Plasma cleaning of carbon species for silicon homoepitaxial growth

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As device dimensions are reduced into the sub-micron region in pursuit of higher integration density and better circuit performance, low temperature processing, including low temperature cleaning and low temperature epitaxial growth, is becoming important. In order to achieve the high-quality epitaxy with the low temperature processing, the technique of *in-situ* plasma cleaning has been developed [1, 2]. Although there have been some reports on the plasma cleaning of surface oxygen prior to epitaxial growth, there are rare reports on the systematic study on the removal of surface carbon. Carbon is much more tenacious and stable on the silicon surface than oxygen and temperatures over 1100 °C are required to remove carbon from the surface by thermal desorption process. Here, we have performed the low temperature *in-situ* cleaning in order to reduce the interfacial carbon concentration.

Substrates were 4 inch, czochralski-grown, p-type (100) silicon with 0.5–20 Ω-cm resistivity. The wafers were RCA cleaned and HF dipped for 20–30 s in 10:1 aqueous solutions and rinsed in DI (deionized) water and then dried by blowing nitrogen on them. All the processes were done inside the class 100 cleanroom and it took only 10 s to load the wafer into the load lock chamber of the CVD reactor after the wafer was blow-dried. After the wafers were transferred and loaded onto the heater stage, the main chamber was pumped down and ultimately 1–2 $\times$ 10^{-8} Torr could be attained.

In-situ predepositon wafer cleaning was done by using ECR hydrogen plasma. The ECR hydrogen plasma is able to deliver a higher density of low energy and light hydrogen ions to the wafer, resulting in highly efficient cleaning without substrate damage [2]. The ECR chamber was at the side of the CVD chamber. ECR was operated at the 2.45 GHz S-band microwave frequency. Depositions were done by flowing 10 sccm SiH_4 without carrier gases, immediately after the plasma was extinguished.

We have applied the *in-situ* cleaning condition with a microwave power of 300 W, DC bias of 10 V, pressure of 1 mTorr, and the cleaning temperature of 600 °C and subsequently have deposited the silicon epitaxial layer. Fig. 1 shows the XTEM image of silicon epilayer and the interface, revealing that the high-quality epitaxial layer is produced by applying the *in-situ* plasma cleaning. Fig. 2 shows the SIMS depth profile of epitaxial film and the interface, revealing that considerable amounts of carbon, nitrogen, and oxygen are accumulated at the epilayer/substrate interface. Regarding the interfacial carbon concentration, the maximum concentration at the interface is about 5 $\times$ 10^{20} cm^{-3} and the integrated dose of interfacial carbon concentration is about 4.5 $\times$ 10^{14} cm^{-2}. Since the integrated dose of the interfacial oxygen concentration is about 4.8 $\times$ 10^{13} cm^{-2}, we realize that the amount of carbon atoms at the interface is greater than that of oxygen atom.

In order to investigate the effect of cleaning condition on the interfacial carbon concentration, we have changed the microwave power, pressure, D.C. bias, and cleaning temperature. Table I shows the *in-situ* cleaning conditions and the SIMS data. We have plotted the column bar graph, indicating the effect of the specific process parameter on the interfacial carbon concentration. Fig. 3 shows the column bar graph showing the effect of cleaning temperature on the interfacial carbon concentration. Samples corresponding to the categories of 1, 2, 3, and 4 are Samples A and E, Samples B and F, Samples C and G, and , Samples D and H, respectively. For every pair of samples, the sample which received the *in-situ* cleaning at 25 °C had a lower carbon concentration in its epilayer/substrate interfaces than the

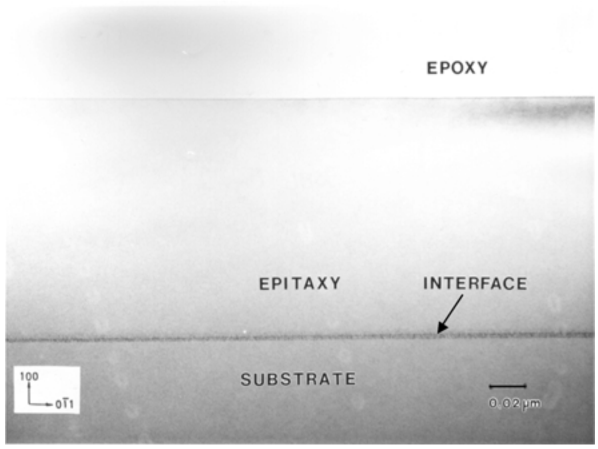

Figure 1 XTEM image of silicon epilayer and the interface, *in-situ* cleaned with a microwave power of 300 W, DC bias of 10 V, pressure of 1 mTorr, and the cleaning temperature of 600 °C. The high-quality epitaxial layer is produced by applying the *in-situ* plasma cleaning.

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TABLE I Summary of cleaning conditions and SIMS data

	Microwave power (W)	D.C bias (V)	Cleaning temperature (°C)	Carbon (cm^{-2})
Sample A^{+}	none	none	none	1.1×10^{14}
Sample A	750	0	25	1.5×10^{13}
Sample B	300	0	25	8.0×10^{12}
Sample C	750	10	25	6.9×10^{12}
Sample D	300	10	25	1.4×10^{13}
Sample E	750	0	600	2.6×10^{13}
Sample F	300	0	600	3.8×10^{13}
Sample G	750	10	600	2.6×10^{13}
Sample H	300	10	600	4.5×10^{14}

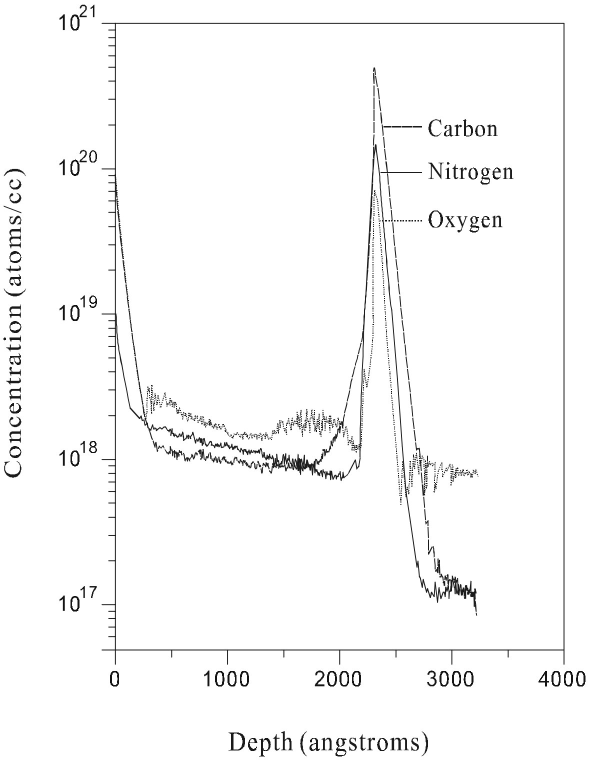

Figure 2 SIMS depth profile of epitaxial film and the interface, *in-situ* cleaned with a microwave power of 300 W, DC bias of 10 V, pressure of 1 mTorr, and the cleaning temperature of 600 °C.

samples which received the *in-situ* cleaning at 600 °C. The SIMS data reveals that the sample which did not receive the *in-situ* cleaning prior to epitaxial deposition, has an interfacial carbon concentration of about 1.1×10^{14} cm^{-2} and the carbon concentration can be reduced by applying the *in-situ* plasma cleaning at 25 °C. Fig. 4 shows the effect of substrate DC bias on the interfacial carbon concentration, respectively, revealing that the DC bias is not an important process variable affecting the carbon removal process. Samples corresponding to the categories of 1, 2, 3, and 4 are Samples A and C, Samples B and D, Samples E and G, and Samples F and H, respectively.

Although there are reports that the low temperature process was more effective in removing carbons from the surface [3, 4], it is unclear why the lower temperature plasma cleaning is more efficient in our work. Since we have revealed that the higher temperature, rather than higher DC bias, is more effective in removing carbon species, we surmise that the chemical reaction, rather than the ion bombardment, plays a crucial role in

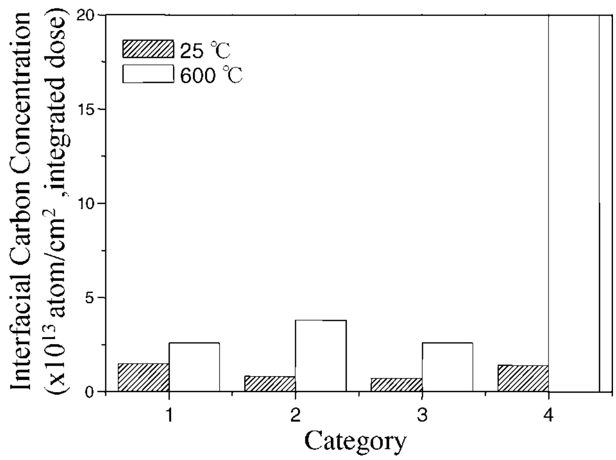

Figure 3 Column bar graph showing the effect of cleaning temperature on the interfacial carbon concentration.

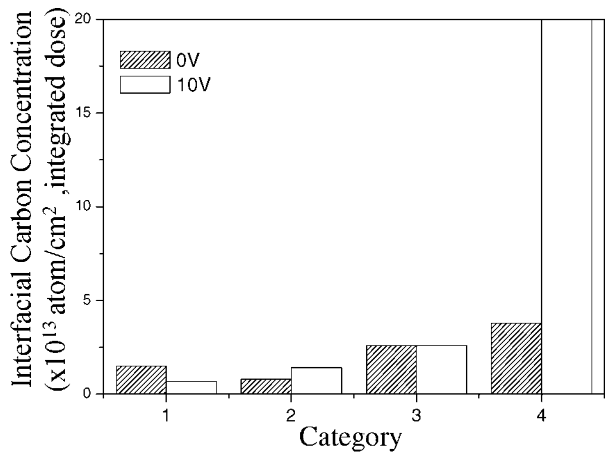

Figure 4 Column bar graph showing the effect of substrate DC bias on the interfacial carbon concentration.

the process. Therefore, we surmise that the carbon removal in our room temperature *in-situ* cleaning process would be a chemical etching process. Further systematic study is necessary to reveal the detailed mechanism of carbon removal processes.

In summary, we have demonstrated that the room temperature plasma cleaning is effective in reducing the interfacial carbon concentration. Since the surface temperature plays a crucial role in removing surface carbon from silicon substrate, we surmise that the carbon removal process is a chemical reaction-limited.

Acknowledgments

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