Effects of Plasma Activation on Hydrophilic Bonding of Si and SiO_2.

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In direct Si wafer bonding high temperature annealing above 1000^{o}C is usually required for achieving a strong bond between the wafers. However, in the bonding of preprocessed wafers it is necessary to restrict the temperature to avoid undesirable changes in the substrate structures. In the case of dissimilar materials, the difference in thermal expansion coefficients may also lead to large residual stresses in the bonded stack. Ideally, the target would be to achieve strong bonding at room temperature. By first activating the surface, strong bonding has been achieved at annealing temperatures below 400°C [1]. We have used low-pressure argon or oxygen plasma to activate the surfaces in hydrophilic bonding of silicon and silicon oxide. Plasma parameters and kinetic energy of the ions have been studied for their effects on the interfacial bond energy.

Czochralski grown <100> oriented p-type hydrophilic silicon wafers were used in our experiments. Some of the wafers were thermally oxidized prior to plasma activation and bonding to obtain hydrophilic Si to SiO_2 bonds (oxide/Si bonds) and SiO_2 to SiO_2 bonds (oxide/oxide bonds). The wafers were subsequently activated in plasma with a variable exposure time and controlled ion energy. Both reactive (O_2) and inert (Ar) gases were used to distinguish between purely physical and chemical effects during the plasma exposure. Experiments were also made using physical ion bombardment with a Kaufmann ion-source or using UV-light for the activation of the wafer surface. After the activation treatment the wafers were cleaned using RCA1-recipy and/or deionized water. The bonding was done either in air or in vacuum at room temperature or at an elevated temperature. The bonded wafer pairs were annealed for 2 hours at 100-500^{o}C. The bond strength was measured using the crack opening method in air. The bonded structures were inspected for interfacial voids using IR transmission and scanning acoustic microscopy.

We found that strong bonding can be achieved using plasma activation in both tested gas environments. A short exposure to the plasma is more efficient than a treatment lasting several minutes. The bond strength was found to be higher in the bonded oxide/Si pairs when compared to the oxide/oxide pairs. A surface energy of 2400mJ/m^2 was achieved at temperatures of 200-400^{o}C for oxide/Si bonds while a value of 1500mJ/m^2 was measured for oxide / oxide bonds. The wafers can be subjected to wet chemistry after the plasma exposure if care is taken not to etch the wafer surface excessively. For example, the RCA1-cleaning can improve the bond quality if the cleaning time is kept short enough not to outweigh the activation of the surface. Bonding in air results in stronger bonds than bonding in vacuum. However, if the air bonding is carried out at elevated temperatures the bond strength approaches that obtained in vacuum bonding.

We also studied the influence of the plasma treatment if only one of the two wafers is activated. For oxide / Si bonds, the activation of the thermal oxide has a larger effect on the bond strength than the activation of the native oxide surface. The results are depicted in figure 1. The observed behavior can be explained by the varying degree of hydrophilicity of the surfaces. The surface of the native oxide can accommodate a higher equilibrium density of silanol groups compared to the thermal oxide [2]. Hence the fewer bonding sites available on the thermal oxide become the strength-limiting factor in bonding. The number of bonding sites is increased during the plasma exposure as the ions impinging to the surface break atomic bonds and enhance the reactivity of the surface. The relative amount of this enhancement is more pronounced in the case of thermal oxide. Figure 1 also shows that after annealing at 200 C, where the majority of silanol groups should have reacted to form Si-O-bonds, the contributions of the two bonded wafers add almost linearly to the final bond strength.

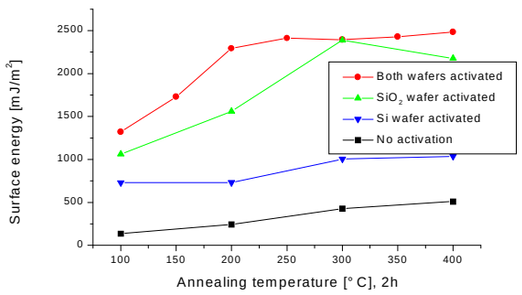

Figure 1. Measured surface energy as a function of the bond annealing temperature for various Ar plasma activation schemes in hydrophilic bonding of Si to SiO_2. The annealing time was 2 hours.

[1] S. N. Farrens, J. R. Dekker, J. K. Smith and B.E.Roberds, J. Electrochem. Soc. **142** (11), 3949 (1995).

[2] Q.-Y. Tong, U. Gösele, Semiconductor Wafer Bonding, Electrochemical Society Series, Wiley, 1999, p. 60.