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**PAPER**

# Determination of capture barrier energy of the E-center in palladium Schottky barrier diodes of antimony-doped germanium by varying the pulse width

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## Abstract

The capture barrier energy of the E-center deep level defect introduced in Pd/Sb-doped Ge by alpha-particle irradiation has been studied. Palladium Schottky barrier diodes (SBDs) fabricated by resistive evaporation technique were successfully characterised by current-voltage (*I-V*), capacitance-voltage (*C-V*), conventional and Laplace deep level transient spectroscopy. The rectification quality of Schottky contacts before and after irradiation was confirmed by *I-V* and *C-V* results. The ideality factor and doping density were determined to be in the range of 1.23 to 1.46 and $3.55 \times 10^{15}$ to $5.25 \times 10^{15}$ cm$^{-3}$, respectively before and after irradiating the device with alpha-particles. The thermal emission activation energy and the apparent capture cross section of the E-center were determined from the Arrhenius plot to be 0.37 eV and $1.3 \times 10^{-15}$ cm$^2$, respectively. The capture barrier energy and the true capture cross section of the E-center were calculated to be 0.052 eV and $2.25 \times 10^{-17}$ cm$^2$, respectively from the experimental findings after varying the pulse width at different temperature range from 145 to 180 K in steps of 5 K.

## 1. Introduction

Germanium is a semiconductor that has a very narrow bandgap of 0.68 eV at room temperature (300 K) [1]. It is suitable for the fabrication of microelectronic devices because of its high electron-hole mobility and the narrow bandgap. Applications of germanium in advanced electronic devices have prompted attention to study the *signature* of deep level defects induced after irradiation. Due to the low effective mass of holes in Ge, further attention has been drawn to the possibility of using Ge in ultrafast complimentary metal-oxide-semiconductor devices [2]. Introduction of defects in the Ge crystal after irradiation and metallisation as well as their attributes have been extensively studied [3–6]. Generally, defects play a major role in the fabrication of devices; they determine their performance [7, 8]. They can be introduced intentionally or unintentionally in semiconductor devices. From our previous work, it has been established that resistive evaporation technique does not introduce deep levels at measurable quantity in semiconductors [3]. Therefore, defects could be induced by high-energy gamma-, proton-, electron- and alpha-particles after deposition before the characterization [9]. It has also been reported that deep level defects could be introduced into semiconductors during fabrication by sputtering or electron beam deposition techniques [3, 4, 10–12]. Deep Level Transient Spectroscopy (DLTS) has been widely known to be a sensitive method for detecting and characterizing deep level defects in semiconductor devices. To determine the signature of defect in terms of energy level, concentration, capture cross section and capture energy, DLTS technique is employed [5, 13]. Conventional DLTS is the usual technique used to determine the capture barrier energy by measuring the amplitude of a DLTS peak as a function of pulse width and temperature [6]. This method was adopted until the invention of high resolution Laplace DLTS which can be

easily used to separate closely spaced defects that appeared as a single broad defect in a convectional DLTS spectrum [14].

One of the dominant deep levels intentionally introduced in Ge after particle irradiation is the E-center. The E-center has been attributed to the pairing of a vacancy with a group *V* donor atom (i.e. V-Sb $(--/\times)$) [15, 16]. The capture barrier energy of the E-center in O-doped Ge after irradiation with 2-MeV electrons or 2-MeV protons has been reported to be 0.041 eV [16]. Markevich *et al.* has also reported a value of 0.083 eV as the capture barrier energy after irradiating Sb-doped Ge with gamma-rays [15]. It should be noted that they determined the capture barrier energy of the E-center in Ge by using conventional DLTS. To the best of our knowledge, the capture barrier energy of the E-center in antimony-doped germanium irradiated with alpha-particles from an [241]Am radionuclide has not been studied. In this work, we report the electronic properties of the prominent deep level defect, the E-center, induced in Ge after alpha-particle irradiation. Also, the capture barrier energy and the true capture cross section will be determined experimentally using the Laplace DLTS technique.

## 2. Experimental

Bulk-grown (111) *n*-type germanium doped with antimony to a level of 2–3 $\times$ $10^{15}$ cm$^{-3}$ was used for this study. The samples were cut into approximately 5 mm $\times$ 3 mm dimension from the wafer. They were thoroughly degreased in an ultrasonic bath for 5 min each in trichloroethylene, acetone and methanol before metallisation. The samples were also etched in a solution containing mixture of 30% $H_2O_2$:$H_2O$ (1:5) for 1 min to remove insoluble organic contaminants and the oxide layer, then rinsed in de-ionized water which was followed by blowing dry with nitrogen gas.

Metallisation of an AuSb (0.6% of Sb) ohmic contact at the higher doping density side of the samples was carried out using the resistive evaporation technique at a chamber pressure of approximately 2.0 $\times$ $10^{-6}$ mbar. The samples were annealed in flowing argon at 350 °C for 10 min to reduce leakage current at the junction as well as lowering the ohmic contact's resistivity. Prior to the fabrication of Schottky contacts, the samples were chemically cleansed as described above without etching. Pd Schottky barrier diodes (SBDs) of 0.60 mm in diameter and 100 nm thick were fabricated using the resistive evaporation technique at a deposition rate of ~0.1 nm s$^{-1}$. After the fabrication of the contacts, current-voltage (*I-V*) and capacitance-voltage (*C-V*) measurements of the Pd/*n*-Ge devices were carried out in the dark at room temperature (300 K) to determine the quality and the suitability of the SBDs for this study. The *I-V* and *C-V* measurements were done by an HP 4140 B pA meter/DC voltage source and an HP 4192A LF Impedance Analyzer, respectively. This characterisation was also repeated after alpha-particle irradiation. Furthermore, the samples were intentionally irradiated by alpha particles by placing [241]Am foil on the SBDs for 15 min. The SBDs received fluence of 6.4 $\times$ $10^9$ alpha-particles/cm$^2$ from the foil at a fluence rate of 7.1 $\times$ $10^6$ alpha-particles/cm$^2$/s. The irradiation was carried out at room temperature (300 K). The samples were characterised before and after alpha-particle irradiation by both convectional DLTS and high-resolution Laplace DLTS. The capture barrier energy and some other properties of the E-center in germanium were also determined by DLTS. The convectional DLTS was performed with different filling pulse widths under a reverse bias of 2 V and forward bias of 0 V at a scan rate of 1 K min$^{-1}$ until the saturation point was reached. At a very high pulse width above the saturation point, the behaviour of the peaks started deviating from the usual trend. The amplitudes started decreasing with increasing temperature at 100 rate window/s. The possible causes of this change will be discussed later. The high-resolution Laplace DLTS technique was also employed to measure the amplitude of the transient due to the defect as a function of the pulse width at constant temperature. The amplitude at which the peak saturated was obtained at each temperature [17].

## 3. Results and discussion

The suitability of the Schottky barrier diodes for conventional DLTS and high-resolution Laplace DLTS measurements was confirmed by *I-V* and *C-V* measurements, the results of which are shown in Figures 1 and 2, respectively. The ideality factor (*n*) and doping density (*N*$_d$) were determined before and after alpha-particle irradiation to be in the range of 1.23 to 1.46 and 3.55 $\times$ $10^{15}$ to 5.25 $\times$ $10^{15}$ cm$^{-3}$, respectively. Figure 3 shows the conventional DLTS spectra of the Pd/*n*-type Sb-doped Ge sample before and after irradiation with alpha particles from an [241]Am radionuclide for 15 min. The spectra were recorded at a rate window of 200 s$^{-1}$. They were obtained over a temperature range of 30-300 K, at a quiescent reverse bias of –2.0 V, filling pulse level of 0 V and a pulse width of 2.0 ms. It could be noticed from the spectrum observed before irradiation that there was no deep level defect present (i.e. no observable peak). This corroborates the fact that resistive evaporation technique does not introduce any measurable defect into devices during fabrication of contacts [12, 18]. In the DLTS
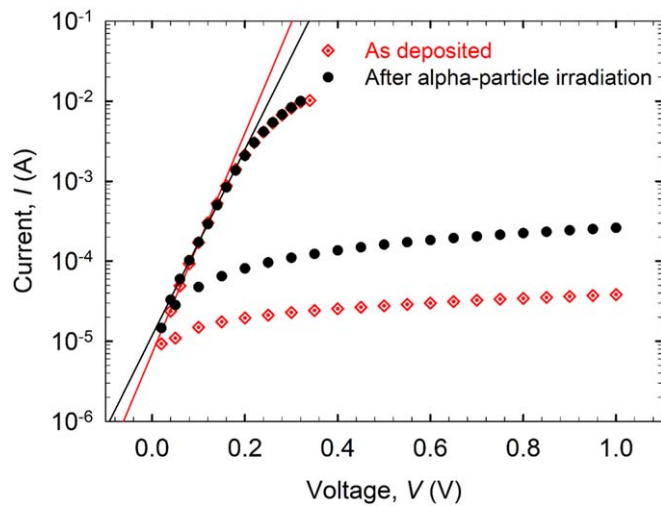
**Figure 1.** *I-V* measurements under forward and reverse bias for the Pd/n-Ge Schottky barrier diodes before and after alpha-particle irradiation. Both measurements were done at room temperature (300 K).
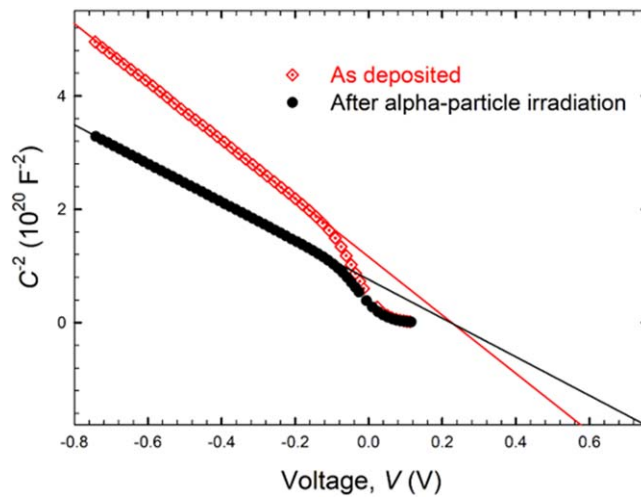


**Figure 2.** Plots of $1/c^2$ as a function of applied voltage characteristics of Pd/n-Ge SBDs before and after alpha-particle irradiation. Both measurements were done at room temperature (300 K).
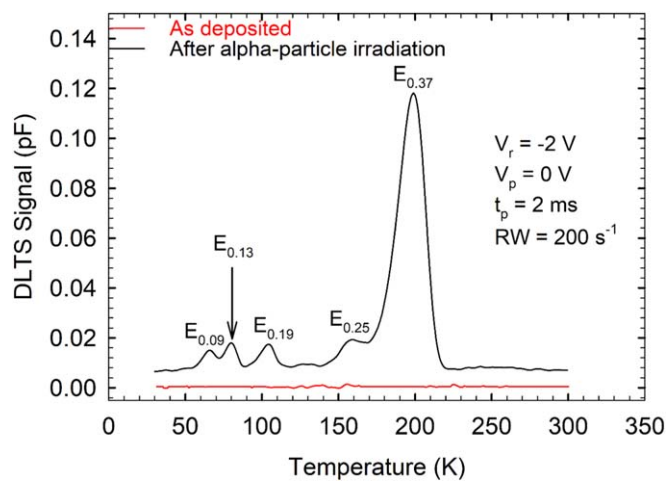


**Figure 3.** Conventional DLTS spectra of Pd/n-Ge SBDs before and after alpha-particle irradiation, measured with a rate window of $20 \ s^{-1}$.
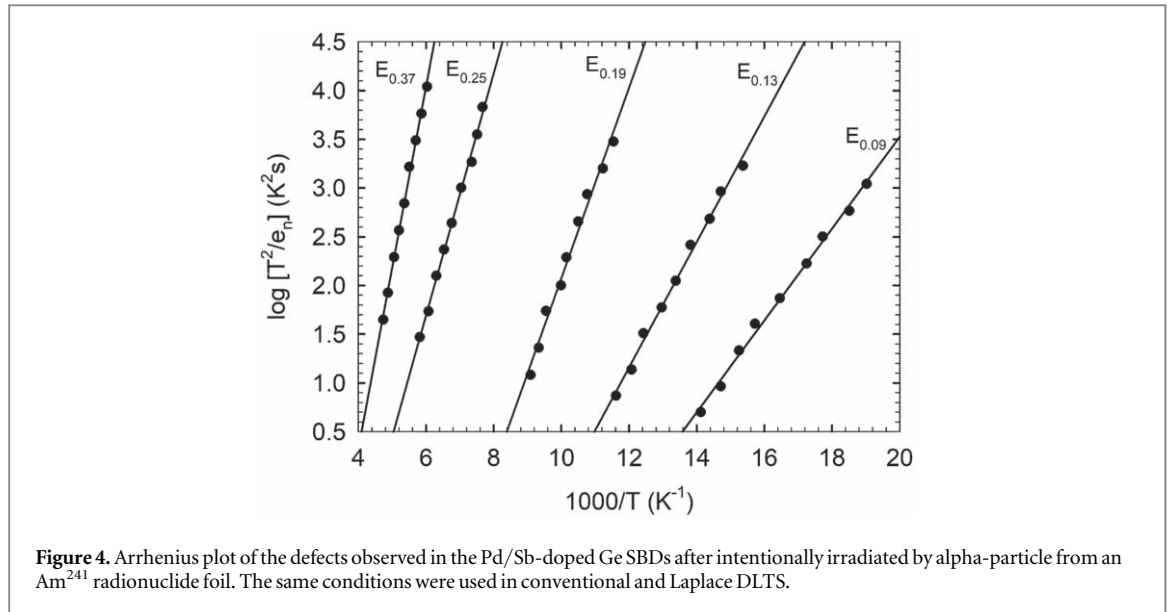
**Figure 4.** Arrhenius plot of the defects observed in the Pd/Sb-doped Ge SBDs after intentionally irradiated by alpha-particle from an Am$^{241}$ radionuclide foil. The same conditions were used in conventional and Laplace DLTS.

**Table 1.** Some electronic properties of deep levels observed by DLTS after alpha-particle irradiation of Pd/Sb-doped Ge Schottky barrier diodes.

| Defect label | $E_C{-}E_T$ (eV) | $\sigma_n$ (cm$^2$) | Similar defects and ID |
|---|---|---|---|
| $E_{0.09}$ | 0.09 | $8.2 \times 10^{-17}$ | $E_{0.10}$ [3] |
| $E_{0.13}$ | 0.13 | $3.8 \times 10^{-16}$ | $E_{0.13}$, Sb and I [15, 16] |
| $E_{0.19}$ | 0.19 | $5.0 \times 10^{-15}$ | $E_{0.20}$, Sb and I [16] |
| $E_{0.25}$ | 0.25 | $6.0 \times 10^{-17}$ | $E_{0.24}$, Sb and I [16] |
| $E_{0.37}$ | 0.37 | $1.3 \times 10^{-15}$ | $E_{0.38}$, V-Sb (−−/−) [15, 16] |

spectrum after irradiation, five deep level defects were observed. Figure 4 shows the Arrhenius plot of the defects observed in the SBD after irradiation. The *signatures* (apparent capture cross section and activation energy) of the defects present in the sample were determined using equation (1) as reported earlier [5].

$$e_n = \frac{\sigma_n v_n N_C}{g} \exp\left[-\frac{E_T}{kT}\right] \tag{1}$$

where $e_n$ is the thermal emission rate, $\sigma_n$ is the apparent capture cross section for electrons which is temperature dependent[5], $v_n$ is the average thermal velocity, $N_c$ is the effective density of states in the conduction band, $g$ is the degeneracy of the defect level, $\exp[-E_T/kT]$ is the Boltzmann factor and $T$ is the absolute temperature in K. From the Arrhenius plot, the values of the activation energies of the five defects below the conduction band minimum, $E_T$, were determined from the slope, and the apparent capture cross sections were evaluated from the intercept by extrapolating the straight line to the abscissa where inverse of temperature equals to zero (i.e. $T^{-1} = 0$). The signatures and other attributes of the defects are shown in table 1. The deep level defects obtained after irradiation were observed and reported earlier [18]. The additional focus in this work is to determine the capture barrier energy of the prominent defect, namely E-center, in Ge after alpha-particle irradiation at fluence of $6.4 \times 10^9$ cm$^{-2}$.
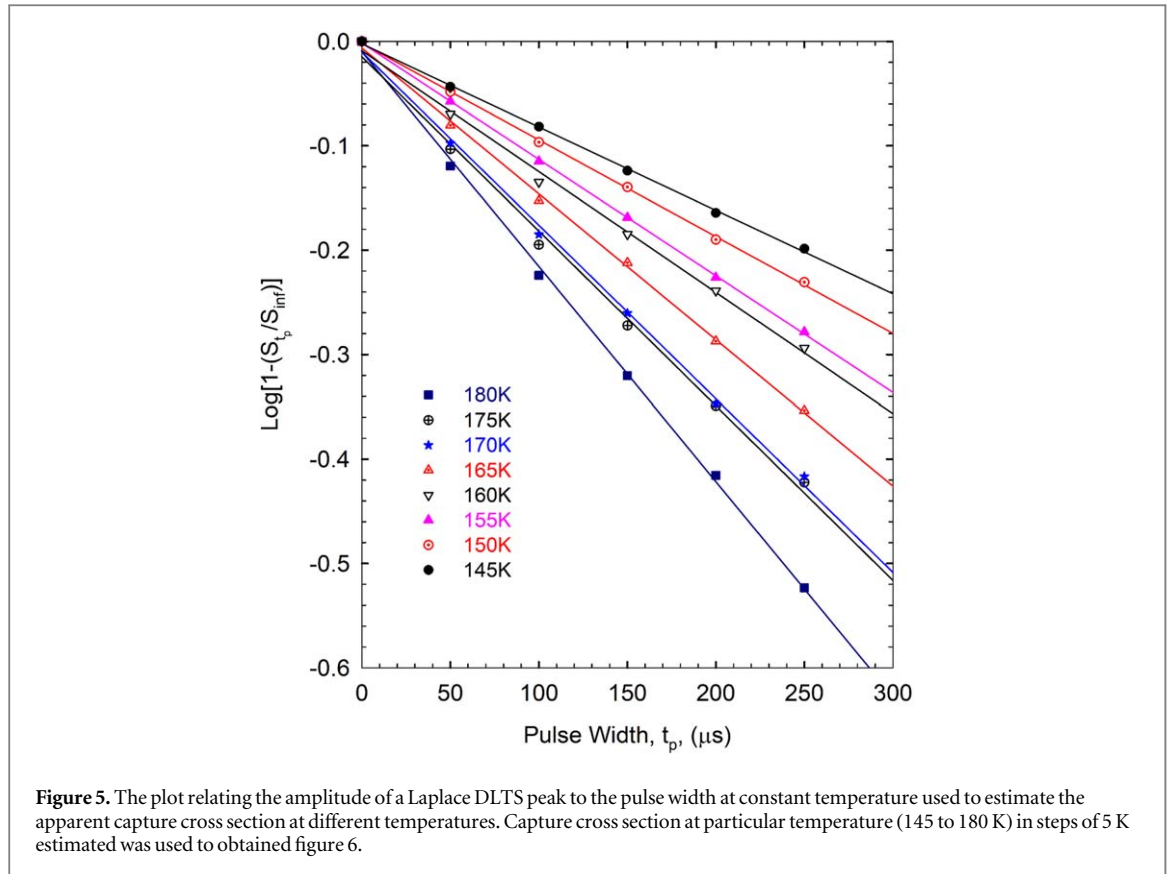
The expression that best described the capacitance DLTS signal produced by thermal emission of electrons from the trap has been reported by Criado [19] in equation (2).

$$S(t_p, T) = S_\infty[1 - \exp(-t_p/\tau_c)] \tag{2}$$

where $S(t_p, T)$ is the capacitance transient signal amplitude at temperature, $T$, that was obtained with a filling pulse width $t_p$. $S_\infty$ is the amplitude of the capacitance transient after a very long filling pulse and $\tau_c$ is the capture time constant. The $\tau_c$ is the reciprocal of capture velocity, $nC_n$, as shown in equation (3)

$$\tau_c = \frac{1}{nC_n} \tag{3}$$

where $n$ is the carrier concentration and $C_n$ is the capture coefficient. Equation (4) shows the relationship between the capture coefficient and the capture cross section.

**Figure 5.** The plot relating the amplitude of a Laplace DLTS peak to the pulse width at constant temperature used to estimate the apparent capture cross section at different temperatures. Capture cross section at particular temperature (145 to 180 K) in steps of 5 K estimated was used to obtained figure 6.

$$C_n = \sigma_n v_{th} \tag{4}$$

where $v_{th}$ is the thermal velocity of carriers. The amplitude of the transients as determined by Laplace DLTS were measured for different filling pulse widths attemperatures ranging from 145 K to 180 K in 5 K steps. The same bias was used for both conventional and Laplace DLTS characterization. The measurements were successfully achieved for short filling pulses ranging from 50 to 250 μs in steps of 50 μs contrary to the proposed method by Jian *et al*. [20], who had earlier reported that short filling pulses are not suitable for this kind of measurement. It is, however, a very time-consuming experimental measurement [20].

The conventional and laplace DLTS have been recorded at different emission rates and filling pulse width. From the Arrhenius plot of $\log [1 - (S_{t_p}/S_\infty)]$ versus pulse width $t_p$ shown in figure 5, the apparent capture cross section as a function of temperature was deduced from the slope. The relationship between the apparent capture cross section, $\sigma$, and the slope can be expressed as shown in equations (5) and (6).

$$\tau_c = 1/(2.303 \times Slope) = 1/(\sigma n v_n) \tag{5}$$
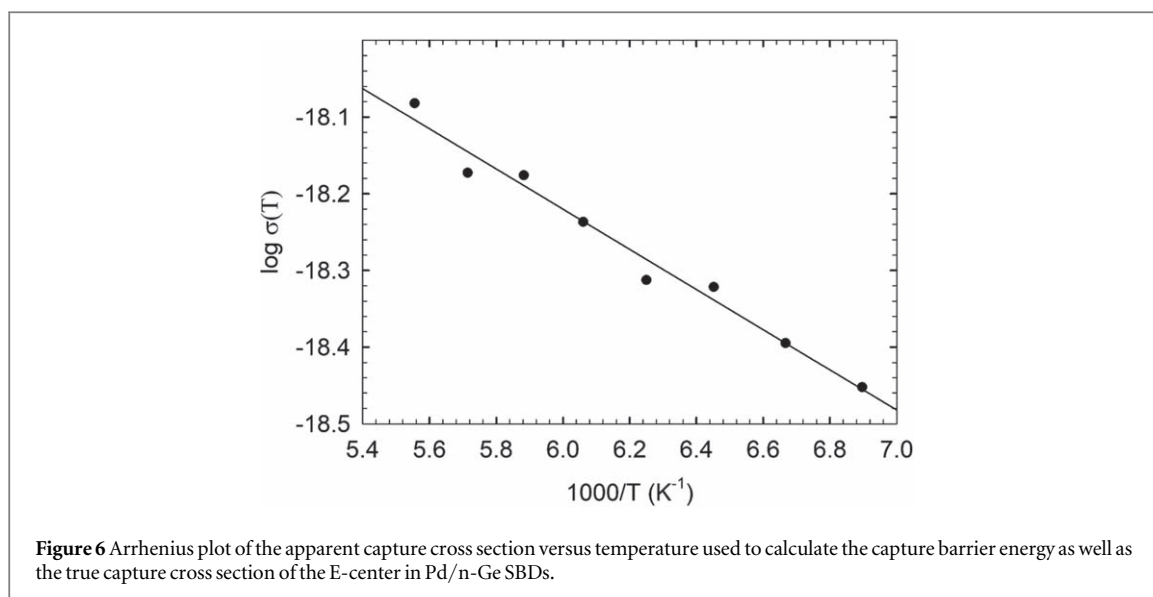
$$\sigma = B \times slope \tag{6}$$

where $B = 2.303/n\langle v_n\rangle$, $v_n = \sqrt{(3kT/m^*)}$ is the thermal velocity of electrons, $n$ is the free carrier concentration, $k$ is the Boltzmann constant and $m^*$ is the effective mass of electrons in Ge.

The apparent capture cross section obtained from figure 5 is related to temperature according to the multiphonon emission process shown in equation (7) [6].

$$\sigma = \sigma_\infty \exp\left(-\Delta E_\sigma/kT\right) \tag{7}$$

where $\sigma_\infty$ is the high temperature limit of the capture cross-section, also referred to as the true capture cross section and $\Delta E_\sigma$ is the thermal activation energy of the capture cross section. The equation (7) was simplified and the graph of $\log\sigma$ against the reciprocal of the temperature ($T^{-1}$) is plotted shown in figure 6. From the plot, the true capture cross section was determined to be $2.20 \times 10^{-17}$ cm$^2$ from the intercept when $T = \infty$. The capture barrier energy was calculated to be 0.052 eV from the slope of the plot. It was observed that the capture cross section of the prominent defect could be temperature dependent. Presence of a repulsive coulombic barrier may be responsible for the variation. The charge carriers may therefore be hindered from reaching the thermal equilirium during the filling process [21]. The result obtained for the electron barrier energy of the E-center in n-Ge after alpha-particle irradiation of Pd/n-Ge SBDs, lies between the values of 0.083 eV as reported by Markevich *et al*. [15] for gamma irradiation and 0.041 eV reported by Fage-Pedersen *et al*. as after 2-MeV electron or 2-MeV proton irradiation [16]. The significant variation in the value of electron barrier energy

**Figure 6** Arrhenius plot of the apparent capture cross section versus temperature used to calculate the capture barrier energy as well as the true capture cross section of the E-center in Pd/n-Ge SBDs.

determined from our findings and the value reported in the literature may be as a result of different interactions with different irradiations.

From the result obtained for the electron capture barrier energy for the E-center, it could be deduced that equation (1) was satisfied for all the small pulse widths at different, fixed temperatures ranging from 145 to 180 K. It was also possible to calculate the apparent capture cross section for the E-center in Ge which in turn gave a good result for the true barrier capture cross section. The expression in equation (8) shows the result for trap capture cross section for E-center in Sb-doped n-Ge at different temperature.

$$\sigma^{E(0.37eV)}(T) = 2.25 \times 10^{-17} \exp(-0.052 \ eV/kT) \ cm^2 \tag{8}$$

Although it had been reported by Cavalcoli *et al.* [21] that temperature dependence of the true capture cross section cannot be deduced experimentally, our result proved that it could be temperature dependent and the result can be successfully determined experimentally by using high resolution Laplace DLTS.

## 4. Conclusions

Rectifying Pd Schottky contacts on Sb-doped Ge were thermally deposited by resistive evaporation techniques. *I-V* and *C-V* measurements were used to ascertain the suitability of the devices by determining the ideality factors and doping density to be 1.23 and $3.55 \times 10^{15} \ cm^{-3}$, respectively before irradiation and 1.46 and $5.25 \times 10^{15} \ cm^{-3}$, respectively after irradiation. The deep level defects intentionally induced by alpha-particle irradiation for 15 min were successfully characterised by conventional and high-resolution Laplace DLTS. Our results from DLTS measurement revealed five defects that have the same electronic properties as those observed after electron and proton irradiation. With the help of high-resolution Laplace DLTS, the electron capture barrier energy and the true capture cross section of the most prominent deep level defect (E-center) in Sb-doped Ge after alpha-particle irradiation were determined to be 0.052 eV and $2.25 \times 10^{-17} \ cm^2$, respectively. In addition, the true trap capture cross-section of the most prominent deep level defect, the E-center, was found to be temperature dependent and can be determined experimentally using Laplace DLTS. The presence of a repulsive coulombic barrier may be responsible for the dependence of the capture cross section on temperature.

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