Steady-state direct-current plasma immersion ion implantation using a multipolar magnetic field electron cyclotron resonance plasma source

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In semiconductor plasma immersion ion implantation (PIII) applications such as the synthesis of silicon-on-insulator by hydrogen PIII and ion cut, only ions arriving at the top surface of the sample stage are important. The ions implanted into the other surfaces of the sample chuck actually not only decrease the efficiency of the power supply and plasma source but also give rise to metallic contamination. In addition, low energy ions introduced by the initial plasma sheath propagation, pulse rise time, and pulse fall time introduce a large surface hydrogen concentration that creates surface damage and affects the wafer bonding efficacy. We have theoretically demonstrated direct-current PIII (DC-PIII) which retains the x–y immersion characteristic while simultaneously reducing this low energy ion component, obviating the need for the expensive power modulator, and extending the voltage ceiling that is no longer limited by the vacuum chamber and power modulator. In this article, we describe our hydrogen DC-PIII experiments using a conducting grid placed between the wafer stage and a multipolar electron cyclotron resonance plasma source. The grounded grid stops the propagation of the plasma sheath, thereby removing the vacuum chamber size limitation. Ions are formed in the plasma sustained by an external plasma source above the grid and accelerated through the lower zone to be implanted into the wafer biased by only a dc power supply. Atomic force microscopy, hydrogen forward scattering, and secondary ion mass spectrometry analyses indicate uniform hydrogen PIII into a 100 mm silicon wafer and the surface hydrogen component is indeed reduced significantly compared to conventional pulsed PIII. © 2001 American Vacuum Society. [DOI: 10.1116/1.1412653]

I. INTRODUCTION

Silicon-on-insulator (SOI) is the preferred substrate to fabricate deep submicrometer low power, low voltage microelectronic devices, and hydrogen plasma immersion ion implantation (PIII) coupled with ion cut is a commercial technique to produce SOI materials. PIII is an attractive alternative to conventional beam-line ion implantation for the hydrogen implantation process due to its high efficiency and small instrument footprint. While the immersion characteristics of PIII introduce a high sample throughput, that is, high ion flux and implantation time being independent of wafer size, ions bombarding the “non-silicon wafer” areas including all exposed surfaces of the wafer chuck are undesirable. These ions not only decrease the efficiency of the power supply and plasma source but also give rise to metallic contamination. The low energy ions introduced by the initial ion matrix sheath as well as the voltage pulse rise time and fall time in pulsed PIII lead to a large surface hydrogen component as well as surface damage. The maximum voltage in PIII is usually limited by the technically complicated and expensive power modulator. For some SOI products such as those for partially depleted complementary metal–oxide–silicon devices, there is a practical need for an implantation voltage much higher than 100 kV. As a result, we have proposed direct-current (dc) PIII and theoretically demonstrated its feasibility.

In this steady-state dc plasma immersion ion implantation (dc-PIII) technique (Fig. 1), the grounded conducting grid stops the propagation of the plasma sheath. Ions are formed in the plasma sustained by an external plasma source above the grid and accelerated through the lower zone to be implanted into the wafer biased by only a dc power supply. Our simulation shows that the ion paths will not change with the negative voltage applied to the wafer stage, mass, and charge states of the ions. The ion dose and impact energy uniformity are totally determined by the ratio of the hardware parameters. Our preliminary experiments performed using an inductively coupled plasma source indicate that high voltage dc-PIII can indeed be realized. However, the efficiency is low due to the low ion density and there is arcing on account of glow discharge. Therefore, in order to perform dc-PIII more efficiently at lower pressure to reduce glow discharge, a more powerful plasma source is required. We conducted dc-PIII experiments at reduced pressure using an electron cyclotron resonance (ECR) plasma source with an axial cyclotron magnetic field, but the ion dose uniformity was not very good and the axial magnetic field induced focusing of the secondary electrons. In this article, we present
our latest results on dc-PIII using a multipolar magnetic field ECR hydrogen plasma source. The results show dramatic improvement with respect to lateral ion dose uniformity and instrument stability.

II. EXPERIMENT

The dc-PIII system with a multipolar magnetic field ECR plasma source is depicted schematically in Fig. 1. The vacuum chamber (420 mm tall and 350 mm diameter) and plasma source chamber (285 mm tall and 176 mm diameter) are made of stainless steel. Eight permanent magnet bars are arranged on the outer surface of the plasma source chamber to form the multipolar cusp magnetic field. The vacuum chamber is pumped by a 1500 l/min turbomolecular pump. The base pressure is $10^{-4}$ Pa and the typical operating pressure is $10^{-3} - 10^{-2}$ Pa. The wafer stage has a water-cooling system to prevent overheating of the silicon wafer during implantation. Our dc-PIII experimental conditions were: $H = 200$ mm, $2r = 175$ mm, $2Gr = 106$ mm, $D = 15$ mm, hydrogen pressure $= 5.0 \times 10^{-2}$ Pa, microwave (2.45 GHz) power $= 400$ W, dc voltage $= -20$ kV, dc current $= 30$ mA, and implantation time $= 5$ min. Half of the 100 mm diam implanted silicon wafer was subsequently annealed at 600 °C for 30 min to attain surface blistering. It should be noted that our experiment was performed at a relatively low voltage of $-20$ V solely for convenience as it is intended to be a demonstration. There is no practical reason why higher voltage experiments cannot be conducted if a suitable dc power supply is available.

The surface morphology and surface blistering of the as-implanted and annealed samples were investigated using atomic force microscopy (AFM). Surface blistering is caused by coalescence of the buried microcavities in the silicon wafer when it is not bonded to another silicon wafer. If a second wafer is bonded to this surface, layer transfer will occur. Visual inspection of the annealed wafer shows uniform blistering over the entire surface, but in order to more accurately

![Fig. 1. Schematic diagram of the dc-PIII system with multipolar magnetic field ECR plasma source.](image)

![Fig. 2. Topographic maps acquired by contact mode AFM: (a) as-implanted, (b) annealed at 600 °C for 30 min.](image)

![Fig. 3. HFS or ERD results acquired from three locations on the 100 mm diam as-implanted silicon wafer: 0 mm (center), 20 mm from center, and 40 mm from the center.](image)
determine the uniformity of the ion implantation dose, hydrogen forward scattering (HFS) or elastic recoil detection (ERD) was conducted on three areas of the as-implanted wafer: center (0 mm), 20 mm, and 40 mm from the wafer center. Secondary ion mass spectrometry (SIMS) was performed to investigate the presence of surface hydrogen and determine the hydrogen ion dose more accurately.

III. RESULTS AND DISCUSSION

AFM topographical maps of the dc-PIII as-implanted and annealed samples are shown in Fig. 2. The surface of the implanted wafer is very smooth before annealing, but layer exfoliation or surface blistering can be observed on the surface of the annealed sample. The surface morphology is similar to one that has undergone conventional pulsed hydrogen PIII. In particular, the size and density of the bubbles observed on the annealed sample are similar to those on a pulsed PIII sample. Even though we did not actually conduct wafer bonding and layer transfer, the severity of surface blistering should be sufficient for successful ion cut and SOI formation.

Visual examination of the annealed sample reveals very uniform surface blistering. In order to quantitatively investigate the lateral ion dose uniformity, we performed HFS or ERD analysis on three locations of the 100 mm diam as-implanted wafer: 0, 20, and 40 mm from the center. The overlaid results in Fig. 3 indicate that the hydrogen dose and in-depth distribution in the three samples are almost the same. The calculated relative ion doses are displayed in Table I which illustrates a lateral dose uniformity of better than 5% across a 100 mm silicon wafer.

Comparison of the hydrogen depth profiles of the dc-PIII and pulsed PIII samples acquired by SIMS is presented in Fig. 4. The detailed breakdown of the total hydrogen doses, surface hydrogen doses, and ratios are shown in Table II. The surface hydrogen component decreases from 61.2% to 30.8% compared to pulsed PIII, as low-energy ions arising from the initial sheath propagation and the rise and fall times of the pulse voltage are mitigated substantially. It should be noted that the total dose required in pulsed PIII is higher because much of it is actually surface hydrogen that does not contribute to the layer transfer process. In other words, the “usable” fraction of the implanted hydrogen ions is larger in DC-PIII and a lower total dose will suffice in this case. The residual surface hydrogen on the DC-PIII sample originates from surface adsorption that can be further reduced by biasing the sample with a dc voltage before the plasma is triggered. Since dc-PIII is more efficient than pulsed PIII, the total exposure time to the plasma is shorter and the total amount of adsorbed hydrogen also diminishes. Our experiments took 5 min, but with improved hardware and sufficient sample cooling, the experiments could have been completed in a fraction of that time. Our study experimentally demonstrates that by using a multipolar ECR source, uniform hydrogen plasma immersion ion implantation can be performed efficiently in the dc mode.

IV. CONCLUSION

Hydrogen dc-PIII was conducted using a multipolar magnetic field ECR plasma source. The lateral ion dose uniformity on a 100 mm silicon wafer is better than 5%, and the amount of surface hydrogen is substantially reduced from 61.2% to 30.8% compared to pulsed PIII. Therefore, the total hydrogen ion dose required for successful layer transfer is less in dc-PIII because the low-energy ion component is smaller. In addition to the high efficiency, the reduction of low-energy ions (consequently less surface damage), as well

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total dose $D_T$ (cm$^{-2}$)</th>
<th>Surface dose $S_H$ (&lt;40 nm) (cm$^{-2}$)</th>
<th>$S_H/D_T$</th>
<th>Pulsing frequency (Hz)</th>
<th>Total implantation time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µs</td>
<td>$1.04 \times 10^{17}$</td>
<td>$6.36 \times 10^{16}$</td>
<td>61.15%</td>
<td>300</td>
<td>60</td>
</tr>
<tr>
<td>dc</td>
<td>$4.32 \times 10^{16}$</td>
<td>$1.33 \times 10^{16}$</td>
<td>30.78%</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

TABLE I. Relative hydrogen doses at different locations on the as-implanted 100 mm silicon determined by ERD.

TABLE II. Total hydrogen doses, surface doses, and ratios of the surface to total doses of samples implanted using conventional pulsed PIII using a pulse duration of 10 µs and dc-PIII.
as ions bombarding the edges and other surfaces of the sample chuck (mitigating sputtered contaminants) are the main advantages of dc-PIII.

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1S. Cristoloveanu and S. S. Li, Electrical Characterization of Silicon-on-Insulator Materials and Devices (Kluwer Academic, Boston, MA, 1995).