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Suppression of surface segregation and heavy arsenic doping into silicon during selective epitaxial chemical vapor deposition under atmospheric pressure

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The authors investigated the effects of the growth rate and temperature on the surface segregation during *in situ* As-doped selective epitaxial growth under atmospheric pressure. It was confirmed that high growth rate and high temperature suppress surface segregation. A film with a high As concentration (7.5×10^{19} at./cm^3) and a smooth surface was obtained by optimizing these conditions. [DOI: 10.1063/1.2778539]

Scaling trend of metal-oxide-semiconductor field effect transistors continues for the 45 nm technology node and beyond. One of the critical issues is suppression of the short-channel effect caused by shrinking dimensions. Reducing the extension junction depth is an effective approach, so that the raised extension structure made by the *in situ* doped selective epitaxial growth (SEG) process has been proposed to solve this problem.[1–4] This process produces an abrupt dopant profile at the junction interface since it does not require activation annealing.

Many studies have been conducted on heavy arsenic doping into Si, owing to its high solubility and its small diffusion coefficient. However, a high concentration of As atoms and high growth rate have not been achieved because of the strong surface segregation of As atoms during growth. The surface segregation reduces the incorporation of As atoms into the film, and the segregated As atoms passivate the growth surface, reducing the growth rate.[5–8]

In our previous studies, we investigated *in situ* As-doped Si SEG under atmospheric pressure, which gave a higher As concentration of 2.2×10^{19} at./cm^3 at a higher growth rate of 3.3 nm/min than under the conventional low pressure.[9,10] This can be explained by the suppression of As surface segregation during growth under atmospheric pressure. However, higher dopant concentration and higher growth rate are required for practical use. In this letter, we studied the effects of growth rate and temperature on the SEG under atmospheric pressure from the viewpoint of further suppression of the surface segregation. We also discuss the effects of growth conditions on surface segregation.

All films were grown in a cold-wall reduced-pressure chemical vapor deposition reactor. The substrates were 8 in. *p*-type Czochralski Si(100) wafers with a resistivity of 8–12 Ω cm. The wafers were cleaned with HF, and then *in situ* H_2 annealing was performed in the growth chamber. SiH_2Cl_2, HCl, and AsH_3 were used as precursor gases for *in situ* As-doped Si SEG under atmospheric pressure. Hydrogen, whose flow rate was 20 SLM (standard liters per minute), was used as the carrier gas. The flow rate of SiH_2Cl_2 was varied from 25 to 100 SCCM (SCCM denotes cubic centimeter per minute at STP), while the flow rate of HCl was constant. The flow rate of AsH_3 diluted to 1% in hydrogen was varied for *in situ* doping. The growth temperature was varied between 700 and 800 °C. The depth profiles of As concentration were measured by secondary ion mass spectrometry, and the surface roughness was evaluated using atomic force microscopy (AFM).

In order to further suppress the surface segregation of As atoms during SEG under atmospheric pressure, we increased the growth rate by increasing the SiH_2Cl_2 flow rate. The high growth rate would suppress the surface segregation because As atoms incorporated into the second layer have little chance to exchange their positions with surface Si atoms adsorbing on the As atoms. Before the exchange, Si atoms adsorb on the surface, so that the As atoms are no longer in the second layer. Rather, they are in the third layer. However, the increase of the growth rate caused by the increase of the SiH_2Cl_2 flow rate would also reduce the As concentration because the fraction of As atoms in the atoms impinging on the growth surface decreases.

Figure 1 shows the As concentration and growth rate as a function of the SiH_2Cl_2 flow rate. With increasing SiH_2Cl_2 flow rate, both the growth rate and As concentration increase. This means that the effect of the suppression of surface segregation is much stronger than that of the decrease in the fraction of As atoms. At the region of high SiH_2Cl_2 flow rate, the As concentration saturates since the fraction of As atoms in the atoms coming on the growth surface becomes very small.

Next, we investigated the temperature dependence of the As concentration and the growth rate because the desorption of surface As atoms is expected to suppress surface segregation. It has been reported that As atoms desorb primarily

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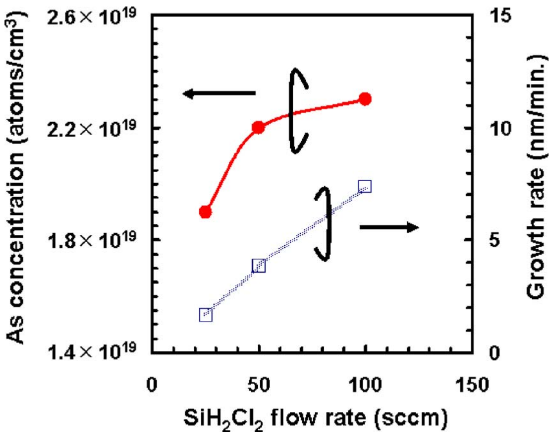

FIG. 1. (Color online) As concentrations and growth rates as functions of the SiH_2Cl_2 flow rate.

above 600 °C, with significant desorption occurring above 800 °C.[11]

The temperature dependences at a constant SiH_2Cl_2 flow rate are plotted in Fig. 2. The As concentration decreases and the growth rate increases with increasing growth temperature. The increase of the growth rates is due to the enhanced decomposition of the reaction gases and the suppression of the surface segregation. According to the discussion of high As concentration caused by high growth rate (see Fig. 1), the As concentration should increase with increasing growth rate. However, the As concentration in the film decreases with increasing growth temperature because the effect of the desorption of surface As atoms is larger than that of the increase of the growth rate.

The relationship between the root mean square roughness (R_{rms}) of the growth surfaces and the As concentration in the films is summarized in Fig. 3, together with the AFM images of the films with an As concentration of $\sim 4.5 \times 10^{19}$ at./cm^3. The R_{rms} corresponds to the concentration of surface As atoms because the segregated As atoms on the surface cause surface roughness through passivation of the growth surface.[12–17] R_{rms} increases rapidly with increasing As concentration in the films grown at both 700 and 750 °C, while it remains constant for the films grown at 800 °C. The surface roughness of the films grown at 800 °C is lowest in comparison of the films with the same As concentration, as shown in Figs. 3(a)–3(c). Thus, it is understood that the surface segregation of As atoms is suppressed during the growth

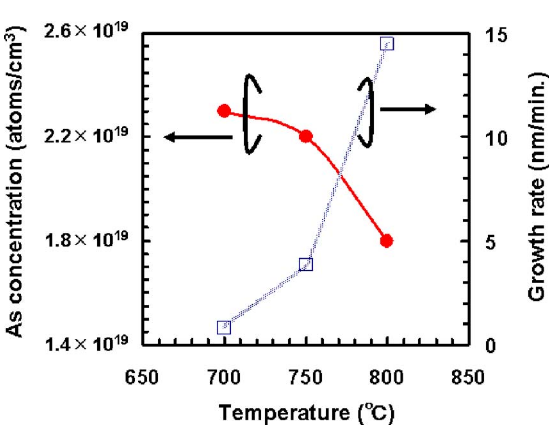

FIG. 2. (Color online) As concentrations and growth rates as functions of temperature.

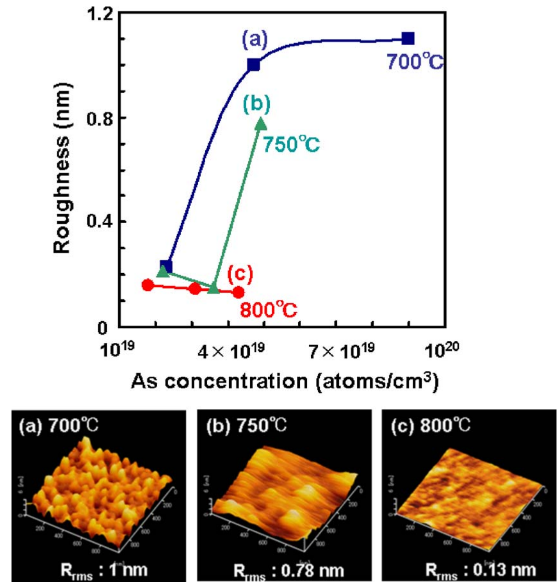

FIG. 3. (Color online) R_{rms} of the Si layer as a function of the As concentration in the film at a constant SiH_2Cl_2 flow rate. The AFM images are of a film with an As concentration of around 4.5×10^{19} at./cm^3 at (a) 700 °C, (b) 750 °C, and (c) 800 °C.

at 800 °C because the ratio of the concentration of surface As atoms to As atoms in the film is lower.

We found that the growth rate and temperature are important for controlling the surface segregation of As atoms in the growth of the films with high As concentration. It should be noted that these growth conditions are not independent of each other. An increase in growth temperature causes an increase in growth rate. However, high growth rate and high temperature are effective in growing highly As-doped Si layers. As shown in Fig. 3, we obtained a film with As concentration of $\sim 4.5 \times 10^{19}$ at./cm^3 by growth at 800 °C. Furthermore, by increasing a SiH_2Cl_2 flow rate to 500 SCCM and an AsH_3 flow rate to 200 SCCM, we achieved Si layers with a high As concentration of 7.5×10^{19} at./cm^3 with a R_{rms} of less than 0.35 nm.

In summary, we investigated the effects of growth rate and temperature on surface segregation during *in situ* As-doped SEG under atmospheric pressure. High growth rate and high temperature suppressed As surface segregation. A film of a high As concentration (7.5×10^{19} at./cm^3) with a smooth surface was achieved by optimizing the growth conditions.

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