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Very-Low-Temperature Epitaxial Silicon Growth by Low-Kinetic-Energy Particle Bombardment

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Low-kinetic-energy particles, i.e., Ar ions having energies comparable to typical crystal interatomic binding energies, have been utilized to control the kinetics of thin film growth as well as to perform very effective predeposition substrate-surface cleaning. As a result, epitaxial silicon layers with a perfect crystallinity are grown on silicon substrates at such a low temperature as 350 °C. The resistivity of an as-grown epitaxial silicon film as low as $0.0018 \ \Omega \ cm$ has been obtained, showing the impurity activation without any heat treatment. A p-n junction formed by growing an n-type epitaxial silicon layer directly on a p-type substrate at $350 \ C_2$ exhibited very low reverse-bias leakage current of $1.88 \times 10^{-4} \ A/cm^{-1}$.

INTRODUCTION

The most essential requirement for future ULSI fabrication with lower submicron design rules is the high precision control of processes as well as the realization of lowtemperature processing. The growth of silicon epitaxial films at low temperatures is of particular importance for fabricating ULSI devices because of the necessity for precise impurity profile control.

Epitaxial growth of silicon is usually performed using chemical vapor deposition (CVD) technologies. However, they require high-temperature heat cycles typically over 1000°C for film deposition and also for substrate surface cleaning. Recently high quality epitaxial silicon was grown at 600°C with a large deposition rate by surface reaction film formation technology utilizing free-jet molecular flow. (1,2) Low-temperature silicon epitaxy below 400 or 730°C has also been reported using ion beam technologies, such as partially ionized vapor deposition⁽³⁾ deposition⁽⁴⁾ ionized cluster or beam respectively. However, in these processes the energies of ions or ionized clusters are in

the range of keV's, which is much higher than the typical crystal interatomic binding energies. This means that these processes can cause damage in the underlying substrates or devices.

The purpose of this paper is to present new results on the formation of high quality epitaxial silicon films at low temperatures below 350°C by a newly developed low-kineticenergy particle process. In the new process the concurrent bombardment of a growing film surface by low-energy Ar ions is utilized to control the kinetics of thin film growth. Since the ion energies of interest in this process are in the range of typical crystal interatomic binding energies, very efficient interaction of in-coming ions with constituent atoms at the surface layer of thin films is expected to occur. As a result, a wide range control of thin film properties has become possible at very low temperatures. (a) Permanent Address: Oki Electric Industry Co., Ltd., Hachioji, Tokyo 193, Japan.

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bias-sputtering system.

EXPERIMENTAL

Thin film formation was carried out using the rf-dc coupled-mode bias sputtering system^(5,6,7) illustrated in Fig. 1. Two external dc voltage sources extract ions from the plasma generated by 100 MHz excitation, thus individually controlling the energies of ions incident to the target and to the wafer. Ion flux density is separately controlled by changing the rf power input. By adjusting these externally controllable parameters, important parameters for thin film growth such as the energy and the flux of ion bombardment and the film growth rate are able to be controlled, independently and precisely. It should be noted that the present technology is in marked contrast with the ionized cluster beam deposition⁽⁴⁾ in energy of individual ions that the are

precisely controlled to a predetermined value in this process. The entire system was constructed based on the philosophy of ultra clean technology (8,9), featuring a base pressure of the main chamber of less than 2×10^{-10} Torr, and the impurity level in Ar gas (mainly H₂O) of a few ppb or below at the inlet to the chamber.

RESULTS AND DISCUSSION

Figure 2 shows the reflection electron diffraction patterns obtained from ~ 0.5 um thick silicon films formed on (100) silicon substrates, demonstrating the effect of ion bombardment on a crystallographic structure of a deposited film. A single crystal Si film with perfect crystallinity as evidenced by the sharp Kikuchi lines is obtained at a substrate bias voltage (V) of 5V. As the substrate potential is reduced or more negatively biased to increase the ion bombardment energy, the structure of a deposited film changes from single crystal silicon to large-grain polysilicon, finegrain polysilicon and to amorphous silicon as shown in Fig. 2.

In order to grow an epitaxial layer with a perfect crystallinity, it is essential to perform in situ substrate-surface cleaning before thin film deposition. Conventional techniques using H₂ or HCl gases require high temperature heat treatment typically over

(d) -15V



Fig. 2. Reflection electron diffraction patterns from silicon films deposited on (100)Si with varying substrate bias voltages. The deposition conditions are: rf power of 40W; target bias of -200V; Ar gas pressure of 8×10^{-3} Torr; and substrate temperature of 320-350°C.

1000°C. A low-temperature damage-free surface cleaning process has been realized for the first time by the low-kinetic-energy particle process⁽⁷⁾. The dramatic effects of the surface cleaning process on the crystallinity of epitaxial Si films are clearly demonstrated in Fig. 3. The top pictures in the figure represent the reflection electron diffraction patterns obtained from grown films, while the bottom pictures the SEM micrographs of Wright-etched film surfaces. The substrate surface was first bombarded with Ar ions with varying substrate bias voltages with a rf power of 5W and a target bias of -25V for 5 min, followed by the sputtering deposition of a Si film using the best condition in Fig. 2. The best quality of a film is obtained at V =7V, at which condition a very thin native oxide layer and/or adsorbed molecules (mainly moisture) on the substrate surface has been completely removed without causing any damages in the substrate. When the ion bombardment energy is

increased or decreased from the optimum condition, the film crystallinity degrades as is seen in the figure. Surface cleaning with excessive ion energies causes damages in the substrate.

When the impurity doped silicon is used as a sputtering target, the impurity atoms are incorporated in the grown film and are electrically activated without any activation heat treatment. An arsenic-doped n-type silicon layer with a resistivity as low as 0.0018 Ω cm is grown at such low temperatures as 320-350°C using a heavily arsenic-doped target. When a phosphorus-doped silicon target of $0.013 \,\Omega$ cm resistivity is used, the epitaxial layer shows a resistivity of 0.020 Ω cm. p-n junctions were fabricated by directly depositing an n-type Si layer on top of an oxidized p-type wafer having openings in the oxide. A very low leakage current level of 1.88×10^{-9} A/cm² at a reverse bias voltage of 5V is obtained as shown in Fig. 4. The diode size is 1mm x 1mm and the range of



Fig. 3. Effect of the predeposition substrate-surface cleaning condition on the crystallinity of epitaxially grown films. Reflection electron diffraction patterns (top) and SEM micrographs of Wright-etched surfaces (bottom) are shown as a function of the substrate bias voltage applied during the cleaning operation. Ion bombardment conditions during film growth are identical for all samples.

data distribution within a wafer was found very small. From these observations we conclude that device grade epitaxial silicon layers are able to be formed at such a low temperature as 350 °C by the low-kineticenergy particle process.



Fig. 4. The reverse current voltage characteristics of a p-n junction diode which consists of an n-type epitaxial silicon layer and a p-type substrate.

(measured at 25°C)

CONCLUSIONS

Very-low-temperature silicon epitaxy with simultaneous impurity doping as well as damage-free, low temperature substrate surface cleaning has been established by lowkinetic-energy particle process. The lowest resistivity of a silicon film epitaxially grown on a (100) silicon substrate is 0.0018 Ω cm. The leakage current observed in lmm x 1mm size p-n junction diode is 1.88x10⁻⁹ A/cm^2 at reverse bias voltage of 5V. From these observations, it is concluded that device grade epitaxial silicon layers are able to be grown at extremely low temperatures by low-kinetic-energy particle process.

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