

The gaussian distribution of inhomogeneous barrier heights in PtSi/p-Si Schottky diodes

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Abstract: The current-voltage characteristics of PtSi/p-Si Schottky barrier diodes were investigated in the temperature range of 85-136K and their barrier height (ϕ_b), ideality factor (n) and series resistance (R_s) were found to be strongly temperature-dependent. While n decreases, ϕ_b increases with increasing temperature and the conventional activation energy plot deviates from linearity. These discrepancies from ideal thermionic emission theory is attributed to Schottky barrier inhomogeneities and the Schottky barrier inhomogeneities are shown to obey a single Gaussian distribution with a mean value of 0.4548 eV and a standard deviation of 0.0607 eV. The modified activation plot which takes into account the barrier height variations through the Gaussian distribution is acceptably linear and gives $(\overline{\phi_b})$ and A^* as 0.4546 eV and $31.47 \text{ Acm}^{-2}\text{K}^{-2}$ respectively.

Keywords: Schottky barrier diodes, temperature dependence, barrier inhomogeneities, gaussian distribution

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Platinum Silicide films are extensively used in silicon devices to form Schottky barriers and ohmic contacts. Infrared detection is a special application of PtSi/p-Si Schottky barrier. PtSi/p-Si detector has received a lot of attention as the most promising infrared sensor for large focal plane array applications due to its ease of fabrication, uniformity, compatibility with today's IC technology and low cost [1].

The I–V–T analysis of Schottky diodes using pure thermionic emission theory usually reveals some abnormal behaviors such as the decrease of barrier height (BH) and increase of ideality factor with decreasing temperature and the nonlinearity of the Richardson plot over a wide temperature range. Some authors have attributed the discrepancies to the barrier inhomogeneities [2]. Various types of distribution functions have been used to describe BH inhomogeneities, among them Gaussian distribution has been widely accepted and used. Chand and Kumar [3] have analyzed the I–V characteristics of Pd₂Si/n – Si Schottky diode and interpreted its abnormal behavior on the basis of the thermionic emission-diffusion theory and the assumption of a Gaussian distribution of barrier height. Similar works have been done on various Schottky diodes [4, 5].

In this work, first we investigated the temperature-dependency of electrical parameters of PtSi/p-Si Schottky diodes using their current-voltage (I–V) characteristics which was measured in the temperature range of 85–136K. Experimental results showed that ideality factor, barrier height and series resistance were strong functions of temperature. Then the temperature dependence of the I–V characteristics of Schottky barrier diodes was explained on the basis of the thermionic emission theory with a Gaussian distribution of the inhomogeneous barrier heights.

2 Experiment

The diodes were fabricated on p-type (100) Si substrate with resistivity of 4–11 Ωcm . The samples were chemically cleaned using the standard RCA cleaning procedure and rinsed in deionized water and dried. Before ohmic contacts formed on the p-type Si substrates, the samples were dipped in dilute HF:H₂O (1:10) for about 3 min to remove any native oxide layer on the surface, and finally the samples were rinsed with deionized water and

dried with high purity nitrogen and inserted into the deposition chamber immediately after cleaning. To form ohmic contacts we thermally evaporated high purity Al with a thickness of 2060 Å on the surface of the samples at the pressure of 10^{-5} mbar and then annealed the evaporated Al at 550 °C for 5 min at the pressure of 7×10^{-6} mbar. All the metal depositions were done through metal shadow masks. To fabricate PtSi layer, Pt film with a thickness of 80 Å was evaporated with an electron gun system on the cleaned Si surfaces and samples were annealed in a vacuum of 7×10^{-6} mbar at 470 °C for 30 min. To form the metal electrodes (rectifier and ohmic contacts), Al usually have been used. But Al has high diffusion ability and can lead to degradation of the contacts therefore in this work to prevent the problem of Al diffusion into Si, we used Ti as a diffusion barrier between PtSi and Al. 800 Å of Ti was evaporated on PtSi layer at the pressure of 10^{-6} mbar and finally, Al films of 3000 Å thickness were evaporated on Ti layer.

For the I-V measurement, the device was mounted on the cold work surface of a Dewar at liquid nitrogen temperature. An HP 4145B instrument was used to measure the I-V characteristics at the PtSi SBD.

3 Results and discussion

3.1 Current-voltage characteristics of the PtSi/p-Si diode

For a Schottky barrier diode with assumption that the current is due to thermionic emission, the relation between the applied voltage and current can be expressed as [6]

$$I = I_o \exp\left(\frac{qV}{nkT}\right) \left[1 - \exp\left(\frac{-qV}{kT}\right)\right] \quad (1)$$

Eq. (1) for $V > 3kT/q$ can be written as:

$$I = I_o \exp\left(\frac{qV}{nkT}\right) \quad (2)$$

where T is the temperature in Kelvin, q the electronic charge, k is the Boltzmann constant and I_o is the reverse saturation current which can be written as:

$$I_o = AA^*T^2 \exp\left(\frac{-q\phi_b}{kT}\right) \quad (3)$$

where A is the effective diode area, A^* is the effective Richardson constant which is equal to $32 \text{ Acm}^{-2}\text{K}^{-2}$ for p-Si and ϕ_b is the zero-bias barrier height. In Eq. (2), n is the ideality factor which is a parameter generally used to measure the deviation of practical diodes from ideal thermionic emission model.

Fig. 1(a) shows the experimental I-V characteristics of our PtSi/p-Si diode at the temperature of 85K in dark. It can be seen from Fig. 1(a) that the current curve in forward bias quickly becomes dominated by series resistance and deviates from linearity. Series resistance R_s which is an important parameter in the electrical characteristics of Schottky barrier diodes is the total resistance of bulk of the semiconductor, contact wires and ohmic contacts. For evaluating n, ϕ_b and R_s , we modeled the real Schottky diode with

an ideal diode in series with a resistance R_s . According to thermionic emission theory, V_D which is the voltage across the metal-semiconductor interface in the Schottky diode can be written as

$$V_D = \frac{nkT}{q} \ln \left(\frac{I}{AA^*T^2} \right) + n\phi_b \quad (4)$$

And V which is the applied or experimentally measured voltage in the Schottky diode circuit considering the equation $V = V_D + R_s I$ can be expressed as

$$V = \frac{nkT}{q} \ln \left(\frac{I}{AA^*T^2} \right) + n\phi_b + IR_s \quad (5)$$

Using Eq. (5) and the (I, V) experimental data, n , ϕ_b and R_s can be determined.

I-V characteristics of diode have been measured in the temperature range of 85-136K. The values of n , ϕ_b and R_s determined from the method described above are shown in Table I for each temperature. It is obvious that the values of n , ϕ_b and R_s are strong functions of temperature.

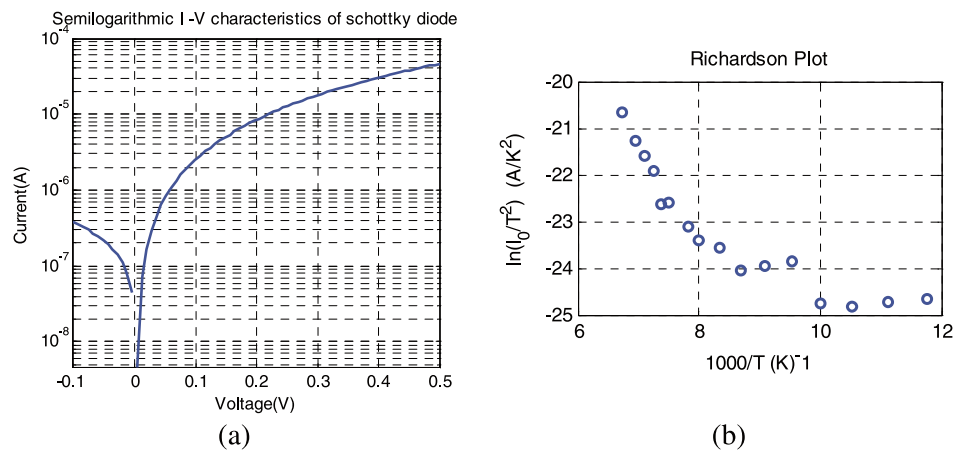


Fig. 1. (a) I-V characteristics of the PtSi/p-Si Schottky diode at the temperature of 85K in dark and (b) Conventional activation energy plot of the PtSi/p-Si diode.

It can be seen from the experimental data given in Table I that series resistance R_s strongly varies with temperature. The increase of series resistance with the fall of temperature is believed to result from lack of free charge carriers at low temperatures [7]. In our case the large values of R_s at low temperatures can also be attributed to the nonideality of the ohmic contact.

It is also clear from Table I that with increasing temperature, barrier height is increased while ideality factor decreased.

Barrier height can also be evaluated by using the Arrhenius or Richardson plot of the saturation current. By taking the natural logarithm of Eq. (3), we will have

$$\ln \left(\frac{I_0}{T^2} \right) = \ln(AA^*) - \frac{q\phi_b}{kT} \quad (6)$$

Table I. Temperature dependent values of various experimental parameters obtained from I–V measurements of PtSi/p-Si Schottky diode.

Temperature(Kelvin)	Barrier height (eV)	Ideality factor	Series resistance ($K\Omega$)
85	0.2044	2.9082	15.033
90	0.2163	2.8613	14.629
95	0.2296	2.7195	14.519
100	0.2412	2.702	14.023
105	0.2451	2.6743	10.426
110	0.2576	2.6401	10.426
115	0.2702	2.6278	10.426
120	0.2772	2.5945	8.129
125	0.2869	2.5626	7.455
128	0.2907	2.5171	6.343
133	0.2971	2.1903	5.115
136	0.3019	2.158	5.115

Plotting $\ln(I_o/T^2)$ versus q/kT should give a straight line which its slope and intercept will give barrier height and Richardson constant respectively. Fig. 1 (b) Shows the conventional activation energy ($\ln(I_o/T^2)$ versus $1000/T$) plot, for the PtSi/p-Si diode based on the experimental data in Table I. It can be seen that the curve strongly deviates from linearity.

The discrepancies from classic thermionic emission theory observed in our PtSi/p-Si Schottky diode such as the increase of barrier height with increasing temperature and the nonlinearity of the activation energy plot can be remedied by considering spatial inhomogeneity of SBH. The spatial inhomogeneity is usually described by some distributed functions, among them Gaussian distribution is the most successful model to explain the non-ideal behavior of Schottky diodes.

3.2 Gaussian distribution of barrier heights and modified Richardson plot

To explain the abnormalities observed in our Schottky diodes, we considered the barrier inhomogeneous, consisting of various patches of relatively lower or higher barriers with respect to a mean value.

Now, using the assumption above, the temperature dependence of barrier height can be attributed to inhomogeneity of barrier height. Since current transport across metal-semiconductor interface is a temperature-activated process, at low temperatures electrons are able to surmount the low barriers and therefore current transport will be dominated by current flowing through patches of lower SBH and a larger ideality factor. In other words, as the temperature increases more electrons have sufficient energy to overcome the higher barrier. Therefore the dominant barrier height will increase with the rise of temperature [2].

We modeled the barrier height inhomogeneities with a Gaussian distribution having a mean value $\bar{\phi}_b$ and standard deviation of δ_s which is expressed as

$$P(\phi_b) = \frac{1}{\delta_s \sqrt{2\pi}} \exp \left[-\frac{(\phi_b - \bar{\phi}_b)^2}{2\delta_s^2} \right] \quad (7)$$

The total current across a Schottky diode containing barrier inhomogeneities can be written as

$$I(V) = \int_{-\infty}^{+\infty} I(\phi_b, V) P(\phi_b) d\phi_b \quad (8)$$

where $I(\phi_b, V)$ is the current for a barrier of height ϕ_b at voltage V based on the ideal thermionic theory and $P(\phi_b)$ is the normalized distribution function giving the probability of the occurrence of barrier height ϕ_b . By introducing $I(\phi_b, V)$ and $P(\phi_b)$ from Eqs. (1) and (7) in Eq. (8) the current of the Schottky diode with the modified barrier will be

$$I(V) = AA^*T^2 \exp \left[\frac{-q}{kT} \left(\overline{\phi_b} - \frac{q\delta_s^2}{2kT} \right) \right] \times \exp \left(\frac{qV}{n_{ap}kT} \right) \left[1 - \exp \left(\frac{-qV}{kT} \right) \right] \quad (9)$$

Comparing Eqs. (1) and (9) leads to an expression for the apparent barrier height ϕ_{ap} as a function of the mean barrier and temperature.

$$\phi_{ap} = \overline{\phi_b} - \frac{q\delta_s^2}{2kT} \quad (10)$$

According to Eq. (10), the plot ϕ_{ap} versus $q/2kT$ should be a straight line with the intercept determining $\overline{\phi_b}$ and the slope giving δ_s . By using the barrier heights obtained from I-V measurements (Table I) the ϕ_{ap} versus $q/2kT$ plot is made and shown in Fig. 2(a). It is obvious that the data fit nicely with a straight line and the intercept and slope of this straight line yields values for $\overline{\phi_b}$ and δ_s of 0.4548 eV and 0.0607 in the 85-159K range.

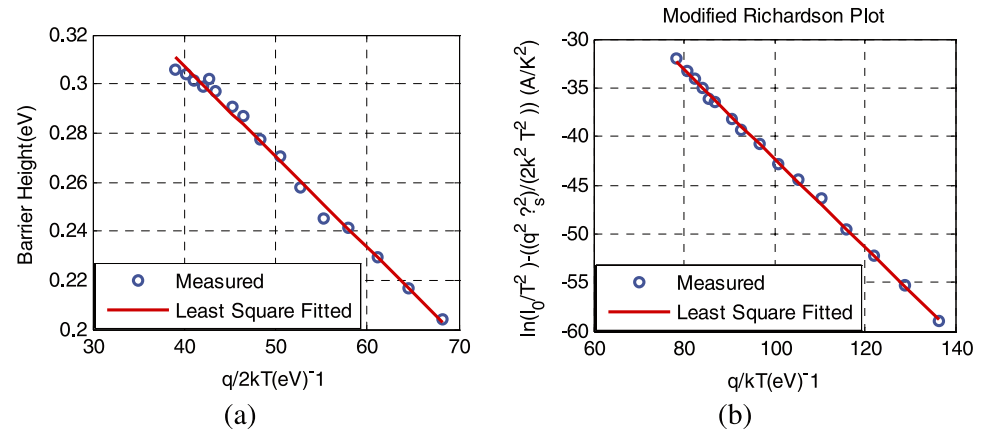


Fig. 2. (a) ϕ_{ap} versus $q/2kT$ curve and (b) Modified Richardson $\ln(I_0/T^2) - (q^2\delta_s^2/2k^2T^2)$ versus q/kT plot for the PtSi/p-Si Schottky diode.

It was shown before in this paper that the conventional activation energy plot of the PtSi/p-Si diode deviates from linearity. To explain this discrepancy, Eq. (6) can be rewritten considering Eq. (10) as

$$\ln \left(\frac{I_0}{T^2} \right) - \left(\frac{q^2 \delta_s^2}{2k^2 T^2} \right) = \ln(AA^*) - \frac{q\overline{\phi_b}}{kT} \quad (11)$$

and based on this equation the modified activation energy plot $(\ln(I_o/T^2) - (q^2\delta_s^2/2k^2T^2))$ versus q/kT is made. This plot takes into account the variations of the barrier height and should give a straight line with the slope directly yielding the mean barrier $(\overline{\phi_b})$ and the y-axis intercept $\ln(AA^*)$ giving Richardson constant (A^*). Fig. 2 (b) shows the modified activation plot for PtSi/p-Si diode which is acceptably linear and from the slope and intercept of the fitted straight line $\overline{\phi_b}$ and A^* were determined to be 0.4546 eV and $31.47\text{ Acm}^{-2}\text{K}^{-2}$ respectively. The value of $\overline{\phi_b}$ matches exactly with mean barrier height obtained from the ϕ_{ap} versus $q/2kT$ plot earlier and the value of Richardson constant is in great agreement with the theoretical value of $32\text{ Acm}^{-2}\text{K}^{-2}$ for p-type Si.

4 Conclusion

In this paper the I-V characteristics of PtSi/p-Si Schottky diodes were measured in the temperature range of 85-136K. The electrical parameters of the diode such as ideality factor and barrier height were found to be strongly temperature-dependent. These departures from the classic thermionic emission theory can be well described by assuming the existence of barrier height inhomogeneities and modeling them with a Gaussian distribution. Using the ϕ_{ap} versus $q/2kT$ plot, the mean value and standard deviation of the Gaussian distribution of barrier heights were determined to be 0.4548 eV and 0.0607 eV respectively. The activation energy plot was seen to deviate from linearity but the modified Richardson plot which considers the Gaussian distribution of barrier heights can be fitted nicely with a straight line. The mean barrier height and the Richardson constant from the modified Richardson plot were determined to be 0.4546 eV and $31.47\text{ Acm}^{-2}\text{K}^{-2}$. The value of Richardson constant obtained from the modified Richardson plot is very close to the known value of $32\text{ Acm}^{-2}\text{K}^{-2}$ for p-type Si. The linearity of the modified activation plot and the closeness of the calculated Richardson constant to its theoretical value are good reasons for the success of the Gaussian distribution model in explaining the temperature dependence of I-V characteristics of the PtSi/p-Si Schottky barrier diodes.