Thickness Uniformity of Silicon-on-Insulator Fabricated by Plasma Immersion Ion Implantation and Ion Cut

Zhineng Fan, Paul K. Chu, *Member, IEEE*, Nathan W. Cheung, and Chung Chan, *Fellow, IEEE*

***Abstract*— Plasma immersion ion implantation (PIII) is an economical means to implant a high dose of hydrogen into silicon and when combined with ion cut, has been demonstrated to be a viable technique to fabricate silicon-on-insulator (SOI). However, its success in the industry hinges on the quality of the SOI wafers produced. One of the most important parameters is the thickness uniformity of the SOI film. We have observed that the thickness variation across a 150–mm wafer follows a pattern in which the transferred silicon film is thickest in the center and thinnest near the edge. Alpha-step and SIMS measurements indicate that the lateral nonuniformity is caused by the different penetration depths of hydrogen across the wafer. The experimental results can be explained quantitatively by an oblique incidence model.**

***Index Terms*— Ion-cut, plasma immersion ion implantation, silicon.**

SILICON-ON-INSULATOR (SOI) is the preferred material to fabricate low-power, low-voltage, submicrometer microelectronic devices [1]. However, thin SOI substrates for fully depleted CMOS (complementary metal oxide semiconductor) devices can be synthesized by the SMART-CUT^{TM} process [2] using conventional beam-line ion implantation but the process is quite expensive due to the long implantation time to attain the high hydrogen dose. It has recently been demonstrated that plasma immersion ion implantation (PIII) is an economical technique to synthesize both separation by implantation of oxygen (SIMOX) and bonded SOI wafers [3]–[14]. A bonded SOI wafer is produced by first introducing a high dose of hydrogen into a silicon wafer by PIII. The implanted wafer (here, referred to as the donor wafer) is bonded to an oxidized wafer (the acceptor wafer) at low temperature and subsequently annealed to create hydrogen micro-cavities. Pressure exerted by the expanding micro-cavities causes the donor wafer to crack. The separated film stays on the acceptor wafer and forms an SOI wafer. The cost saving stems from the efficient PIII process and reusing of the donor wafer. The benefit is greater for larger wafers as the implantation time is independent of the wafer size.

In spite of the demonstrated viability of the PIII/ion cut technique, refinement of the technology must be made before it can be adopted by the industry. One of the most important parameters is the thickness uniformity of the SOI. For an ion cut process utilizing conventional beam-line ion implantation with mechanical scanning such as SMART-CUT^{TM}, the implantation energy and angle are the same over the entire wafer. Any variation in the silicon film thickness, thus, depends on the cracking mechanism, that is, how smoothly the silicon layer separates along the micro-cavity plane. However, for PIII, since the whole wafer is implanted simultaneously inside the plasma, there is the possibility that the projected range of the implanted hydrogen can vary laterally on the wafer due to plasma nonuniformity and sample stage effects [15]. This is also true for beam-line ion implantation if electrostatic beam scanning is employed. In our PIII equipment, the plasma density uniformity is better than 2% [16] and if there is no other factor, the resulting dose and energy uniformity achievable in the silicon wafer should be acceptable to the semiconductor industry which usually demands a lateral uniformity of better than $\pm 3\%$. Therefore, we have performed a systematic study on the thickness variation on a 150-mm SOI wafer produced by PIII and ion cut. It is observed that the thickness is quite uniform near the center but is smaller toward the edge of the wafer. The magnitude of this variation cannot be explained by plasma nonuniformity alone. Our secondary ion mass spectrometry (SIMS) results indicate that the discrepancy can in fact be quantitatively correlated to the variation of the projected range of the implanted hydrogen and the phenomenon can be simulated using an oblique incidence model.

Hydrogen PIII was performed in a custom designed instrument [16] on P-, 150 mm, $\langle 100 \rangle$ CZ-Si. The resistivity was 1–100 Ω-cm. The implantation conditions were: implantation voltage $= -20$ kV, pulsing frequency $=$ 100 Hz, pulse duration $= 30\ \mu$s, radio-frequency (RF) power $= 900$ W, and pressure $= 0.4$ mtorr. The implanted wafer was bonded to a thermally oxidized wafer at low temperature and then annealed at 450 °C to achieve separation. Because bonding was not done in an extremely clean environment, small bonding voids can be found on the wafer. They are ideal for local thickness measurement of the transferred layer using a Tencor Instruments Alpha-step 500. The vertical resolution of this machine is 0.1

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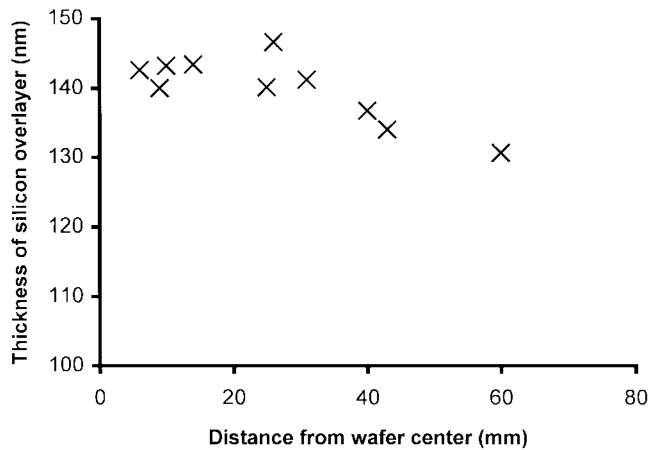

Fig. 1. Thickness of the top silicon layer of the SOI wafer at various radial locations determined by Alpha-step measurements.

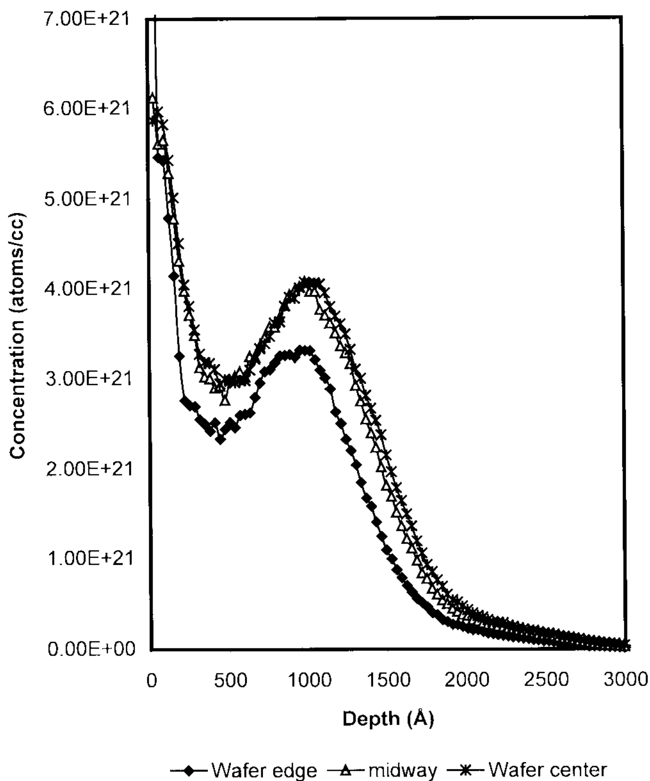

Fig. 2. Hydrogen depth profiles of the three regions on a 150-mm wafer determined by SIMS: wafer center, 30 mm from center (midway), and 60 mm from center (wafer edge).

nm for the range of ± 6.5 μm. Fig. 1 displays the thickness distribution of the silicon layer across the wafer. The x-scale shows the distance of the measured area from the center of the wafer. It can be observed that the silicon overlayer thickness is quite uniform within a radius of about 35 mm and drops off toward the edge. The average thickness is 140 nm and the standard deviation is 5 nm. The thinnest silicon layer at 60 mm from the center is 90% of that in the center.

To investigate the origin of the thickness variation, samples were taken from the center, 30 mm from the center, and 60 mm from the center to perform SIMS analysis. The hydrogen

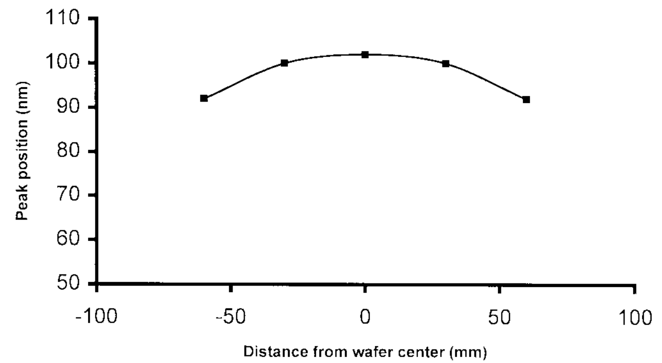

Fig. 3. Hydrogen projected ranges across the 150-mm wafer determined by SIMS.

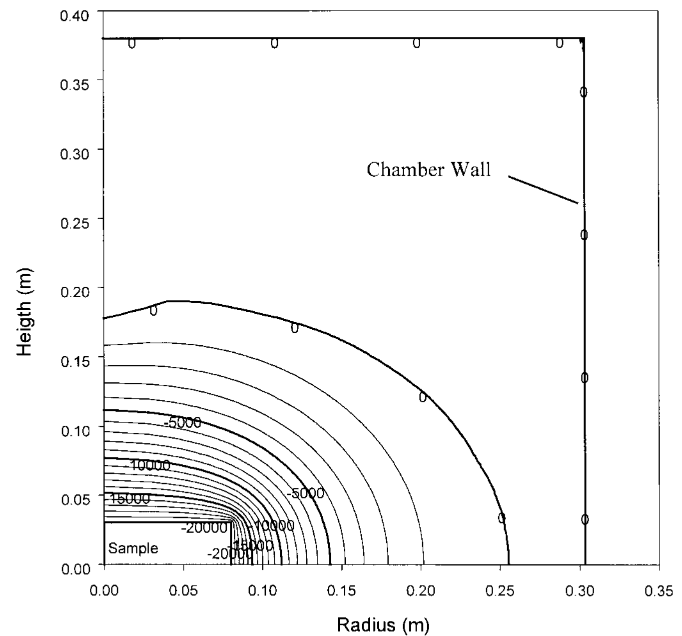

Fig. 4. Potential distribution map for −20-kV implantation.

profiles are depicted in Fig. 2. A high concentration of surface hydrogen is observed just beneath the surface in all three samples but appears to be unimportant to the layer transfer process even though it may influence the amount of surface defects in the SOI wafer. Provided that the hydrogen dose is above a certain threshold value, the most important cracking parameter is the depth of the hydrogen peak at about 100 nm. Fig. 3 shows that the peak position is about the same in sample 1 (center) and sample 2 (30 mm from center) but shallower in sample 3 (60 mm from center). The difference in the projected range between samples 1 and 3 is 9% and agrees well with the thickness data. It should be mentioned that the peak depth determined by SIMS and the thickness obtained by Alpha-step measurement differ by about 40 nm. The discrepancy is due to a SIMS artifact. In the presence of a large amount of hydrogen near the surface and peak, the sputtering rate is faster, and since an average sputtering rate is used in the depth calibration, the SIMS peak depths are shallower than what they should be. However, the relative difference in the

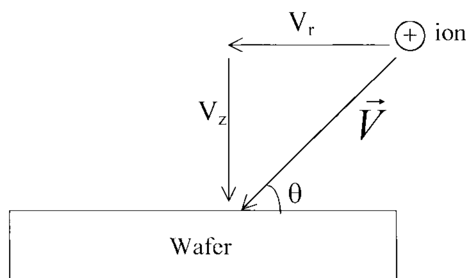

Fig. 5. Schematic diagram of the incident angle.

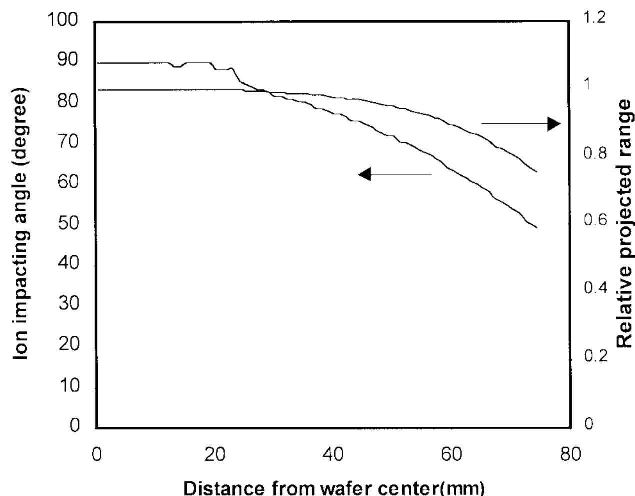

Fig. 6. Simulated incident angle (θ) and normalized projected range ($\sin\theta$) across a 150-mm wafer.

peak position is still valid as all three samples have similar hydrogen doses.

In PIII, it is usually assumed that ions impact the wafer at a normal angle. However, it is not the case in the vicinity of a corner such as the edge region of a silicon wafer. Fig. 4 displays the particle-in-cell (PIC) [17], [18] simulation of the field lines around the silicon wafer on a sample stage of approximately the same size. The PIC codes have been discussed elsewhere [15]. It can be seen that the field lines are curved toward the wafer edge and ions will not impact the wafer at a normal angle. As shown in Fig. 5, there are two velocity components, V_r that is the radial velocity and V_z which is the axial velocity. The implantation angle θ is defined by

$$\tan(\theta) = V_z/V_r. \tag{1}$$

The axial velocity determines how deep the ion will traverse into the silicon. Based on the field lines, ions implanted into the center of the wafer have a zero V_r, but the incident angle becomes progressively more glancing toward the edge. Fig. 6 depicts the incident angle (θ) and normalized projected range ($\sin\theta$) as a function of distance from the center. The results show that the impact angle and projected range are almost the same within 40 mm from the center. Ions are implanted at a normal angle in this region. Closer to the edge, ions are collected not only from the region directly above but also from the side. The radial velocity component is increased and the incident angle is shallower resulting in a smaller projected range. Our model predicts that the difference between the center and edge is about 10% and it correlates well with our experimental data. It implies that the observed thickness variation on the silicon wafer can be explained adequately by our oblique incidence model. In order to attain uniform implantation across the whole wafer, the difference in the incident angle must be minimized by for example, using a sample platen larger than the wafer. A larger stage may require a larger vacuum chamber thereby impacting the design of a suitable PIII chamber.

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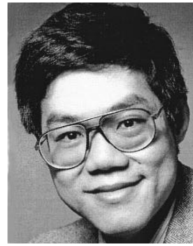

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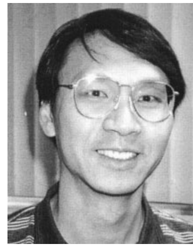

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