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Microstructure effects on quantum efficiency in PtSi/p-Si(1 0 0) Schottky barrier detector

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Abstract

The microstructure effects on the performance of the PtSi Schottky barrier detector (SBD) have been investigated in detail. The growth temperatures were ranged from 350 to 550°C. The thickness of the PtSi film measured by high resolution transmission electron microscopy (HRTEM) is around 4 nm. The electron diffraction pattern shows an intermingling of both $(1\,\bar{1}\,0)$ and $(1\,\bar{2}\,1)$ orientations when the PtSi film is formed at 350°C. However, the diffraction patterns show only $(1\,\bar{2}\,1)$ orientation when the PtSi films are formed above 450°C. It was found that the electrical barrier height of the Schottky barrier detector formed at 350°C is about 0.02 eV higher than that formed above 450°C. The microstructure of the PtSi film does not change even though the formation temperature is further increased to 550°C. Nevertheless, the higher the formation temperature, the larger is the grain size. It was also observed that the grain size does not change the electrical barrier height. However, the quantum efficiency of the detector is much higher if the grain size is larger. The results indicate that the quantum efficiency of the detector can be improved if the PtSi film has $(1\,\bar{2}\,1)$ orientation and larger grain size. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: PtSi Schottky barrier detector (SBD); HRTEM; Electron diffraction pattern

1. Introduction

The PtSi Schottky barrier detector (SBD) has found applications in the detection window of 3–5 μm. Since its compatible fabrication with standard silicon wafer process, large two-dimensional PtSi arrays combined with charge coupled devices (CCD) readout structure have been reported by several authors [1–4]. The detectors with excellent signal-to-noise ratio, which were fabricated on p-Si(1 0 0) substrate, have been reported in the literature. However, most of the studies were focused on the performance of the detectors. The microstructure effects on the detector performance have not been fully understood yet. It has been reported in Ref. [5] that PtSi film shows two different orientations by two different formation mechanisms for relatively thicker film (i.e. 50 nm). It was shown that Pt_2Si phase is formed first and then transferred to PtSi phase with $(1\,\bar{1}\,0)$ orientation when formed at 320°C. However, the PtSi formation is along the $(1\,\bar{2}\,1)$ plane and undergoes no further change when the PtSi is formed at 400°C. The effect of silicon substrate orientation on the Schottky barrier height of the PtSi detector has been studied by Pellegrini et al. [6]. Their results showed that the Schottky barrier height could have 0.076 eV of difference when the PtSi is formed at different interfaces. It has also been reported that the formation conditions of thin PtSi layer can strongly affect the detector performance [7,8].

In this paper, the microstructure dependence of the PtSi film on the detector performance has been investigated in detail. Both high resolution transmission electron microscopy (HRTEM) and electron diffraction are used to characterize the microstructure of the PtSi film at different formation conditions. The electrical Schottky barrier height is determined by the current–voltage characteristics at different temperatures (*I*–*V*–*T*) under 4 V reverse bias. The quantum efficiency of the Schottky barrier detector is calculated from the responsivity result. It reveals that the electrical barrier heights are different when the PtSi films have different orientations. The quantum efficiency of the detector can be improved when the film formed with $(1\,\bar{2}\,1)$ orientation and larger grain size.

2. Experimental

Fig. 1 is the cross-sectional diagram of the PtSi SBD. In order to reduce the leakage current of the PtSi SBD, an

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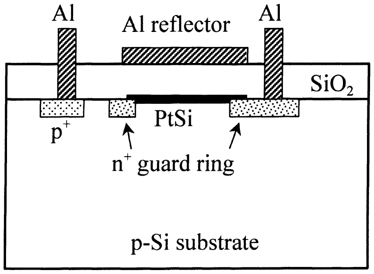

Fig. 1. The cross-sectional diagram of the PtSi Schottky barrier detector.

Table 1
The formation conditions of the PtSi Schottky barrier detectors

Type	Temperature for Pt deposition (T_s)	In situ annealing for PtSi formation
A	350°C	350°C/30 min
B	450°C	450°C/20 min
C	550°C	550°C/10 min

n-type guard ring was provided on the periphery of the detector. An undoped dielectric layer was deposited on the PtSi film to form an optical cavity. The substrate used was p-type Si(1 0 0) with a resistivity of 25–30 Ω cm. Thin Pt films were deposited on Si substrate at different temperatures in an ultra high vacuum chamber. The base pressure of the chamber was 2×10^{-10} mbar. The thickness of the deposited Pt film was in situ monitored by microbalancer quartz crystal. Immediately after the Pt film deposition, the PtSi film was formed through the solid state reaction between Pt and Si at elevated temperature in the same chamber. The formation temperatures of the PtSi film were varied from 350 to 550°C. Table 1 lists the growth conditions of the PtSi film. Three different formation conditions were applied to obtain different microstructure films. The film thickness and uniformity were monitored through high resolution cross-sectional TEM. The plain view of the HRTEM in dark field was used to investigate the characteristics of the PtSi grain. The phase and the orientation of the film were determined from the electron diffraction patterns. In order to measure the electrical characteristics of the Schottky barrier detector, the current–voltage characteristics at different temperatures under 4 V reversed bias were measured at the temperature range from 80 to 150 K. The temperature was monitored by a calibrated Si diode directly attached on the detector carrier. The electrical Schottky barrier height was determined by extracting the slope of the Richardson plot at 4 V reversed bias [9]. The quantum efficiency of the PtSi SBD was measured at 77 K with the method described in Ref. [10].

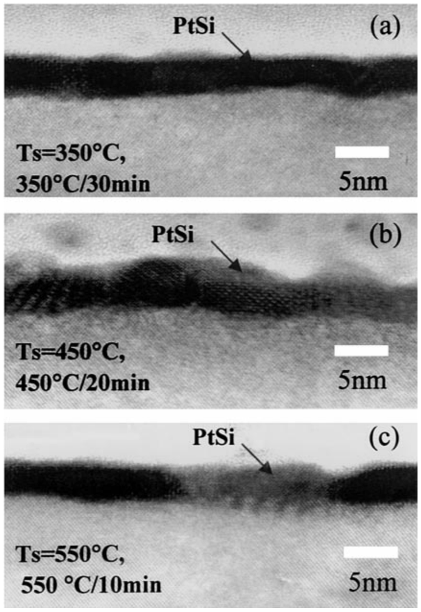

Fig. 2. The high resolution cross-sectional TEM for the PtSi films formed at different growth conditions. The film thickness is 4 nm. (a) Substrate temperature (T_{sub}) is 350°C, annealing condition is 350°C for 30 min; (b) T_{sub} is 450°C, annealing condition is 450°C for 20 min; (c) T_{sub} is 550°C, annealing condition is 550°C for 10 min.

3. Results and discussions

Fig. 2 shows the cross-sectional views of the PtSi films formed at different conditions. The film thickness is about 4 nm on each formation condition. From the plain view pictures of the PtSi films analyzed by HRTEM, see Fig. 3, the PtSi grains are quite different at different formation temperatures. The PtSi grains are observed to have small round shape and relative disorder if the PtSi film is formed at 350°C, as shown in Fig. 3a. However, the round-shape grains seem to turn into small rectangular shape and show orientation when the PtSi is formed at 450°C, as illustrated in Fig. 3b. When the formation temperature is increased to 550°C, the PtSi grains keep the same shape but the grain size is increased when compared to that obtained at 450°C. This result is shown in Fig. 3c. Fig. 4 shows the electron diffraction patterns for these films. All of the diffraction patterns have scattered spots. It indicates that the PtSi films are epitaxially grown on Si(1 0 0) substrate. The diffraction pattern of the PtSi film formed at 350°C shows that the film has both $(1\,\bar{1}\,0)$ and $(1\,\bar{2}\,1)$ orientations, as illustrated in Fig. 4a. This result is consistent with the previous report by Ghozlene et al. [5]. However, for the PtSi film formed at 450 and 550°C, the electron diffraction patterns show that the film is only in $(1\,\bar{2}\,1)$ orientation. The results are illustrated in Fig. 4b and c. The only difference between the two films formed at 450°C and at 550°C is that the diffraction pattern is more repeatable for the film formed at 550°C. It means that the film formed at 550°C is more crystalline than that formed at 450°C. This observation is consistent with the result from the plain view of the HRTEM that the grain size formed at 550°C is much larger than that formed at 450°C. Nevertheless, the X-ray diffraction provides a better method to determine the crystalline quality of the film. However,

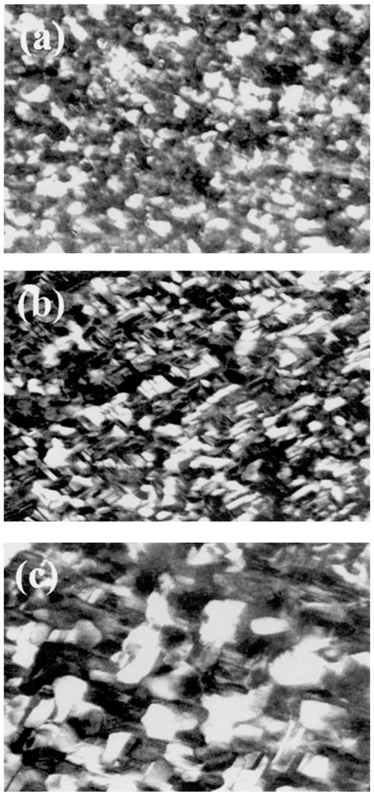

Fig. 3. The plain views of the PtSi grain formed at different conditions. (a) T_{sub} is 350°C, annealing condition is 350°C for 30 min; (b) T_{sub} is 450°C, annealing condition is 450°C for 20 min; (c) T_{sub} is 550°C, annealing condition is 550°C for 10 min.

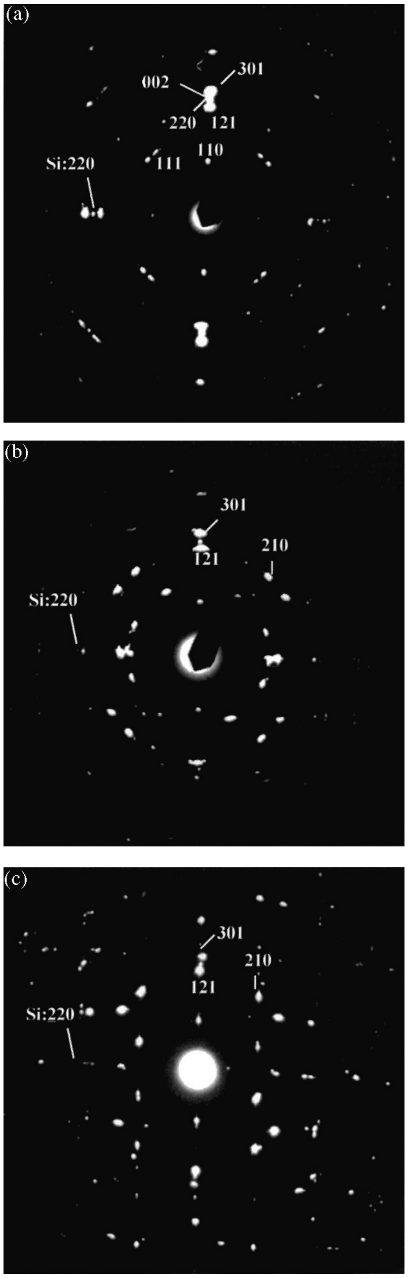

Fig. 4. The electron diffraction patterns of the PtSi grain formed at different conditions. (a) T_{sub} is 350°C, annealing condition is 350°C for 30 min; (b) T_{sub} is 450°C, annealing condition is 450°C for 20 min; (c) T_{sub} is 550°C, annealing condition is 550°C for 10 min.

the diffraction signal is quite small due to the relatively thin PtSi layer (i.e. 4 nm).

The current of the Schottky barrier detector as a function of the applied voltage can be expressed as follows:

$$I = A_e J_s \left[\exp\left(\frac{qV}{nkT} \right) - 1 \right] \tag{1}$$

$$J_s = A^* T^2 \exp\left(-\frac{q\phi_b}{kT} \right) \tag{2}$$

where J_s is the saturation current density, n the ideality factor, A^* the effective Richardson constant, T the device operation temperature, A_e the detector area, and ϕ_b the electrical barrier height of the Schottky diode. The saturation current (I_s) of the PtSi/p-Si Schottky diode can be obtained from the reverse I–V characteristic at different temperatures. It can be expressed as follows:

$$I_s = A_e A^* T^2 \exp\left(-\frac{q\phi_b}{kT} \right) \tag{3}$$

The electrical barrier height can be derived from the slope of the Richardson plot described in Ref. [9]. Fig. 5 shows the Richardson plot of the PtSi/p-Si SBDs under 4 V reversed bias for each formation condition. The electrical barrier height, including the barrier height lowering effect, is derived from the slope of each line. The derived barrier heights are 0.221, 0.201, and 0.200 eV for the PtSi SBDs formed at 350, 450, and 550°C, respectively. This shows that the barrier height of SBD formed at 350°C is about 0.02 eV higher than that formed at 450 and 550°C. The difference is possibly due to the microstructure of the PtSi film. For the PtSi film formed at 350°C, the film has an intermingling of both $(1\,\bar{1}\,0)$ and $(1\,\bar{2}\,1)$ orientations. However, only $(1\,\bar{2}\,1)$ orientation was observed for those PtSi films formed at 450 and 550°C. This indicates that the $(1\,\bar{2}\,1)$ orientated PtSi film has

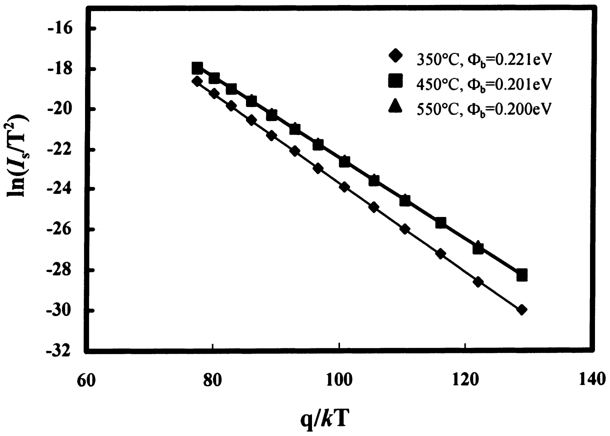

Fig. 5. The Richardson plot of the PtSi/p-Si SBDs operated at 4 V reversed bias voltage for different formation conditions.

larger metal work function than the film with $(1\bar{1}0)$ orientation. Thus, the electrical barrier height of the PtSi/p-Si(1 0 0) diode can be reduced when the film is formed with $(1\bar{2}1)$ orientation. On the other hand, if the formed PtSi films have the same orientation, the barrier heights will remain at the same value even though the grain size is totally different.

Fig. 6a shows the responsivity of the PtSi SBD as a function of wavelength under different formation conditions. The responsivity can be expressed as follows:

$$R = C_1 \left(\frac{h\nu - \varphi_{\mathrm{ms}}}{h\nu}\right)^2 \tag{4}$$

where R is the responsivity, C_1 the quantum efficiency coefficient, φ_{ms} the optical Schottky barrier height, and $h\nu$ the photon energy of the infrared radiation. The optical Schottky barrier height (φ_{ms}) and the quantum efficiency coefficient (C_1) can be determined by the modified Fowler plot, as indicated below:

$$(\eta \times h\nu)^{1/2} = C_1^{1/2}(h\nu - \varphi_{\mathrm{ms}}) \tag{5}$$

where $\eta = Rh\nu$ is the quantum efficiency. The quantum efficiencies calculated from the responsivity measurement at 4 μm wavelength are 0.65, 0.74 and 0.88% for the PtSi films formed at 350, 450, and 550°C, respectively. The theoretical calculations of the responsivity with quantum efficiency of 1 and 0.1% are also included in Fig. 6a for comparison. Fig. 6b shows the quantum efficiency as a function of the wavelength. The lowest quantum efficiency for the case of 350°C formation is attributed to the highest electrical barrier height. This is due to the existence of the $(1\bar{1}0)$ orientation rather than the $(1\bar{2}1)$ orientation. However, the PtSi SBD formed at 550°C has higher quantum efficiency compared to that formed at 450°C even though the electrical barrier height is identical. Since the PtSi film formed at 550°C has larger grain size, the defect states at the grain boundaries are reduced. Therefore, the energy relaxation via defect scattering can be decreased [8]. The emission yield is improved by the reduction of this kind of scattering.

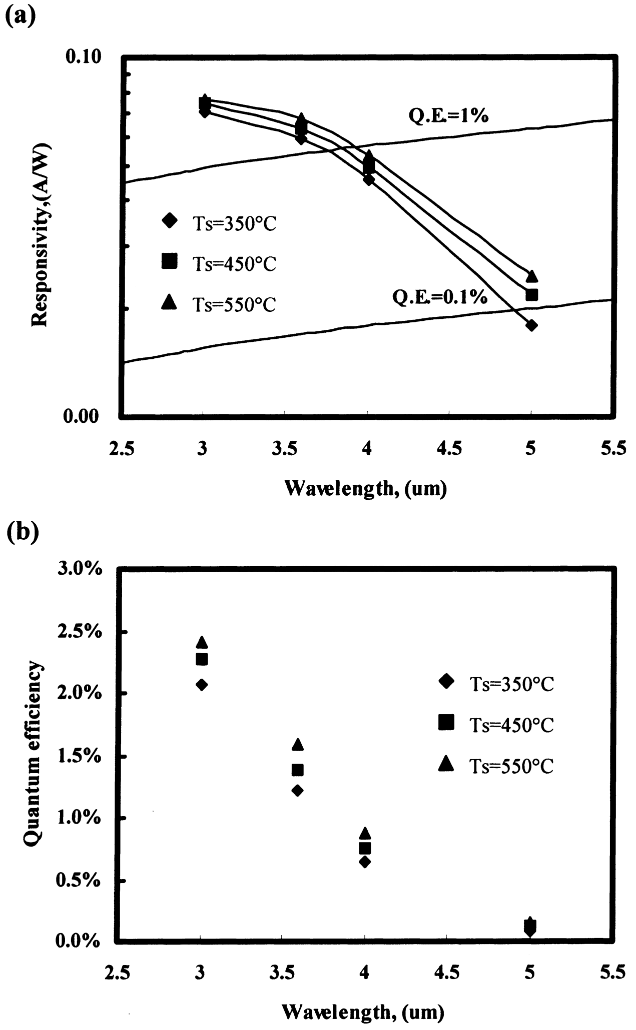

Fig. 6. (a) The responsivity of the PtSi/p-Si SBDs as a function of the wavelength; (b) the quantum efficiency of the PtSi/p-Si SBDs as a function of the wavelength. The SBDs are measured under 4 V reverse bias voltage at 77 K temperature.

4. Conclusions

The microstructures of the PtSi films formed at different formation conditions were investigated by the high-resolution transmission electron microscope and electron diffraction. The microstructure effects on the electrical barrier height and quantum efficiency were also investigated. It is seen that the PtSi film has both $(1\bar{1}0)$ and $(1\bar{2}1)$ orientations when it is formed at 350°C. The existence of the $(1\bar{1}0)$ orientation increases the electrical barrier height of the detector. From the electron diffraction patterns, it is observed that the orientation of the PtSi film formed at 450°C is identical to that formed at 550°C. Although the grain size formed at 550°C is much larger than that formed at 450°C, the electrical barrier heights are the same. However, the quantum efficiency is enhanced when the formed PtSi film has $(1\bar{2}1)$ orientation and larger grain size.

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