Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 210-212

Impact of High-Precision RF-Plasma Control on Very-Low-Temperature Silicon Epitaxy

Masaki HIRAYAMA[1,2), Wataru SHINDO[1,2)] and Tadahiro OHMI[1)]

1) Department of Electronics, Faculty of Engineering, Tohoku University, Aza-Aoba, Aramaki, Aoba-ku, Sendai 980, Japan
2) Laboratory for Microelectronics, Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aobaku, Sendai 980, Japan

We have clarified the effect of ion bombardment energy and ion flux density on the quality of very-low-temperature epitaxial silicon film. It was found that the activation level of dopants in grown Si films can be widely varied, while keeping the best crystallinity by controlling appropriately both the ion bombardment energy and the ion flux density. In order to achieve higher carrier concentration films, the ion bombardment energy must be controlled at low level, while keeping the ion flux density high enough to sufficiently activate the film surface. The ion bombardment energies were carefully decided based on plasma potential measurement by an advanced Langmuir probe technique for rf discharges.

Introduction

Lowering processing temperature for a total semiconductor device fabrication process is now becoming a critical issue. We have established low temperature silicon epitaxy at temperatures as low as 250°C utilizing a low-energy ion bombardment process.[1-2] In this process, the epitaxial growth of silicon is promoted not only by substrate heating, but by concurrently bombarding the growing film surface by low energy ions. The purpose of this study is to investigate clearly the effect of ion bombardment energy and the ion flux density on the crystal growth at low temperatures.

The ion bombardment energy e_i is determined by the difference between the plasma potential (V_p) and the externally applied substrate bias voltage (V_s) Therefore, in order to precisely control the ion bombardment energy, the accuracy measurement technique for the plasma potential is essential. While the use of conventional Langmuir probe in rf discharge plasmas has the fatal problems of rf interference[3-4]. The advanced single probe for measurements of rf discharge plasma parameters will be introduced in this article.

Experimental

Si films were deposited using the rf-dc coupled mode bias sputtering system[1]. The target of this system was a phosphorous-doped Si wafer, and the substrates used in this study were p-type(100) Si wafers. The plasma potentials were evaluated using an advanced probe technique developed for measurements of the rf discharge plasma parameters.

Measuring technique for rf plasma Parameters

Fig. 1 shows briefly the differences between the conventional Langmuir probe and the advanced one. In rf plasmas the plasma potential fluctuates with time at the plasma excitation frequency, causing the probe potential to also fluctuate. The amplitude and phase of the probe potential are generally different from those of the plasma potential. Since the instantaneous probe current is a function of the difference between the probe potential and the plasma potential, it also fluctuates with time. Thus the time-averaged I-V characteristics of the conventional Langmuir probe are distorted. In order to eliminate the rf interference, the probe potential must be completely forced to follow the instantaneous plasma potential.

The schematic diagram of the single probe used to measure the plasma potential in this study is illustrated

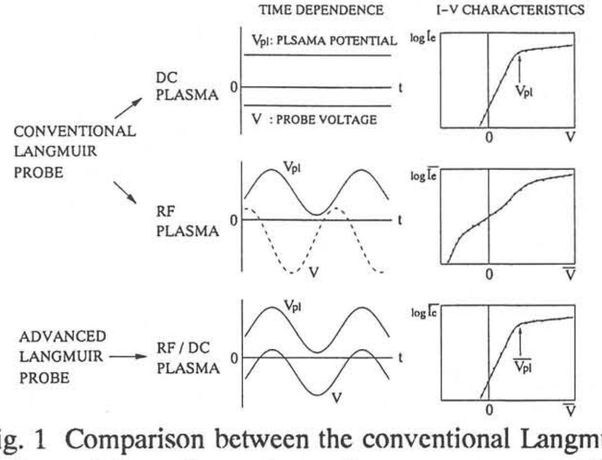

Fig. 1 Comparison between the conventional Langmuir probe and the advanced one for measurements of rf discharge plasmas.

in Figure 2. This probe was designed based upon two basic concepts for forcing the probe potential to follow the instantaneous plasma potential. One is increasing the capacitance of the sheath between the probe electrode and the plasma(C_s) (i.e., decrease the sheath impedance), and the other is increasing the impedance between the probe electrode and the ground(Z_p). A 0.2mm diameter tungsten wire forms the probe tip. In order to increase the sheath capacitance, an aluminum tube is connected to the tungsten wire via a 1000pF capacitor.

The probe body is formed by a semi-rigid coaxial cable. The length is equal to a quarter of a wave length of the plasma excitation frequency. The semi-rigid cable is terminated by four 1000pF tip capacitors. A $4/\lambda$ transmission line which is shorted at one end like this has an infinite input impedance from the other end. Therefore, the probe-ground impedance Z_p of this probe is much larger than that of the conventional Langmuir probe.

Fig. 3 shows the differences of I-V characteristics between the conventional Langmuir probe and the advanced one illustrated in Fig. 2. The evaluated value of a plasma potential by the conventional Langmuir probe is about 24V smaller than that by the advanced one. The rf plasma parameters never be precisely estimated by the conventional Langmuir probe. The ion bombardment energy, one of the key parameters of the low-energy ion bombardment process, was decided on plasma potential measured by this advanced probe.

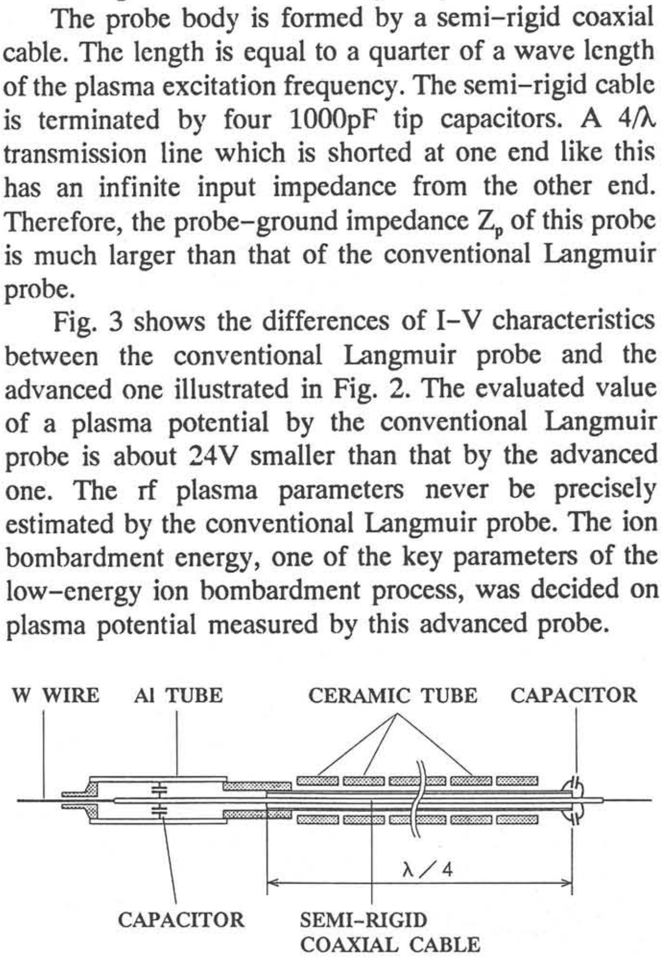

Fig. 2 Schematic diagram of the advanced Langmuir probe for measurements of rf discharge plasmas.

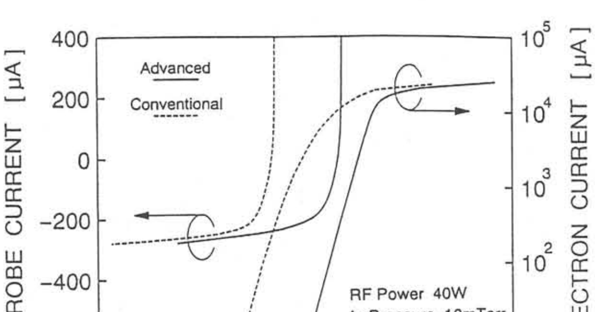

Fig. 3 I-V characteristics of the conventional Langmuir probe (----) and the advanced Langmuir probe (—).

Results and discussion

Fig. 4 shows the resistivities of Si films deposited at 300°C as a function of the ion bombardment energy(e_i). The normalized ion flux density(n_i) is fixed at 9. Here the normalized ion flux density n_i is defined as the number of Ar ions bombarding the film surface for a single deposited Si atom. It can be seen that the resistivities are very sensitive to the ion bombardment energy and reach a minimum of $2.8\times10^{-3}\Omega$cm at around 16.5eV. This result strongly suggests that the argon ion bombardment needs to be performed with a precisely controlled energy and with a negligible small spread of energy distribution. We have also shown the properties of the silicon films deposited below 16.5eV are fundamentally different from those deposited above 16.5eV, even if the values of resistivities are identical.

Fig. 5 shows carrier concentrations and mobilities of the deposited silicon films as a function of the ion bombardment energy. When the ion bombardment energy is below 16.5eV, while the carrier concentration does not change appreciably, the mobility becomes smaller with the decrease of the ion bombardment energy. This result suggests the crystallinity of the deposited silicon film becomes poorer with a lack of the ion bombardment energy. On the other hand, when the ion bombardment energy is above 16.5eV, the carrier concentration becomes smaller with the increase of the ion bombardment energy. It is known from SIMS

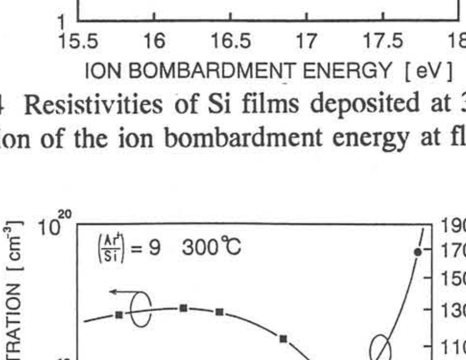

Fig. 4 Resistivities of Si films deposited at 300°C as a function of the ion bombardment energy at flux density n_i=9.

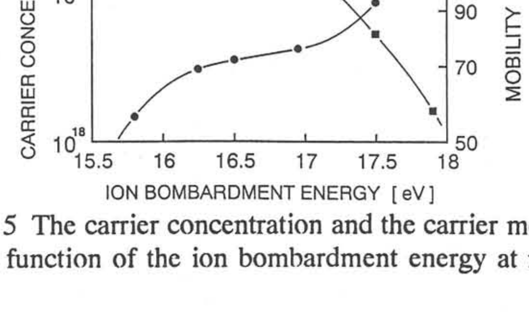

Fig. 5 The carrier concentration and the carrier mobility as a function of the ion bombardment energy at n_i=9.

analysis that the incorporation rate of the dopant phosphorus is invariable in relation to changes in the ion bombardment energy. Therefore, the decrease of the carrier concentration is due to the decrease of dopant activation level. The mobility becomes larger due to the decrease of the ionized impurity scattering. In this region, ideal crystallization occurs, for the sufficient amount of energy is provided for activating the growing film surface. These results suggest it is possible to vary the carrier concentration over a wide range while keeping the best crystallinity.

Fig. 6 demonstrates how the resistivities of the deposited Si films change as the ion bombardment energy is varied while the epitaxial growth is carried out. The top figure shows the ion bombardment energy as a function of the deposition time. The bottom figure shows the resistivities of the deposited silicon films as a function of the depth from the film surface. It can be seen that the resistivities are very sensitive to the ion bombardment energy. These results suggest it is possible to form an arbitrary carrier depth profile while keeping the best crystallinity by using the low-energy ion bombardment process.

Fig. 7 shows the resistivities of the Si films deposited at 350°C as a function of the ion bombardment energy for two different values of the normalized ion flux densities. In both cases, while the ion flux densities are different, the silicon deposition rates are identical. At the normalized ion flux density of 6.9, the resistivity reaches a minimum of $2.2\times10^{-3}\Omega$cm at around 15eV. When the ion flux density is increased, this minimum point moves gradually to lower energy side, because in order to achieve same total energy provided for activating the growing film surface, the higher ion flux density reduces the individual ion bombardment energy. At the normalized ion flux density of 15.4, the resistivity reaches a minimum of $1.9\times10^{-3}\Omega$cm. This value is smaller than that at the normalized ion flux density of 6.9, originating from the differences in the mobilities. This result suggests in order to achieve low resistivity Si films, it is desirable to keep the ion bombardment energy low while keeping the ion flux density high enough to sufficiently activate the growing film surface.

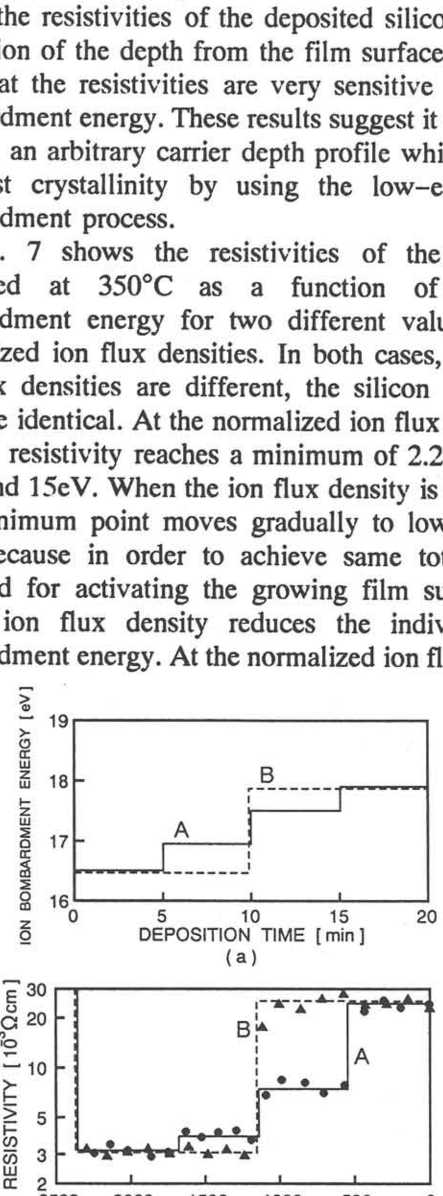

Fig. 6 (a) Ion bombardment energy as a function of the deposition time. (b) Resistivity depth profile of deposited Si films.

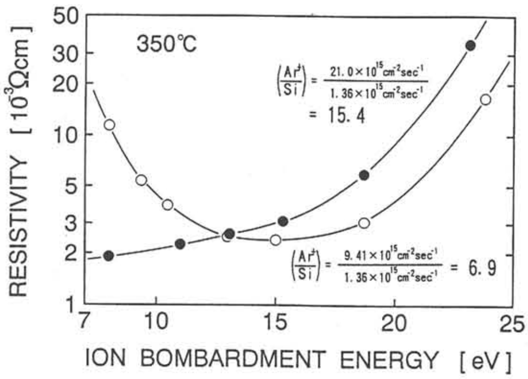

Fig. 7 Resistivities of Si films deposited at 350°C as a function of the ion bombardment energy for two different ion flux densities : n_i=15.4(●); n_i=6.9(○).

Conclusion

The activation level of dopants in grown Si films can be varied over a wide range by controlling appropriately the ion bombardment energy and ion flux density while keeping the best crystallinity. In order to achieve higher carrier concentration films, the ion bombardment energy must be controlled at low level, while keeping the ion flux density high enough to sufficiently activate the film surface.The ion bombardment energies were carefully decided based on plasma potential measurement by an advanced Langmuir probe technique for rf discharges.

Acknowledgement

The majority of this work was carried out at the Superclean Room of the Laboratory for Microelectronics, Research Institute of Electrical Communication, Tohoku University.

References

[1] T. Ohmi, K. Hashimoto, M. Morita, and T. Shibata, J. Appl. Phys. **69**, 2062(1991).

[2] T. Ohmi, T. Ichikawa, T. Shibata, K. Matudo, and H.Iwabuchi, Appl.Phys.Lett. **53**,346(1988).

[3] A. P. Paranjpe, J. P. McVittie, S. A. Self, J.Appl.Phys. **67**, 6718(1990).

[4] N. St. J. Braithwaite, N. M. P. Benjamin, and J. E. Allen, J. Phys. E **20**, 1046(1987).