Sample stage induced dose and energy nonuniformity in plasma immersion ion implantation of silicon

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Plasma immersion ion implantation has been demonstrated to be a viable technique for microelectronics processing such as fabrication of shallow junction and silicon on insulator. However, a wider acceptance of this fledgling technology by the semiconductor industry is not possible unless the stringent dose and energy uniformity requirements can be met. We have recently discovered that the lateral dose and energy nonuniformity that is unacceptable to the silicon industry stems from the insulating shroud commonly used around the sample stage to reduce the current demand on the power supply. We have developed a theoretical model to explain the experimental results. The model can also be used to optimize the operating conditions and equipment design to achieve the desired dose and energy uniformity across a planar silicon wafer to satisfy the semiconductor industry. © *1998 American Institute of Physics.* [S0003-6951(98)00328-3]

Plasma immersion ion implantation (PIII) is a technology emulating conventional ion implantation in many areas, such as lower cost, higher throughput, and non-line-of-sight processing.[1] It has traditionally been used in metallurgical and tribological applications but has recently found commercial applications in semiconductor processing.[2–14] In PIII, all surfaces exposed to the plasma and under a negative bias are implanted, including both the sample as well as the unprotected sample stage. It is not uncommon in PIII that a large portion of the implanted current is wasted on the sample stage. Quartz is usually used to cover the sample stage in order to reduce the wasted power, improve the implantation efficiency, and minimize metallic contamination arising from unintentional sputtering of the sample stage. However, we have recently found that the quartz cover strongly alters the electric field distribution around the sample and changes the ion trajectories. Consequently, ions are not implanted uniformly across the sample and it presents a big problem to semiconductor applications.

In our study, pure hydrogen was used to form the plasma and hydrogen was implanted into a silicon wafer 150 mm in diameter. The schematic of our PIII instrument is illustrated in Fig. 1(a).[15] A patented radio frequency plasma source consisting of four coupling coils to improve plasma uniformity is positioned on top of the chamber. The stainless steel sample stage is placed in the center of the chamber. It consists of a cylindrical platen surrounded by a quartz shroud on the side and underneath. The platen is supported by a quartz-covered stainless steel rod and connected to an external power modulator. In our experiments, the sample was biased to -20 kV at 100 Hz. The pulse duration was 30 μs. The wafer was implanted at a hydrogen pressure of 0.4 mT for 30 min.

Figure 2 depicts the photograph of the as implanted Si wafer. The center (region A) of the wafer shows a grotesque feature referred to as the "arcing spot" in this letter. The diameter of the arcing spot is around 1 cm. A white ring is observed at about 4 cm from the center (region C). The width of the white ring is about 3 mm. Under the microscope, innumerable bubbles can be observed at the arcing spot and the white ring. It has been shown that a high dose of implanted hydrogen ($>4\times10^{15}$ ions/cm^2) can induce the formation of bubbles at temperature as low as 325 °C.[10,11,13] The bubbles change the light reflection on the silicon surface and can be detected by the naked eye. The visual appearance indicates that regions A (arcing spot) and C (white ring) have received a larger hydrogen dose. Though the wafer is not heated intentionally during implantation, the high ion flux

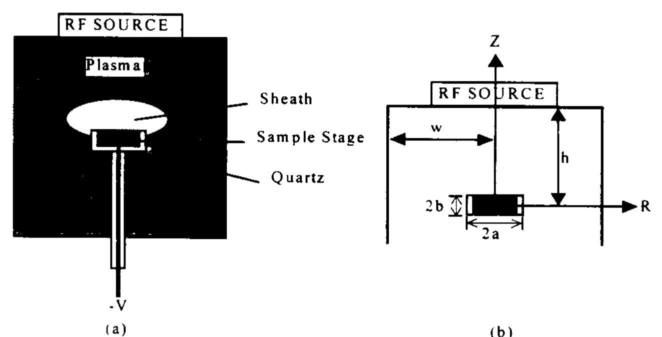

FIG. 1. (a) Schematic of the PIII equipment, and (b) model used in our simulation.

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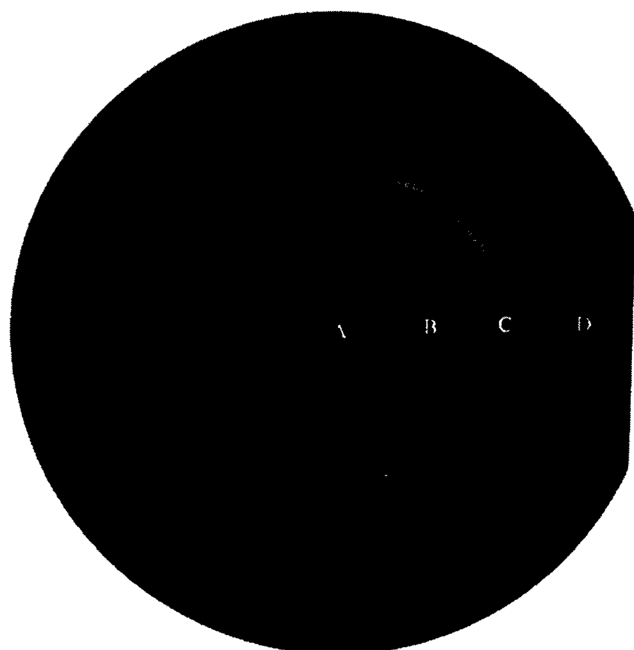

FIG. 2. Optical photograph of the as implanted 150 mm diam Si wafer. The four distinct areas are marked.

causes some sample heating and it is believed that regions A and C reach a temperature as high as several hundred degrees Celsius during PIII.

To investigate the cause of the arcing spot and the white ring, a two-dimensional particle-in-cell method[16] is used to simulate the implantation process. Our model is illustrated schematically in Fig. 1(b). The $R-Z$ origin (cylindrical coordinates) is the center of the sample holder. The initial velocities of the ions and electrons are chosen from a Maxwellian distribution having 0.026 eV ions and 3.0 eV electrons. The simulation commences at time $t=0$ as soon as a negative voltage is applied to the sample stage. The time step is selected to be 10^{-10} s. To simplify the calculation, the following assumptions are made in our simulation code:

(1) The processing chamber has a vertical symmetry, and only particles in the upper part are simulated. Ions and electrons have the same possibility moving from the upper part to the bottom part and vice versa. If an ion (or electron) moves from the upper part to the bottom part with velocity (V_r, V_z) and stops at position (r,z), another ion (or electron) must come from the bottom part to the upper part with velocity $(V_r, -V_z)$ and stop at position $(r,-z)$.
(2) At a pressure of 0.4 mT, collisionless conditions are achieved.
(3) Secondary electrons are not considered in our calculation as they do not contribute to the ion implantation dose.
(4) Abrupt -20 kV pulses with zero rise time are applied to the sample stage.
(5) Ions around the quartz cover are accelerated by the electrical field and impinge onto the surface of the quartz cover as soon as a negative voltage is applied to the sample stage. It is assumed that quartz is an ideal insulator where the charge does not leak out but can be neutralized by incoming ions or electrons. The time to reach equilibrium is small and the equilibrium voltage on the quartz due to charging is negligible when compared to the high sample bias. The boundary condition on this side can thus be written as:
$$\phi|_{r=a,0\leq z\leq b}=0. \tag{1}$$
(6) The silicon wafer is considered to be a good conductor, and no charge is accumulated on the wafer surface. It, therefore, has the same potential as the sample stage. The boundary condition is then:
$$\phi|_{0\leq r\leq a,z=b}=V, \tag{2}$$
where V is the voltage applied to the sample holder.
(7) The plasma density is uniform throughout the process chamber and only H^+ ions are considered.

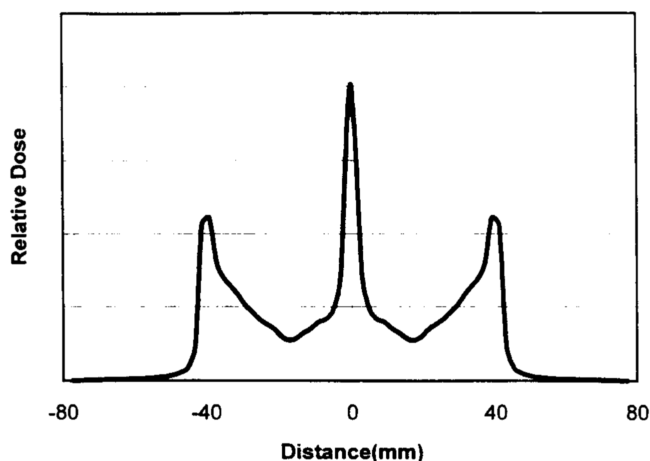

FIG. 3. Relative accumulated doses in the silicon wafer derived by our model.

The potential ϕ is solved from the following Poisson's equation using a five-point finite-difference approach:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\phi\right)+\frac{\partial^2}{\partial z^2}\phi=-\rho/\epsilon_0, \tag{3}$$

where ρ and ϵ_0 are the charge density and the permittivity of free space, respectively. The additional boundary conditions are:

$$\phi|_{r=w}=0, \tag{4}$$

$$\phi|_{z=h}=0. \tag{5}$$

Because the time step is smaller than the inverse of the electron plasma frequency ω_{pe}, electron oscillation is observed at the beginning of the simulation. From the field distribution map, a strong electric field is created at the edge of the sample stage. This field directs ions to the center of the sample stage. Figure 3 shows the calculated accumulated dose across the Si wafer. Salient peaks can be observed at the center and 39 mm on both sides from the center of the wafer. Comparing Figs. 1 and 2, our simulation results accurately model the white ring.

Our model also predicts that the wafer center will receive the highest hydrogen dose while there are much fewer ions implanted into the edge region. The extra hydrogen ions implanted into the center will result in local heating and accelerate bubble formation. The arcing spot (region A) exhibited in Fig. 2 indeed confirms the prediction. The area between regions A and C is predicted to have a lower dose.

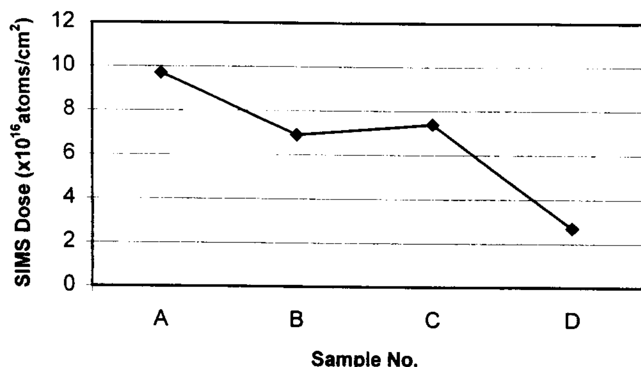

FIG. 4. Hydrogen doses determined in the four areas shown in Fig. 2 by SIMS.

The size of region B where uniform implantation can be achieved depends on the size and location of the quartz cover, applied voltage, and plasma density.

The hydrogen in-depth distributions and doses in the four regions are determined by secondary ion mass spectrometry (SIMS). The SIMS hydrogen doses are shown in Fig. 4. The trend is similar to our model prediction, even though the relative difference is smaller. There are two reasons affecting the doses measured in region A (arcing spot) and region C (white ring). First, the surface roughness (due to bubbles) and matrix effects arising from the presence of microcavities make accurate SIMS quantification very difficult.[13] Second, hydrogen loss and diffusion during implantation can be substantial in the arcing spot and white ring since the areas are heated by the higher ion fluxes during PIII. The local temperature of the arcing spot and the white ring must be higher than 300 °C since bubble formation can be observed.[10] The hydrogen diffusion coefficient at 300 °C is 5.3×10^{-10} cm^2 s^{-1},[17] and the characteristic diffusion distance for 30 min is 9.7 μm. The projected range of hydrogen in Si is 250 nm by TRIM simulation and is much smaller than the characteristic diffusion distance. Hence, a substantial loss of hydrogen is expected from regions A and C during implantation. The SIMS results show a hydrogen dose of 2.7 $\times 10^{16}$ atoms/cm^2 in region D (edge), but our model predicts much fewer implanted ions. We attribute it to one of our assumptions. According to assumption No. 5 described previously, the potential abruptly changes from -20 kV at the edge of the sample stage to 0 kV on the quartz shroud. As a result, a very strong electrical field is created to expel ions from region D. However, in reality, this field is weaker than that assumed in our formalism.

In summary, focusing effects giving rise to nonuniform implantation have been observed. Our experimental and theoretical results suggest that they are due to charging of the quartz shroud commonly used in PIII to reduce contamination and current demand on the modulator power supply. Consequently, the electric field and ion trajectories are altered, and ions are selectively implanted into the center and a ring about 4 cm from the center. Our model predicts that the location and dimension of the white ring will change with the applied voltage and plasma density. Hence, in order to reduce the focusing effects and improve the implant uniformity while limiting the total impacting ion current, the size and location of the quartz cover must be optimized. Careful design of the sample stage must be implemented in order to meet the stringent demands of the semiconductor industry.

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