (thickness between 0.65 nm and 1.6 nm) is formed between the two wafers. XPS analysis confirms the presence of oxide on both Si and SiC surfaces.

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