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Influence of He-ion irradiation on the characteristics of Pd/n-$Si_{0.90}Ge_{0.10}$/Si Schottky contacts

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Abstract
Current–voltage (I–V) and capacitance–voltage (C–V) characteristics of He-ion irradiated Pd/n-$Si_{09}Ge_{0.10}$ Schottky contacts have been measured in the temperature range from 100 to 300 K. Schottky barrier properties such as the Schottky barrier height (Φ_{bn}) and ideality factor (n) have been studied as a function of temperature. The degree to which their characteristics deviated from the ideal case increased as the temperature decreased. A decrease in Φ_{bn} and an increase in n with decreasing temperature are observed. Additionally, linear dependence between the so-called temperature factor T_0 and temperature as well as between Φ_{bn} and n are shown. This type of strong temperature dependence indicates the presence of a large degree of lateral inhomogeneities of the barrier height, resulting from the He-ion irradiation induced defects and traps which produce a variation in the number of free carriers. The presence of electrically active defects introduced by He-ion irradiation at and below the $Si_{0.90}Ge_{0.10}$ surface support this interpretation.

1. Introduction

There has been considerable interest in integrating high speed and novel devices made from $Si_{1-x}Ge_x$ materials [1], since the alloy is compatible with the silicon based technology. The band structure of strained layers can be engineered by varying the Ge concentration, which has made it possible to fabricate a large family of devices such as heterojunction bipolar transistors [2], modulation doped field effect transistors [3] and infrared photodetectors [4]. In compound semiconductors, ion implantation is particularly attractive due to its many promising applications in integrated devices and is widely used during several electronic devices fabrication steps. In particular, ion implantation is used to improve the fast switches [5] and the performance of photodiodes [6]. Moreover, it is well known that ion implantation into semiconductor materials has a profound influence on the structural and electronics properties of their surface and subsurface region, and hence governs the characteristics of metal contacts formed on the semiconductor [7]. It has been also shown that ion implantation induces defects in the band gap which affects the free carriers concentration and leads to an increase (decrease) of barrier height in p-type (n-type) semiconductors [8, 9]. The knowledge of the influence of radiation damage on the Schottky barrier diodes (SBDs) performance is a fundamental field of research, having technological relevance for many applications in the semiconductor electronic devices. The influence of ion implantation induced changes of Schottky barrier height (SBH) in silicon and GaAs has been reported [10, 11]. However, improving the SiGe based device processing requires an understanding of the electrical properties of Metal/$Si_{1-x}Ge_x$/Si SBDs subjected to ion implantation. It is, therefore, imperative to investigate the effect of ion implantation on the electrical characteristics of Metal/$Si_{1-x}Ge_x$/Si SBDs. Although the electrical characterization of Schottky barrier junctions (SBJs) fabricated on non-implanted $Si_{1-x}Ge_x$ samples is well conducted [12–14], little is known about the effect of ion irradiation on the electrical properties of Schottky diodes fabricated on $Si_{1-x}Ge_x$. Moreover, most of the studies of SBDs on $Si_{1-x}Ge_x$ were limited to the effect of Ge-content on the SBH. In previous studies we have demonstrated that the barrier height either of W or Sc on p-type $Si_{1-x}Ge_x$ alloys varies with x and indicates the same variations as the band gap, while the barrier height on n-$Si_{1-x}Ge_x$ with Fe, Pd and Pt metals does not change with both Ge-content and strain relaxation, indicating that the Fermi level at the interface is pinned with respect to the conduction band edge [14, 16, and references therein]. In most of the previous investigations, the SBH was determined at room temperature by measuring the forward and reverse current as well as the capacitance of the SBJ. Important additional information can be obtained from the temperature dependence of the forward and reverse as well as the capacitance characteristics.

In this paper, the effect of He-ion irradiation on Pd/n-$Si_{0.90}Ge_{0.10}$ SBD was studied. The decrease in the barrier height after ion irradiation can be correlated with the modification of free carriers concentration at the Pd/n-$Si_{0.90}Ge_{0.10}$ interface induced by the He-ion irradiation. We also report on the temperature dependent SBHs fabricated on He-ion irradiated n-$Si_{0.90}Ge_{0.10}$ and the impact of this irradiation on the conduction mechanism in Pd/n-$Si_{0.90}Ge_{0.10}$ SBDs. We show that the measured temperature dependent SBHs and idealities factor can be explained in terms of inhomogeneities due to the presence of defects introduced by high energy He ions irradiated Pd/n-type $Si_{0.96}Ge_{0.10}$ SBD.

2. Experimental details

Phosphorous-doped (∼8×10^{16} cm^{-3}) n-type (001) oriented, $Si_{0.90}Ge_{0.10}$ layers grown by chemical vapour deposition (CVD) on a lightly doped (4–6 × 10^{16} cm^{-3}) Si buffer layer which was grown on an n^+-Si substrate were used for this study. The Ge-content (x = 0.10) was determined by Rutherford backscattering spectrometry (RBS) and was found to be uniform within the SiGe epilayers. The thickness of the $Si_{0.90}Ge_{0.10}$ epilayer was 480 nm. Since this thickness was slightly higher than its critical thickness, the $Si_{0.90}Ge_{0.10}$ epilayer was partially relaxed [16]. From x-ray diffraction measurements, it was confirmed that there was a partial relaxation in the n-$Si_{0.90}Ge_{0.10}$ epilayers and the relaxation factor was determined to be about 22% [16]. After chemical cleaning, circular palladium (Pd) contacts, 0.77 mm in diameter and 200 nm thick were resistively evaporated on the n-type $Si_{0.90}Ge_{0.10}$ through a metal contact mask. SBDs fabricated on clean SiGe samples were irradiated with 5.4 MeV He ions from an ^{241}Am source to the fluence of 8×10^{11} cm^{-2} at a dose rate of 7.1×10^6 cm^{-2}s^{-1}. For comparison purpose, the control diode (unirradiated Pd/n-$Si_{0.90}Ge_{0.10}$ SBD) was fabricated under identical experimental conditions. The SBDs were electrically characterized by current–voltage (I–V) and capacitance–voltage (C–V) measurements at various temperatures ranging from 100 to 300 K. The details of all I–V and C–V measurements at various temperatures were performed using a set-up as described elsewhere [17].

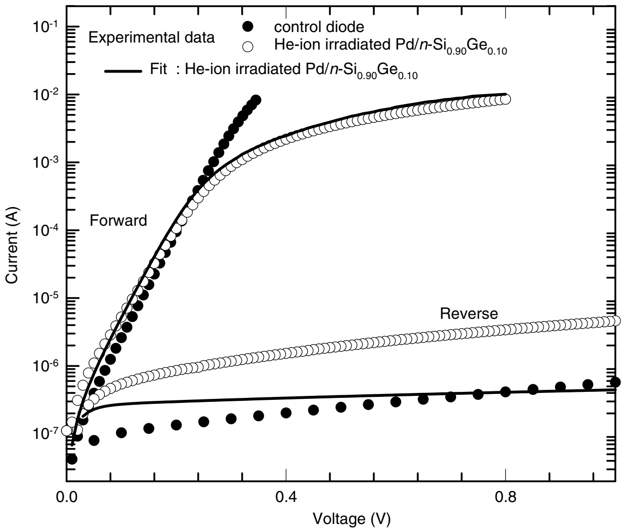

Figure 1. Forward and reverse I–V characteristics at room temperature (300 K) of He-ion irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ SBD, as well as control Pd/n-$Si_{0.90}Ge_{0.10}$ SBD.

3. Results and discussion

3.1. *I–V and C–V characteristics*

The electrical behaviour of He-ion irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ Schottky contacts (referred to as irradiated diode) was characterized by current–voltage and capacitance–voltage measurements. Figure 1 shows an example of the forward and reverse I–V characteristics at room temperature (T∼298 K) of the irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ SBDs. The I–V characteristics at room temperature of the Pd SBDs fabricated on unirradiated Pd/n-$Si_{0.90}Ge_{0.10}$ (referred to as control diode) are also shown in this figure. For both the diodes, the forward log(I)–V characteristics are found to be linear over a large range of voltage and only limited by the series resistance effect. The I–V characteristics exhibit roughly ideal behaviour and can be described by the thermionic emission theory. The current through the metal–semiconductor interface due to the thermionic emission (TE) theory can be expressed as [18]:

$$I = I_s \left[\exp\left(\frac{q(V - R_s I)}{n k_B T} \right) - 1 \right], \tag{1}$$

where

$$I_s = A^* S T^2 \exp\left(-\frac{\Phi_{0bn}}{k_B T} \right), \tag{2}$$

where Φ_{0bn} is the effective barrier height at zero bias, A^* the Richardson constant calculated by assuming a linear dependence on Ge-content, S the area of the diode, T the temperature of the metal/semiconductor junction, k_B the Boltzmann constant, n the ideality factor of the diode and R_s the series resistance. The Schottky barrier height obtained from I–V data does not correspond to the full SBH, since, for instance, the barrier lowering effect and the contribution of βE_m [18, 19] are not considered (E_m is the electric field at the interface and β a constant, which is a function of the interface state density and interface layer thickness, i.e. related to the quality of the interface). The full SBH is the barrier height at zero electric field E_m at the metal–SiGe interface and is determined by taking into account the image force lowering $\Delta\Phi_{bi}$ and βE_m and therefore, it does not depend on the doping concentration.

In the control diode, the ideality factor n is 1.08 as determined by the Werner method [20] and the effective barrier height Φ_{0bn} is 0.69 as determined by extrapolation of the forward characteristic to 0 V. After He-ion irradiation, the ideality factor, n, is determined to be 1.09 and a decrease of the barrier height to 0.67 eV is observed. Comparison between I–V characteristics of control and irradiated diodes reveals first that the quality (in term of ideality factor and effective barrier height) of the control diode was slightly superior to that fabricated on the He-ion irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ SBD. Second, figure 1 shows that higher series resistance and higher reverse current were obtained for He-ion irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ SBD compared with the control diode. From capacitance measurement (not shown here), it is worth noting that $1/C^2$ is almost a linear function of reverse bias for the control diode, indicating a uniform doping concentration within the depletion layer. While for the He-ion irradiated SBD, $1/C^3$ is found to be a linear function of bias (see figure 2), which would indicate a linearly graded junction. The ionized doping level as determined from C–V characteristic is not uniform and is slightly higher for He-ion irradiated SBD compared with that determined for control diode. Extracted barrier heights and ideality factors of control and irradiated SBDs as well as their average ionized doping levels are displayed in table 1. The flat band barrier height Φ_{Fbn} determined at zero electric field and given by the relation [21]:

$$\Phi_{Fbn} = n\Phi_{0bn} + (n-1)k_bT \ln \frac{N_D}{N_C} \qquad (3)$$

is also indicated in table 1, where N_C is the effective density of states in the conduction band, N_D the average donor density

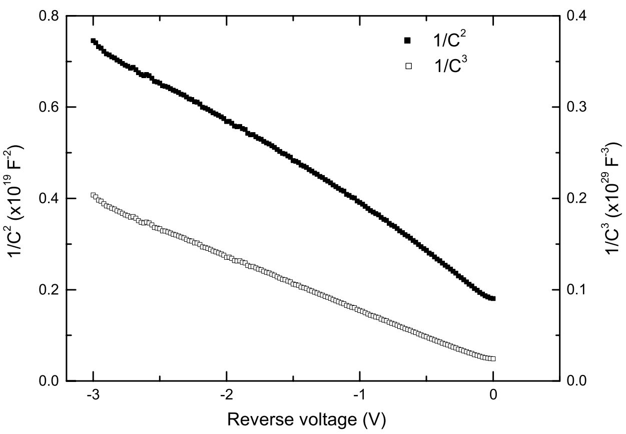

Figure 2. $1/C^2$ and $1/C^3$ versus V plots for He-ion irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ SBD measured at room temperature (300 K).

and the other entries as defined above. This flat band barrier height which is determined at zero electric field does not vary upon doping and is therefore the fundamental barrier height. The TE is also supposed to govern current transport at the reverse characteristic and the saturation current (I_s) could be determined from the measurement of the current at a reverse voltage V_R. I_s is described by [18]:

$$I_s \approx I(V_R) = A^*ST^2 \exp\left(-\frac{\Phi_{bn}(V_R)}{k_BT}\right), \qquad (4)$$

where $\Phi_{bn}(V_R)$ is an effective barrier height which depends on the voltage through the image force lowering $\Delta\Phi_{bi}(V) = \sqrt{qE_m/4\pi\varepsilon_{sc}}$ and on the contribution of βE_m. The calculated image force lowering $\Delta\Phi_{bi}(V)$ for both SBDs at $V = 0$ and $V_r = 1$ V are listed in table 1.

To investigate the origin of the difference of SBDs characteristics between the control diode and the irradiated one, we analysed carefully figure 1 and table 1. From the inspection of figure 1 and table 1, it is seen that the ideality factor is close to 1.08 at room temperature for both SBDs, indicating that TE is the dominating conduction mode in our SBDs. The decrease of the barrier height in the He-ion irradiated SBD with respect to the control diode can be understood by noting that He-ion processing introduces donor-like defects in the near surface region of the $Si_{0.90}Ge_{0.10}$ material. This result is consistent with the generally accepted trend of increase or decrease in the barrier height of diodes fabricated on p- or n-type substrates, respectively. A model concerning the increase of barrier height of diodes fabricated on ion processed p-type semiconductor can be found in reference [22]. We have previously observed the latter effect on p-type $Si_{1-x}Ge_x$ [15]. The change in the effective barrier height results from the change in image force lowering on the processing induced doping modification. The induced variation in the doping concentration after irradiation will influence the image force barrier lowering which in turn leads to lower effective barrier height. The latter effect is in fact more pronounced for barrier height extracted from reverse current. Therefore, as seen in table 1, a large difference in barrier heights between Φ_{0bn} (0 V) and Φ_{bn} (1 V), determined from forward and reverse characteristics, respectively, was observed for He-ion irradiated SBD and could not be quantitatively explained by only the image force effect. Whereas the difference in barrier height between Φ_{0bn} (0 V) and Φ_{bn} (1 V) for control diode is well accounted for by the image force effect. The reason for the large difference in the barrier height between Φ_{0bn} (0 V) and Φ_{bn} (1 V) in He-ion irradiated diode could be either due to the presence of an interfacial layer and then surface states through the contribution of βE_m or contribution of recombination–generation (RG) current or both

Table 1. Electrical properties Pd/n-$Si_{0.90}Ge_{0.10}$/Si control diode and He-ion irradiated Pd/n-$Si_{0.90}Ge_{0.10}$/Si

SBDs Pd/n-$Si_{0.90}Ge_{0.10}$	n	Φ_{0bn} (0 V) forward I–V (eV)	Φ_{bn} (1 V) reverse I–V (eV)	Average N_D (cm^{-3})	$\Delta\Phi_{ibn}$ (0 V) (meV)	$\Delta\Phi_{ibn}$ (1 V) (meV)	Φ^a_{Fbn} (eV)
Control diode	1.08	0.69±0.01	0.65±0.01	1.0×10^{17}	46±5	52±5	0.73±0.01
Irradiated diode	1.09	0.67±0.01	0.59±0.01	2.5×10^{17}	58±5	65±5	0.72±0.01

[a] Room temperature flat band barrier as determined from $\Phi_{Fbn} = n\Phi_{0bn} + (n-1)k_bT \ln \frac{N_D}{N_C}$.

contributions [18]. In order to get further insights into the conduction mechanism of reverse characteristics through the irradiated contact, we calculated the reverse current including the image force lowering of He-ion irradiated diode and the result is shown by the solid line in figure 1. Obviously, there is no agreement between the experimental and the calculated reverse current. Although the ideality factor n for He-ion irradiated SBD is close to the unity and the dominant conduction mode is TE in the forward characteristic, it is likely that deep levels can act as recombination centres and often play the role of carrier recombination in the reverse characteristic at room temperature. The flatband barrier height, which is obtained by modifying the measured zero barrier height from forward current, is more meaningful. By doing so, using equation (3), the flatband barrier heights at room temperature for control and irradiated SBDs were determined from forward I–V measurement to be 0.73 and 0.72 eV, respectively.

On the other hand, we modelled the forward I–V data of irradiated diode by assuming that the current consists of TE and RG, including series resistance effect:

$$I \approx I_{\mathrm{TE}} + I_{\mathrm{RG}} = I_{\mathrm{s}}\left[\exp\left(q\frac{(V - IR_{\mathrm{s}})}{nk_{\mathrm{B}}T}\right) - 1\right] + I_{\mathrm{g}}\left[\exp\left(q\frac{(V - IR_{\mathrm{s}})}{2k_{\mathrm{B}}T}\right) - 1\right], \quad (5)$$

where I_{S} is the saturation current for TE as defined above, I_{g} the saturation current for RG given by $\approx qSn_{\mathrm{i}}W/2\tau$, n_{i} the intrinsic carrier concentration, W the depletion width and τ the effective carrier lifetime. The ideality factor is equal to 2 in the case of RG. The other symbols have their usual meaning. Good fits (solid line in figure 1) could, however, be obtained by using only the TE term in equation (5) with $I_{\mathrm{s}} = 2 \times 10^{-7}$ A, $n = 1.09$ and $R_{\mathrm{s}} = 50\Omega$ indicating again here that the conduction mode is pure TE in He-ion irradiated SBD.

On the basis of the results presented above (both reverse and forward I–V), we believe that He-ion irradiation induced defects into n-$Si_{0.90}Ge_{0.10}$ lead to spatially inhomogeneous Schottky contacts, to a degree which may depend on the processing conditions, i.e. dose, ion mass and energy. Irradiation can cause metallurgical effects between the metal and the semiconductor as well as non-uniform interfacial charges and defects which may induce interfacial inhomogeneities at the Schottky contacts. Defects introduced in n-$Si_{0.96}Ge_{0.04}$ by He-ion irradiation have been characterized and identified using deep level transient spectroscopy [23]. These defects produce a variation in dopant surface concentration at and below the interface which in turn leads to a certain level of lateral barrier inhomogeneities at the Schottky contacts [24]. The presence of inhomogeneities at the irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ Schottky contact will be verified below by the presentation of I–V–T results.

3.2. I–V–T characteristics

In this section, the I–V–T results for He-ions processed Pd/n-$Si_{0.90}Ge_{0.10}$ will be discussed. The I–V–T measurements may provide complementary information to the non-idealities of the Pd/n-$Si_{0.90}Ge_{0.10}$ Schottky contact subjected to He-ion irradiation. Figure 3 illustrates the temperature dependent current–voltage (100–300 K) curves for the irradiated diode.

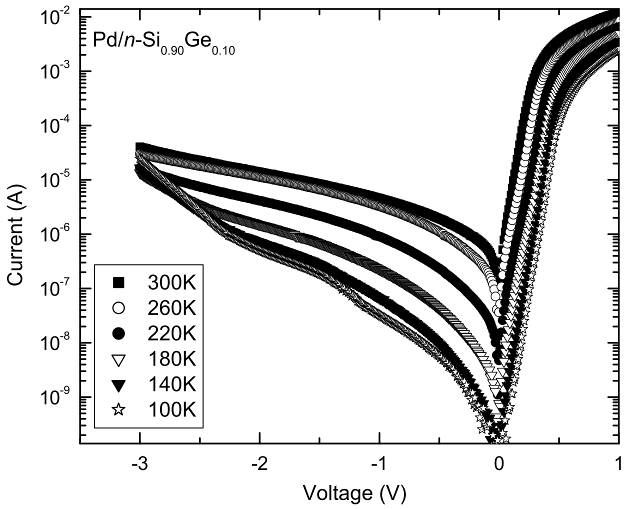

Figure 3. I–V characteristics of He-ion irradiated Pd/n-$Si_{09}Ge_{0.10}$ Schottky diodes measured at different temperatures (100–300 K).

The I–V–T curves appear linear on the semilog plot. The ideality factor at different temperature was extracted using the Werner method [20], while the saturation current I_{s} was calculated from the linear portion intercept of $\log I$ at $V = 0$ and the zero barrier height was calculated with the help of equation (2) using I_{s} values at the different temperature. Above 200 K, the variations of the SBH and the ideality factor with temperature are limited. Below 200 K, we have observed a respective increase and decrease in the ideality factor and the barrier height. Similar trends have already been reported recently for contacts on other semiconductors and have been explained by assuming lateral inhomogeneities at the interface [25–28]. The temperature dependence of the ideality factor $n(T)$ has been frequently found to have the form of $n(T) = 1 + (T_0/T)$, where T_0 is constant, independent of temperature [29–31]. From this equation, one can obtain that $T_0 = (n - 1)T$. By plotting T_0, as determined from our data, as function of T (see figure 4), it is found that T_0 has the form

$$T_0 = T_0^* + \alpha T \quad (6)$$

and is linearly dependent on T, where T_0^* is found to be 289 K and the constant $\alpha = -0.92$. As can be seen from figure 4, in the temperature range between 240 and 300 K, the T_0 parameter lies between 60 and 30 K which is in accordance with the reported T_0 values in Si [24] and GaAs [32]. Such strong temperature dependence of T_0, which to the best of our knowledge has never been reported before, results from the stronger dependence of n and Φ_{bn} on temperature and suggests a large degree of interfacial inhomogeneities in the He-ions irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ Schottky contact. Based on the physical meaning of the T_0 anomaly which is attributed to the temperature equivalent of the narrowing of the Gaussian barrier distribution upon the application of a bias voltage [24], the observed variation of the so-called T_0 parameter with temperature suggests a temperature dependence of the standard deviation of the barrier distribution with the applied voltage at inhomogeneous Schottky contacts and hence a variation of the lateral inhomogeneities with temperature. According to Werner *et al* [24], the large observed increase of T_0 at low

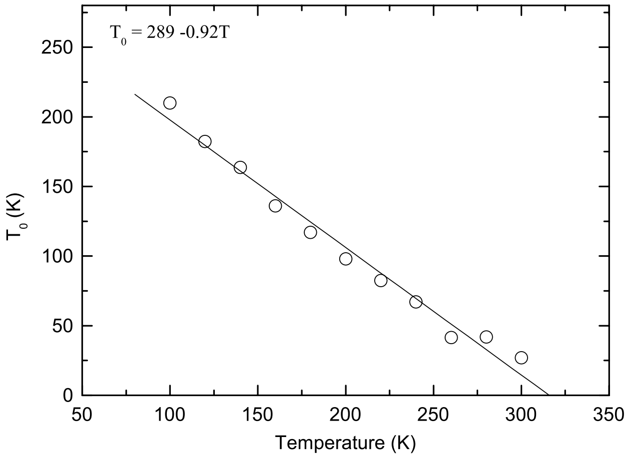

Figure 4. Temperature dependence of the so-called T_0 parameter.

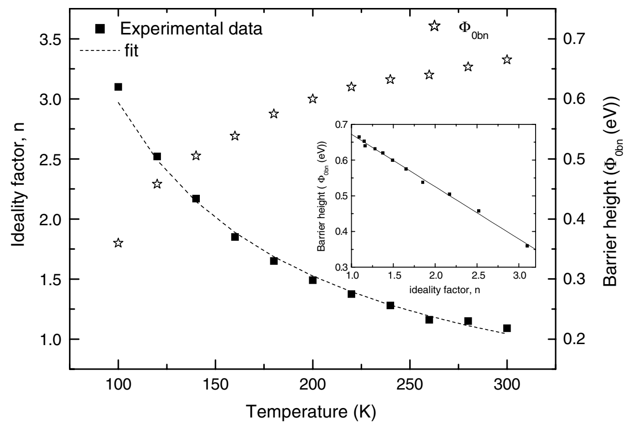

Figure 5. Measured ideality factor and effective barrier height at 0 V of He-ion irradiated Pd/n-$Si_{09}Ge_{0.10}$ SBD as a function of temperature. Correlation of the effective barrier height at 0 V and the ideality factor is shown in the insert.

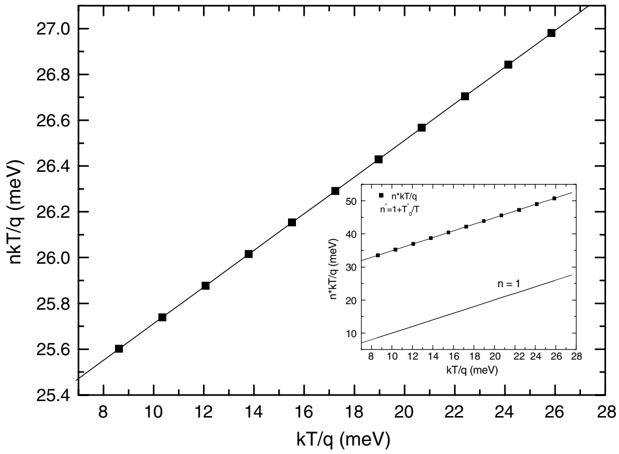

Figure 6. Measured values of $E_0 = nkT$ as a function of kT for He-ion irradiated Pd/n-$Si_{09}Ge_{0.1}$ SBD. The insert shows the temperature dependence of n^*k_BT (where $n^* = n - \alpha = 1 + T_0^*/T$).

temperature indicates a large increase of the negative value of the coefficient which describes the narrowing of the Gaussian distribution upon applied forward voltage; and suggests large changes of the barrier fluctuation at low temperature with respect to the zero bias voltage. This result can be explained by the temperature dependence of surface charges at the irradiated Pd/n-$Si_{0.90}Ge_{0.1}$ Schottky contact.

From the linear fit of the data T_0 (T), the variation of the measured ideality factor n is, therefore, fitted using a modified form:

$$n(T) = 1 + \alpha + \frac{T_0^*}{T}. \tag{7}$$

Figure 5 shows the variation of the ideality factor as well as the effective zero barrier height as a function of temperature. A good fit of $n(T)$ is obtained by using equation (7) over the whole temperature range (100–300 K), as shown in figure 5 (dashed-dot curve). Further, a linear dependence as shown in the inset of figure 6 is observed between the SBH Φ_{0bn} and the ideality factor n. In fact the laterally homogeneous SBH of Pd/n-$Si_{0.90}Ge_{0.10}$ Schottky contact (Φ_{bn}~0.72 eV [16] is expected to be obtained by extrapolation of the experimental Φ_{0bn} (n) plots to $n = 1$. However, the extrapolation leads to an SBH value (0.67 eV) lower than 0.72 eV for the He-ion irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ Schottky contact. This decrease in the SBH can be explained by He-ion irradiation inducing a positive charge at the surface of n-$Si_{0.90}Ge_{0.1}$, which decreases the barrier height through the increase in image force lowering. The latter effect is due to the increase in free carrier concentration upon the He-ion irradiation.

The strong dependence of $n(T)$ could be due to another conduction mode at the irradiated Pd/n-$Si_{0.90}Ge_{0.1}$ Schottky contact such as the thermionic field emission or recombination-generation across our Pd/n-$Si_{0.90}Ge_{0.1}$ Schottky contact. The forward biased I–V–T relationship is given by the following equation based on the thermionic field emission model [18]:

$$I = I_s\left[\exp\left(\frac{q(V - R_sI)}{E_0}\right) - 1\right] \tag{8}$$

and

$$E_0 = E_{00}\coth(qE_{00}/kT), \tag{9}$$

where E_{00} is the parameter defined by $E_{00} = (\hbar/2)[N_D/m^*\varepsilon_s]^{1/2}$, where $m^*$is the effective mass of electron in the semiconductor, ε_s its permittivity and the other symbols have their usual meaning. Figure 6 displays $E_0 = nk_BT$ as a function of k_BT. For the whole temperature range (100–300 K) considered in this work, a linear relationship of E_0 and k_BT is obtained, indicating that, for the whole temperature range (100–300 K), the TE is the dominant conduction mode in our SBD. On the other hand, our data could not be represented with the theoretical expression of E_0 given by equation (9).

It is important to point out that by plotting n^*k_BT versus k_BT, where $n^* = 1 + T_0^*/T = n - \alpha$, the data is well fitted with a straight line parallel to the unity slope line ($n = 1$). The latter result has to be further investigated in more detail.

4. Conclusion

In conclusion, it has been found that He-ion irradiated Pd/n-$Si_{09}Ge_{0.10}$ Schottky contacts have a lower effective barrier height with respect to the control diode. This result can be explained by the presence of donor-type defects in the near surface region of $Si_{09}Ge_{0.10}$ epilayer. At room temperature, the analysis of reverse characteristics of irradiated diode has shown that the contribution of interface states and recombination-generation of carriers is noticeable. From this it is clear that deep levels introduced by He-ion irradiation at and below the $Si_{0.09}Ge_{0.10}$ surface act as recombination centres and play the role of carrier recombination in the reverse characteristic at room temperature.

I–V–T studies of He-ion irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ Schottky contacts have been performed over a large temperature range 100–300 K which revealed TE as the dominant transport mechanism in the forward direction with ideality factors near 1.09 at room temperature. Further, a larger degree of inhomogeneities is observed in the irradiated Pd/n-$Si_{0.90}Ge_{0.10}$ Schottky diode. Strong temperature dependences of the SBH and ideality factor as well as a linear dependence between Φ_{0bn} and n were observed. For the first time, we have shown a temperature dependence of the so-called T_0 anomaly which indicates that the narrowing of the Gaussian barrier distribution upon the application of bias voltage might be temperature dependent. Finally, the existence of the large inhomogeneities is related to the presence of defects created by He-ions irradiation which induced a variation in the number of free carriers at and below the surface of the $Si_{09}Ge_{0.1}$ epilayer.

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