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High-Rate Growth of Defect-Free Epitaxial Si at Low Temperatures by Atmospheric Pressure Plasma CVD

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1. Introduction

Epitaxial Si wafers are important for next generation ULSI devices. In the current production process of epitaxial Si wafers, thermal CVD at temperatures higher than 1000°C is adopted. High temperature processes, however, cause inevitable problems such as dopant redistribution, auto doping, susceptibility to slip generation, and high costs due to large thermal budget. Therefore, low temperature process is highly desirable in epitaxial Si growth. Recently, several researchers have studied low temperature epitaxial Si growth by using plasma-enhanced CVD method [1, 2]. However, the reported growth rate of epitaxial Si (about 80nm/min at 800°C) is too small to be applied for industrial process. In this paper, we propose atmospheric pressure plasma CVD (AP-PCVD) of epitaxial Si [3, 4] and describe optimization of the AP-PCVD conditions to achieve low-temperature growth of high-quality epitaxial Si films at high growth rates.

2. Atmospheric pressure plasma CVD

In the AP-PCVD method, atmospheric plasma is generated in a narrow gap (< 1mm) between a rotary electrode and a substrate (Fig.1). Combination of the rotary electrode and 150 MHz very high frequency (VHF) power supply makes it possible not only to generate the high-density atmospheric pressure plasma but also to avoid ion bombardment against the film. By rotating the electrode, source gases are easily fed into the narrow gap. Also, it is possible to cool the electrode surface effectively, so that high power can be supplied without thermal damage of the electrode. In addition, we can make a film of a large area by scanning a substrate. Details on the AP-PCVD technique are described in other papers [3, 4].

3. Experimental

Our CVD apparatus has turbo molecular pumps, and its base pressure is about 10^{-6}Pa. The reactor chamber is filled with gas mixtures containing He, H_2, and SiH_4 to the pressure of 760 torr. In the AP-PCVD method, growth conditions such as electrode rotation speed, deposition gap (distance between the electrode and the substrate), gas composition, substrate temperature, and VHF power are important parameters for realizing low temperature Si epitaxy at high rates.

4. Results and Discussion

Thickness profile of the deposited films

Figure 1 schematically illustrates a side view of the plasma area and the thickness profile of deposited films. The atmospheric pressure plasma is confined in the gap region with a defined plasma length. The plasma length was about 40 mm. We found that the position, where we obtained the highest growth rate, shifted to the upstream region from the minimum gap region with increasing VHF power. With increasing VHF power, the gas temperature within the plasma may increase. Therefore, the decomposition of a larger amount of source gas molecules may be finished in the upstream region, resulting in the thicker film in this region as indicated by the dotted curve shown in Fig. 1.

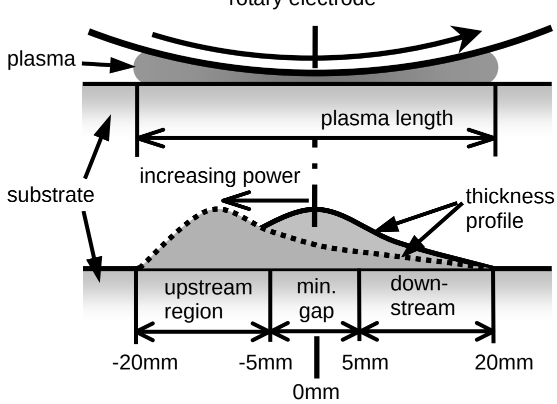


Fig.1 Side view of the plasma generated area and the thickness profile of deposited films.

Optimization of electrode rotation speed, deposition gap, and gas composition

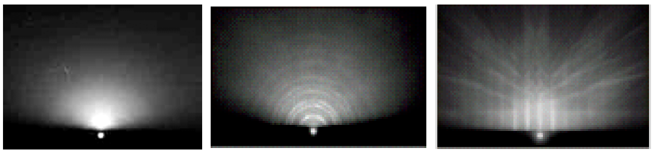
Table I summarizes the results of our experiments under various growth conditions. It's clear that film crystallinity is determined by the growth conditions. Electrode rotation speed has influence on the gas flow rate into the plasma. When we decreased the deposition gap, the amount of supplied gas into the plasma decreased. With a larger deposition gap than 1mm, however, the plasma becomes unstable. In addition, source gas composition had influence on the film crystallinity. Our results shown in Table I reveal that the optimum rotation speed, deposition gap, and gas composition were 2000rpm, 0.7mm, $SiH_4$0.1%, and $H_2$1%, respectively.

Table I optimization of growth conditions (630°C, 1100W).

deposition gap 0.7mm, H_2 concentration 1%				
rotation speed	500rpm	2000rpm	3000rpm	5000rpm
crystallinity	poly	epi	epi	poly
rotation speed 2000rpm, H_2 concentration 1%				
deposition gap	500μm	700μm	1000μm	1500μm
crystallinity	poly	epi	poly	poly
rotation speed 2000rpm, deposition gap 0.7mm				
H_2 concentration	0%	1%	10%	30%
crystallinity	epi	epi	poly	poly

Effects of VHF power on Si film crystallinity

Next, we have studied the effect of VHF power on Si epitaxial growth. Fig.2 shows RHEED patterns of deposited Si films with various VHF powers. Halo pattern is observed in a RHEED image of the Si film deposited with 800W. Polycrystalline ring pattern is observed for 1100W, and epitaxial Si growth is observed for the VHF power of 1550W. These results indicate that the crystallinity depends on the VHF power, and suggest that we can reduce growth temperature by optimizing growth conditions.



800W 1100W 1550W

Fig.2 RHEED patterns.
substrate temperature: 570°C, deposition gap: 0.7mm
electrode rotation speed: 2000rpm, H_2: 1%, SiH_4: 0.1%

Reduction of growth temperature

Figure 3 summarizes the crystallinity of the deposited film as functions of susceptor temperature and VHF power. We can obtain epitaxial Si films by increasing VHF power, and achieve Si epitaxial growth at 500°C with the VHF power of 3000W. Compared with the conventional thermal CVD, this temperature is 500°C lower or more. The growth rate with this condition is 0.25 μm/min.

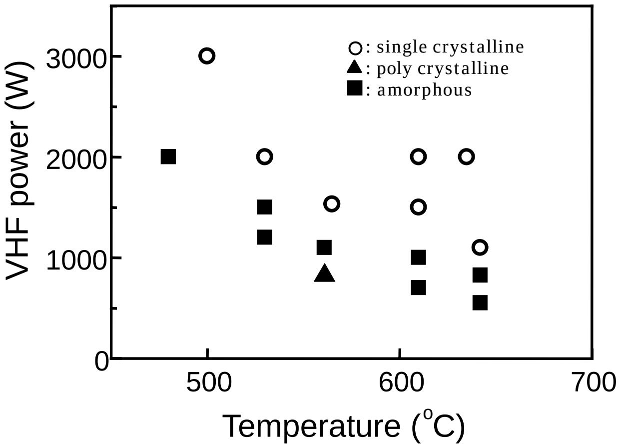
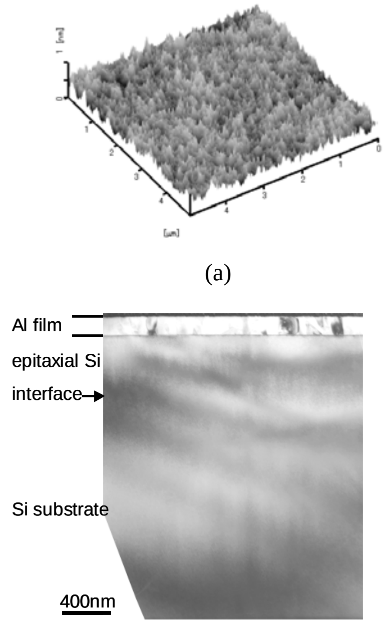


Fig. 3 Crystallinity of the deposited film as functions of susceptor temperature and VHF power.

Surface morphology and crystallinity of epitaxial Si film

We also investigated surface morphology and crystallinity of the epitaxial Si films. Fig. 4 shows atomic force microscopy (AFM) and cross-sectional transmission electron microscopy (XTEM) images. AFM observation of the film showed that the film surface is very smooth with a root mean square (rms) roughness of 0.1nm. In the XTEM image, no defect or no film/substrate interface contrast is seen in the epitaxial film. Therefore, it is concluded that defect-free epitaxial Si growth at 500°C is achieved with the VHF power of 3000W.

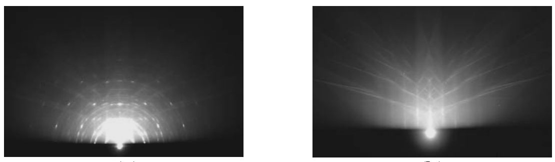


(b)

Fig.4 (a)AFM image (5x5 μm) and (b)XTEM image
VHF power: 3000W, substrate temperature: 570°C
deposition gap: 0.7mm, H_2: 1%, SiH_4: 0.1%
electrode rotation speed: 2000rpm.

Uniformity of the film

Figure 5 shows a typical RHEED pattern of the deposited Si surface and the RHEED pattern at the edge of the upstream region. Although poly crystalline growth is observed at the edge of the upstream region, we observed single crystal growth at the rest of the whole surface. Thus, we need to overcome this polycrystalline growth at the film edge to obtain wafer-size epitaxial films.



(a) (b)

Fig. 5 (a) Typical RHEED pattern of the deposited Si film. (b) RHEED pattern at the film edge of the upstream region.

5. Conclusions

We have studied the optimum conditions for the growth of epitaxial Si films by AP-PCVD method. Under the optimum conditions, we demonstrated that defect-free epitaxial Si with excellent surface flatness can be grown at 500°C with an average growth rate of 0.25 μm/min.

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