The Effect of Hydrogen Plasma on Surface Roughness and Activation in SOI Wafer Fabrication

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The hydrogen plasma treatment of silicon wafers in the reactive ion-etching mode was studied for the application to silicon-on-insulator wafers which were prepared using the wafer bonding technique. The chemical reactions of hydrogen plasma with surfaces were used for both surface activation and removal of surface contaminants. As a result of exposure of silicon wafers to the plasma, an active oxide layer was formed on the surface. This layer was rendered hydrophilic. The surface roughness and morphology were examined as functions of the plasma exposing time and power. In addition, the surface became smoother with the shorter plasma exposing time and lower power. The value of the initial surface energy estimated by the crack propagation method was 506 mJ/m^2, which was up to about three times higher as compared to the case of conventional direct bonding using the wet RCA cleaning method.

Keywords : Hydrogen Plasma, RCA, SOI, Direct Wafer Bonding

1. INTRODUCTION

Direct wafer bonding has been extensively studied as an approach to fabricate a silicon-on-insulator (SOI) wafer [1-3]. SOI structure can completely isolate the devices from each other and offers inherent advantages of high reliability, high packing density, high-voltage capability, and low thermally generated current [4]. SOI technology based on direct wafer bonding and thinning is an attractive method for high-performance integrated circuits and power devices because the crystalline perfection of conventional bulk silicon wafers is completely maintained in the SOI layer [5,6]. But improvements are still required in this direct wafer bonding and thinning process. The presence of an interface bubble at the bonded surface is one of them. Mainly carbon impurities or dust particles being trapped at the interface during the bonding process cause the interface bubble and are mostly responsible for electrical properties such as high leakage current density and low breakdown field. Commercially available direct bonding methods using a wet chemical clean achieve the surface activation by immersion in sulfuric acid solutions or alkaline solutions, which result in hydrophilic surfaces [7-12]. However, these wet chemical treatments have the following disadvantages; they increase the possibilities of chemical contamination or surface roughening, must be customized for each substrate material, and are not appropriate for multilayer materials with different chemical reactivity [13].

In this paper, we have studied an improved method of direct wafer bonding using the surfaces activated by hydrogen plasma treatment for SOI applications. The goal of this study is to investigate the influence of hydrogen plasma on the bondability of silicon surfaces and the change of surface chemistry and morphology.

2. EXPERIMENTS

Boron-doped Czochralski-grown silicon wafers were used in these experiments. They were 100 mm in diameter, with an orientation of (100), a thickness of 525 μm, and a resistivity of 10-20 Ωcm. The bare silicon substrate was used as a base wafer, and the bonded wafer was oxidized to form the underlying oxide layer. A 1.2 μm thick SiO_2 layer was thermally grown on the bonded wafer in a wet oxidation tube furnace at 1100 °C. In all plasma preparation below, a low pressure radio-frequency (RF) plasma was used. The samples were always at negative potential, i.e., the cathode. The base pressure in the chamber was adjusted to 2×10^{-5} Torr before the introduction of the plasma gas, and the pressure during the plasma treatment was maintained at

200 mTorr. The surface activation and cleaning processes were carried out in 20 sccm hydrogen gas flow rate with a RF power in the range of 50 to 200 W at room temperature. Each pair of wafers was then taken out from the chamber, rinsed in de-ionized (DI) water for 5 min and spin dried only just before bonding. At the next stage, the base wafer was brought in contact with the bonded wafer at room temperature without the use of external pressure. These wafer pairs were then annealed at 900°C for 2 hours in an oxygen atmosphere. For the comparison of cleaning and bonding efficiencies, the hydrophilic surfaces were formed by the typical wet RCA cleaning solution (H_2O:H_2O_2:NH_4OH = 5:1:1 in volume ratio) for 5 min at 80 °C.

The effect of the plasma treatment on the surface chemistry was investigated by means of the contact angle measurement and Fourier transform infrared spectroscopy (FTIR) measurement. The contact angles for the plasma-cleaned surfaces were measured by the sessile drop method at ambient temperature. To study the effect of the plasma exposing time and power on the surface roughness, the surface morphology was observed by an atomic force microscope (AFM). AFM measurements for the hydrogen plasma-cleaned surfaces were made in contact mode. Infrared (IR) transmission photographs of the whole wafers were taken for failure analysis in the bonding area using an IR light source, an IR filter, a charge coupled device (CCD) camera for IR detection, a monitor, and a video printer. The surface energy of the bonded wafers was measured to determine the bonding quality by inserting a razor blade into the bonding interface, as shown in Fig. 1.

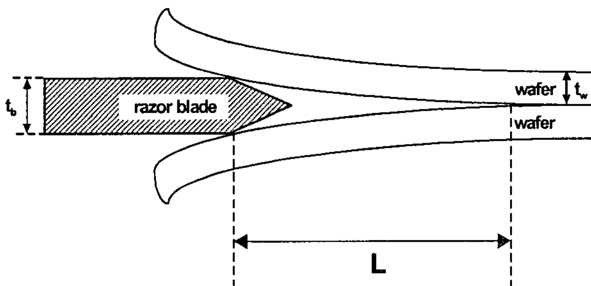
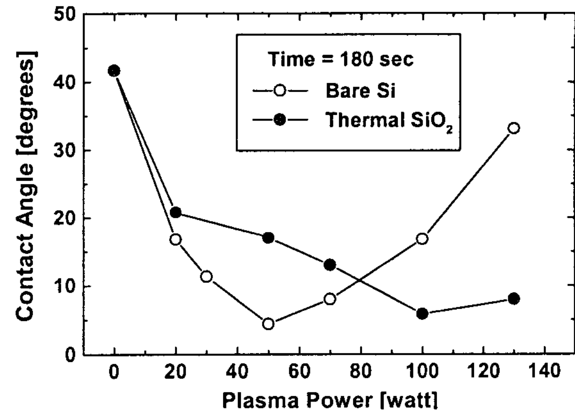


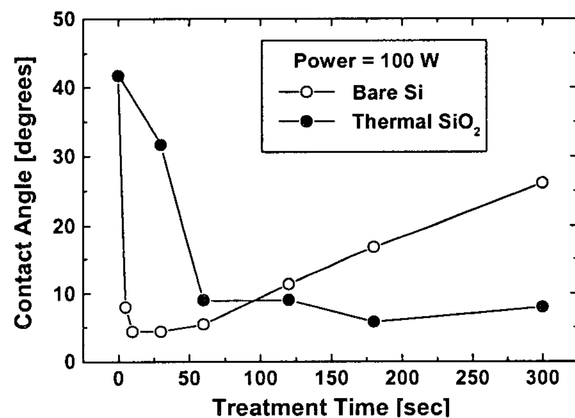
Fig. 1. Schematic diagram of the crack propagation method.

3. RESULTS AND DISCUSSION

The surface chemistry plays a critical role in determining the surface energy of direct wafer bonding. Surface termination with desirable chemical groups leads to the increase of the surface energy. In a reactive ion-etching mode of the hydrogen plasma, hydrogen radicals preferentially break Si-O bonds at the top of the SiO_2 surface, which causes a generation of chemically active dangling bonds.



(a) Plasma power

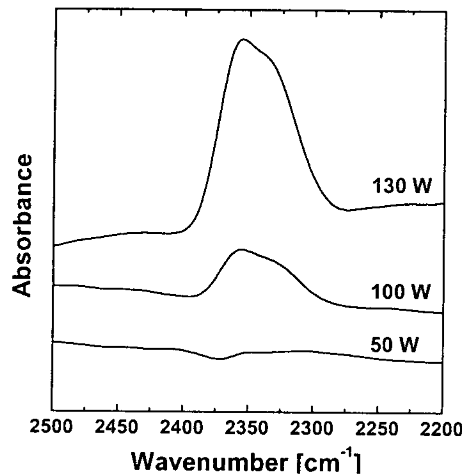


(b) Plasma exposing time

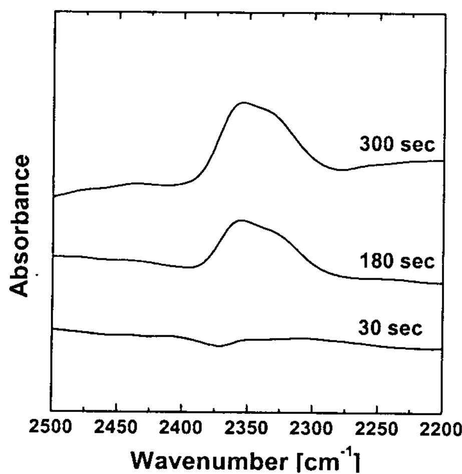
Fig. 2. Influence of hydrogen plasma power (a) and exposing time (b) on the contact angle.

This is in agreement with the results of the contact angle measurement that the hydrogen plasma-activated samples possess hydrophilic surfaces. The water bubble contact angles using DI water were evaluated as functions of plasma power as well as of treatment time for both base and bonded wafers. The measurement of contact angle shows that the surfaces are rendered hydrophilic by the hydrogen plasma treatment with contact angles ranging from 5.5 to 35°, as shown in Fig. 2. The influence of the plasma power on the contact angle is illustrated in Fig. 2(a). At a given time of 180 sec, the contact angle of the bonded wafer decreases with power and gradually approaches a saturated value. The lowest contact angle of the base wafer is obtained for the hydrogen plasma treatment at a power of 50 W. When the plasma power is fixed at a constant power of 100 W, the plasma treatment time determines the contact angle

of the base wafer as well as the bonded wafer in Fig. 2(b). With increasing the treatment time of the bonded wafer, the contact angle reduces and then remains at a saturated level of 5.5°. In the case of the base wafer, the contact angle decreases rapidly during the short time treatment and gradually increases with time. Therefore, the lowest values of contact angle should be used in any discussion unless specifically indicated.



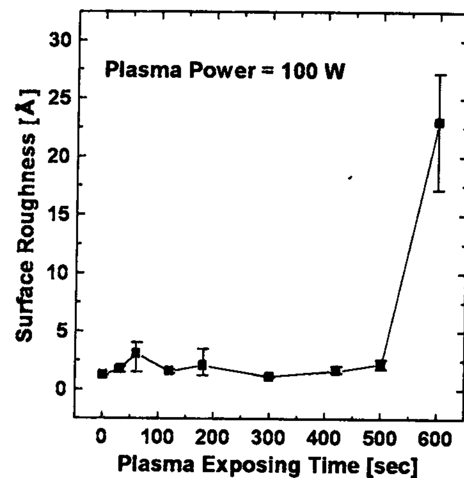
(a) Plasma power



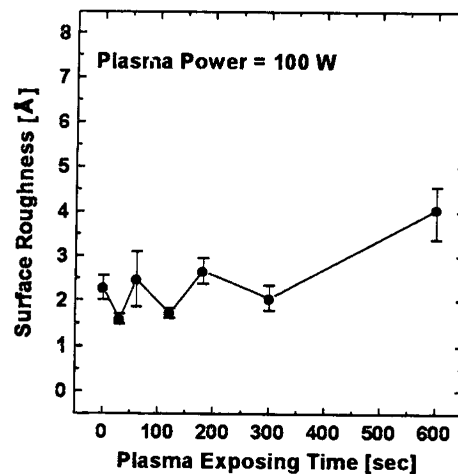
(b) Plasma exposing time

Fig. 3. FTIR spectra obtained from base wafers after hydrogen plasma treatment: (a) dependence of plasma power at the exposing time of 3 min, and (b) dependence of exposing time at the plasma power of 100 W.

Fig. 3(a) shows the Si-H absorption spectra of base wafers after hydrogen plasma treatment for 3 min at various plasma powers obtained by FTIR measurement. Some significant change appears in the 2350 cm^{-1} band that is attributed to the stretching vibrations of Si-H bonds in the oxide. The plasma power higher than 50 W leads to the formation of the hydrophobic layer due to the rapid absorption of hydrogen. The lower plasma power exhibited absorption behavior similar to that at the higher plasma power, if the exposing time was elongated as shown in Fig. 3(b). When the plasma power is fixed at the constant power of 100 W, the absorption intensity of the 2350 cm^{-1} band increases with the longer exposing time. The tendency of these results corresponds to that obtained by the wetting angle measurement.



(a) Bare Si



(b) Thermal SiO_2

Fig. 4. Effect of plasma exposing time on the rms value of wafer surface roughness: (a) the base wafer, (b) the bonded wafer.

One of the primary problems limiting applications of direct wafer bonding consists in surface roughness. Silicon wafers, either atomically or microscopically, cannot bond due to conformal limitations, if they are too

rough. The influence of the plasma exposing time and power on the surface roughness was examined for the substrate with reference to the results of AFM analysis. Fig. 4 shows typical experimental results of the root-mean-square (rms) value of a wafer surface roughness. Before the hydrogen plasma treatment, the rms values of base and bonded wafers are 0.12 and 0.23 nm, respectively. The surface roughness as a function of the plasma exposing time for the constant plasma power of 100 W, with both base and bonded substrates, is shown in Fig. 4. The surface becomes slightly rougher with the longer plasma exposing time. When the treatment time exceeds a threshold value of 600 sec, the roughness increases rapidly. The influence of the plasma power on the surface roughness was examined for both base and bonded substrate in Fig. 5. Roughness increases with power and is always higher with a bonded substrate than with a base substrate. It is likely that the higher degree of roughness observed with the bonded substrate results from the oxygen being liberated from the oxide as it is etched.

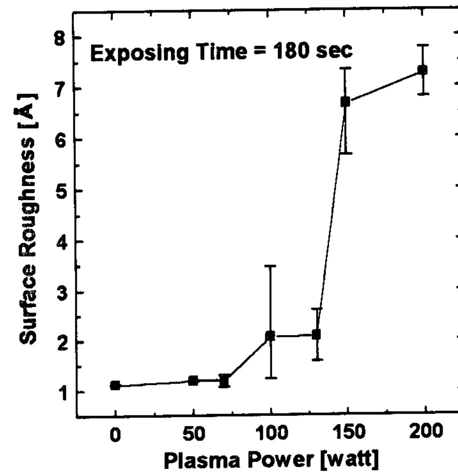
To verify the hydrogen plasma effect on the rapid increase of the surface roughness in more depth, a three-dimensional (3D) AFM analysis was used. In the case of the base wafer, the reason of this increase is known to be caused by {111} platelet defects [14]. The highly concentrated hydrogen ions in silicon tend to precipitate along {111} silicon planes and the silicon etching reaction occurs preferentially at positions where the {111} platelets intersect the surface, resulting in miniature V-grooves on the surface. As the plasma exposing time goes up, the base substrate temperature increased by hydrogen ion bombardment enhances the recombination of chemically active defects created in {111} platelet. Through the silicon etching reaction volatile molecules such as SiH_x might be disrobed from the surfacė. Fig. 6(a) shows an AFM image of the base wafer surface, which reveals {111}-platelet-induced surface roughening. However, as the AFM result of the bonded wafer is shown in Fig. 6(b), the rapid increase of the microscopic roughness is not influenced by any platelets and the etching reaction over the whole surface seems to be the most probable reason for this surface roughening.

Fig. 7 shows the IR transmission image of the specimen bonded at room temperature by hydrogen plasma activation and annealed at 900°C in an O_2 atmosphere for 2 hours. The dark regions of the bonded wafer pair are the voids because of the presence of particles in the interface.

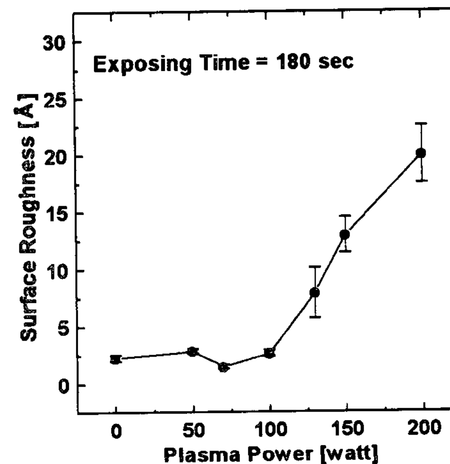
The high surface energy of room temperature-bonded wafers is desirable to make polishing and cleaning of the bonded wafers easier. The high surface energy also increases the probability of closing the gap between wafers that are rough on a microscopic scale. The bonding energy Γ was measured by the crack propagation method using a razor blade and evaluated according to

$$\Gamma = \frac{3}{32} E \frac{t_w^{\ 3} t_b^{\ 2}}{L^4} \tag{1}$$

with E being the elastic modulus of silicon, t_w the thickness of the wafer and t_b the thickness of the razor blade. The length L was evaluated by using the IR equipment. A large difference in surface energy was observed between the hydrogen plasma cleaning and RCA cleaning. The initial surface energy of specimen bonded by hydrogen plasma cleaning was 506 mJ/m^2. This value is largely three times higher than that of a conventional RCA cleaning method.

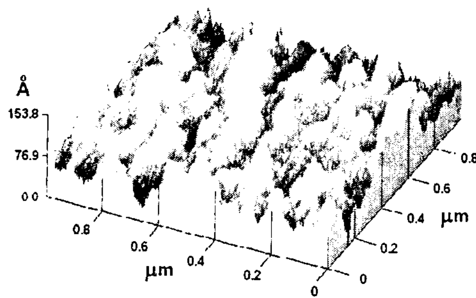


(a) Bare Si

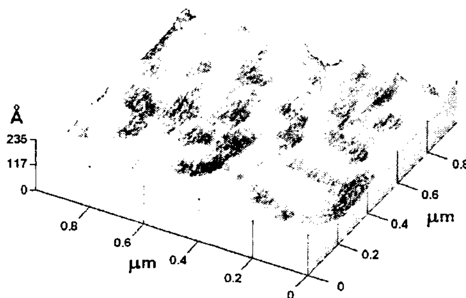


(b) Thermal SiO_2

Fig. 5. Effect of plasma power on the rms value of wafer surface roughness: (a) the base wafer, (b) the bonded wafer.



(a) Base wafer



(b) Bonded wafer

Fig. 6. AFM images of (a) the base wafer treated at plasma power of 100 W for 600 sec, (b) the bonded wafer treated at plasma power 200 W for 180 sec.

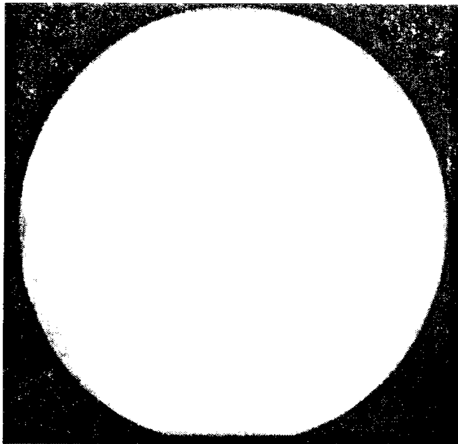


Fig. 7. IR transmission image of the bonded wafer pair.

4. CONCLUSIONS

The surface hydrophilicity was realized by the cleaning and activation treatment in the hydrogen plasma. A large difference in surface energy was observed between the hydrogen plasma cleaning and RCA cleaning. The initial surface energy of specimen bonded by hydrogen plasma cleaning was 506 mJ/m^2, which was up to about three times higher than that of a conventional RCA cleaning method. The chemical effect caused by the hydrogen plasma seems a prospective candidate for activation of the silicon surface.

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