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Very low temperature silicon epitaxial growth by partial plasma enhanced chemical vapor deposition

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This article presents the very low temperature ($\sim$300 °C) silicon epitaxial growth on p-type, <100> Si wafers by plasma enhanced chemical vapor deposition (PECVD) with a stainless steel mesh (i.e., partial PECVD). The epitaxial layer was grown at 300 °C following a modified ex-situ spin etch cleaning and an in-situ H_2 baking step.

The kinetics of very low temperature silicon epitaxial growth (288 °C $\sim$ 375 °C) by plasma enhanced chemical vapor deposition with stainless steel mesh is studied. A Langmuir-Hinshelwood rate expression correlates all rate data with rf powers and pressures. A higher growth rate facilitates better quality epitaxial films.

1. INTRODUCTION

Low temperature silicon epitaxy becomes more and more important for fabricating submicron devices with abrupt dopant transition and minimal dopant redistribution [1]. A natural method of achieving such epitaxial layers is the low temperature silicon epitaxial growth which avoids autodoping [2,3] and dopant redistribution via solid-state diffusion. Plasma-enhanced chemical vapor deposition (PECVD) [4], is a promising technique to obtain low temperature silicon epitaxy.

It is known that the key to reduce epitaxial growth temperature is to promote the precursor's surface mobility. However the surface mobility decreases with decreasing temperature. The plasma is used to supply the non-thermal energy to maintain a sufficiently high surface mobility. However, ion bombardment in PECVD may promote surface mobility but damage the substrate surface [5]. In this work, the addition of a stainless steel mesh between two electrodes is used to reduce ion bombardment and eliminate polymer generated by plasma while still promote epitaxial growth. With the addition of a stainless steel mesh, the PECVD silicon epitaxial growth is (named partial PECVD here) feasible at 300 °C as shown in the previous report [6,7].

2. EXPERIMENTAL PROCESS

The epitaxial growth was carried out in a flat-bed parallel planar type reactor (ULVAC model, CH-100) consisting of two electrodes separated by 4.5 cm to couple the radio-frequency (rf) plasma. The schematic diagram of the PECVD system and the geometric feature of the mesh were shown in the previous publication [6,7]. The

Table 1 Summary of epitaxial growth at a substrate temperature of 300°C, a H_2 flow rate of 22 sccm, a SiH_4 flow rate of 30 sccm, and a rf power of 10 w for 60min.

Film	Thickness (nm)	Growth rate (nm/min)	Mesh	Film type	XTEM
A	140	2.3	Yes	Epitaxy	Fig.1(a)
B	470	7.8	No	Saw-tooth Epitaxy	Fig.1(b)

stainless steel mesh was set between electrodes so that the plasma was generated between mesh and lower electrode. A diffusion pump was connected to the chamber to achieve a base pressure of $3x10^{-5}$ Torr and was shut off prior to the epitaxial growth. During deposition the system was pumped down by a mechanical roots pump backed with a rotary pump keeping the chamber pressure over a wide range.

The substrates used for depositions are silicon wafers, <100> oriented, p-type with a resistivity of $2 \sim 5$ ohm-cm, cut into 30 mm x 30 mm pieces. The wafer was ex-situ cleaned by a modified spin-etching method to provide a hydrogen-terminated silicon surface, which is believed to have the passivation effect [8] because the hydrogen-silicon bond can prevent surface oxidation during air exposure [9].

The substrate was then loaded into the reactor within 5 min. The substrate was faced down and loaded onto the upper-electrode which was heated by a resistance heater. After wafer loading, the system was pumped down to $2 \sim 5x10^{-5}$ Torr by the diffusion pump prior to epitaxial deposition. An in-situ cleaning process was carried out during the heating of the substrate to the deposition temperature by flowing H_2 and keeping the chamber at a pressure of 80 mTorr for 30 min. Immediately after in-situ cleaning, SiH_4/H_2 was introduced for the epitaxial growth with a process pressure of 40 ~ 120 mTorr. The substrate temperature was 288 ~ 375 °C and the rf power density was from 0.015 to 0.15 W/cm^2. The epitaxial films were characterized by cross-sectional transmission electron microscopy (XTEM).

3. RESULTS AND DISCUSSIONS

Silicon epitaxial growth at 300 °C without stainless mesh which requires an appropriate H_2 to SiH_4 flow ratio has been reported in our group [10]. In this work, it was found that the epitaxial growth still can be achieved without the need of an appropriate H_2/SiH_4 flow rate reported [10], when the mesh was added. Table 1 lists the results of the silicon epitaxial growth at 300 °C and a rf power of 10 W for 60 min from SiH_4/H_2. Figure 1(a) and (b) show bright field XTEM micrographs of film A and B, respectively. Film A (Fig.1(a)) is of epitaxial structure while film B (Fig.1(b)) exhibits a thin saw-tooth epitaxial layer with amorphous Si on top. Comparing film A and film B, one can find that silicon epitaxial growth can be achieved even the H_2/SiH_4 flow ratio is low with the use of stainless steel mesh, which is unlikely for the one without mesh.

Figure 2 shows silicon deposition rate versus P_{SiH4}/P_{H2} ratio for rf powers between 10 and 40 W. The epitaxial growth was carried out at 313 °C and a hydrogen pressure of 53 mTorr with silane

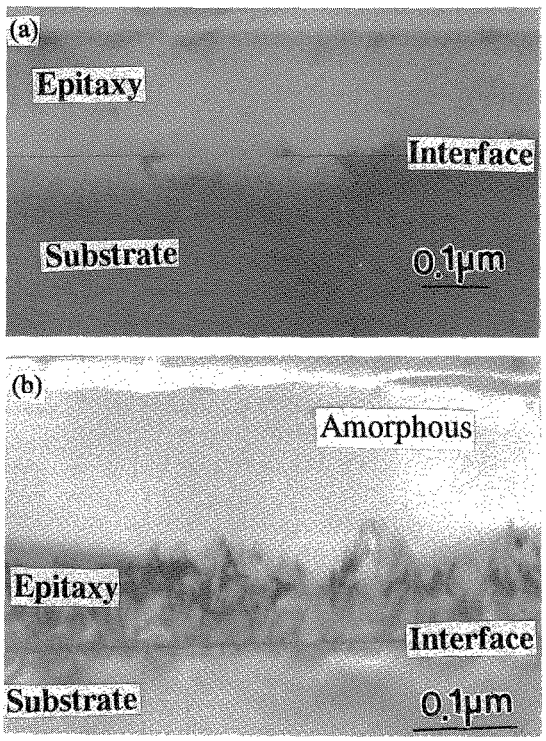

Fig. 1. The bright field XTEM micrographs of (a) film A, (b) film B.

pressures between 18 and 58 mTorr. This plot indicates a linear dependence in P_{SiH_4}/P_{H_2} at high powers. It also shows that the growth rate becomes independent of P_{SiH_4}/P_{H_2} at low powers and high P_{SiH_4}/P_{H_2}.

These pressure and power dependences indicate that the growth rate (R) may be given by a Langmuir-Hinshelwood rate expression [11]

$$R=\alpha(P_{SiH_4}/P_{H_2})/[1+\beta(P_{SiH_4}/P_{H_2})](nm/min) \quad (1)$$

where $\alpha = 4.270 + 0.076\ W_{rf}$ (nm/min) (2)

and $\beta = 6.619\ W_{rf}^{-0.7}$ (3)

In the above equations, α and β are the combination of many constants which are functions of the rf power (Wrf). Solid lines in Fig. 2 are those calculated from equation (1) with parameters from equations (2) and (3).

In this work, PECVD with stainless steel mesh (i.e., partial PECVD) differs from those without mesh in that the plasma does not contact the substrate, i.e. the substrate is not immersed in the plasma region. The mesh is used to reduce the direct high energetic bombardment of positive ions but still allows some energetic particles to pass, so that the plasma-induced surface damage is minimized.

During the deposition, SiH_4 and H_2 were decomposed in plasma to produce more reactive precursor species such as SiH_2 or SiH_3 which were adsorbed onto the surface where they were able to diffuse to a step or kink site and be incorporated into the lattice. The release of H_2 from the adsorbed SiH_2 seems to be the rate determining step of the epitaxial growth. At the same time, polymerization occurs simultaneously in the plasma. When the polymer is deposited on the substrate surface, the growing layer may become polycrystalline or amorphous. Since the polymer will mostly deposit on the surface which

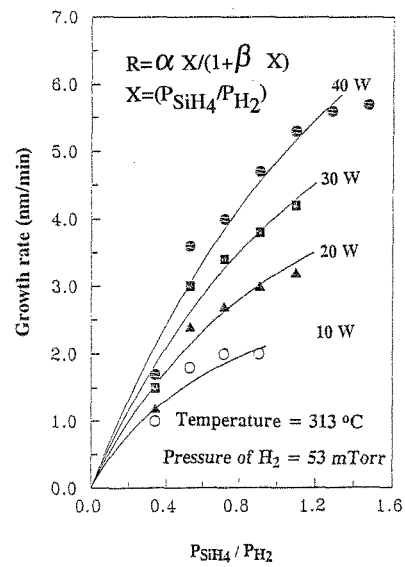

Fig. 2. Plot of growth rate R versus P_{SiH_4}/P_{H_2} for different rf powers. The solid lines are growth rates predicted by Eqs. (1), (2), and (3).

contacts the plasma directly [12], a stainless steel mesh which is used to maintain the plasma between the mesh and the lower-electrode can keep the substrate surface from the contamination of polymer during epitaxial growth.

4. SUMMARY

In summary, this article presents that following a modified ex-situ spin etch cleaning and an in-situ H_2 baking step the epitaxial growth can be carried out at 300 °C using PECVD of SiH_4/H_2 with a stainless steel mesh (i. e., partial PECVD). The stainless steel mesh which is used to maintain the plasma between the mesh and the lower electrode can allow the energetic precursors to pass, minimize high energetic bombardment of ions on the substrate surface, and reduce the contamination of polymer during epitaxial growth. SiH_4 is dissociated in plasma to form SiH_2 and H_2 The release of H_2 from the adsorbed SiH_2 seems to be the rate determining step of the epitaxial growth. The agreement between the predictions of the Langmuir-Hinshelwood rate expression and the experimental data is very good.

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