Temperature dependence of current-voltage characteristics of *p*-silicon Schottky diodes for radiation-hard detectors.

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Abstract: Current-voltage measurements were carried out on Schottky diodes in the temperature range of 280 – 330 K. The diodes were fabricated on undoped and on gold-doped *p*-type silicon. The temperature dependence of the saturation current, Schottky barrier height and the ideality factor were investigated. The results obtained are in good agreement with those presented in the literature and are interpreted in terms of defect levels that are induced by gold in the energy gap of silicon material. These levels are responsible for the conversion of silicon from a lifetime material to a relaxation material. The diodes fabricated from relaxation material are characterized by the Ohmic behavior and low conductivity due to the recombination of charge carriers by the levels. Properties of these relaxation diodes are not affected by the incident radiation. Thus, the diodes can be used to devise the radiation-hard detectors.

1. Introduction

Silicon diodes are used widely to fabricate radiation detectors [1]. However, the detectors do not operate efficiently due to the defect levels that are induced by the incident radiation in the energy gap of silicon [2]. In trying to improve the efficiency, much work has been carried out on silicon doped with gold [3]. This metal creates "midgap defect" (~ 0.56 eV) which is a defect level that is found very close to the centre of the energy gap [4]. The defect level is responsible for the relaxation behavior of the material [4]. The diodes fabricated from the relaxation material show the Ohmic behavior with high resistivity [4]. In silicon material, the midgap defect suppresses the effects of the incident radiation and makes properties of the diodes fabricated from the material to be independent of the incident radiation, hence to be the radiation-hard [3-4].

The results presented in the reviewed literature are based only on gold-doped *n*-type silicon [5]. At this stage the results obtained from these studies have not been fully analyzed nor understood. There is also not much literature available on gold-doping in *p*-type silicon that could be used to compare the results obtained on *n*-type silicon. It is thus essential that the effects of gold in *p*-type silicon are investigated. This paper attempts to address this weakness.

In this work Schottky diodes were fabricated on undoped and on gold-doped *p*-silicon. The diodes were characterized by current-voltage (*I*-*V*) technique at the temperature ranging from 280 to 330 K. The measured current is found to be increasing with temperature. This increase in the current has been found to be more pronounced on the undoped diodes than on the gold-doped diodes. This shows that the temperature does not have strong effects on the gold-doped diodes. This effect of the metal on the properties of the diodes is discussed in the paper.

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2. Experimental procedure

Current-voltage (*I-V*) measurements were carried out on the undoped and on the gold-doped *p*-silicon diodes placed in the dark. The data were acquired using a Keithley 6487 picoammeter with a voltage source. The measurements were carried out at the temperature ranging from 280 to 330 K. The data were taken from -10 V to 10 V with a voltage step of 0.01 V. A detailed description of the material preparation, device preparation and characterization has been given [6] elsewhere and will not be repeated here.

3. Results and discussion

3.1. Undoped p-silicon diodes

A variation of the reverse *I-V* characteristic with temperature for the undoped *p*-silicon diodes is shown in figure 1. It can be seen from the figure that the current increases with temperature at voltages lower than the break down voltage. The current increases by a factor of 5.0 from that of 280 K to the one of 330 K. These results show that as the temperature increases more carriers with sufficient energy are collected to the opposite electrodes to contribute to the measured current.

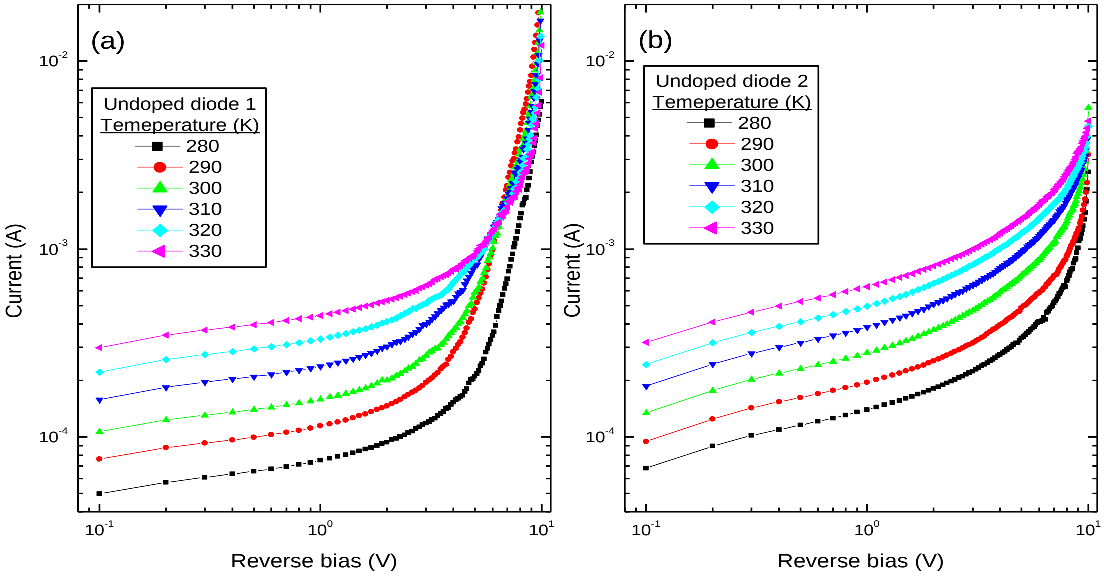

Figure 1. *A variation of the reverse I-V characteristic with temperature for the undoped p-silicon diodes.*

The reverse current (I) varies with temperature [7] as

$$I \propto \exp\left(\frac{E_a}{k_B T}\right) \tag{1}$$

where E_a is the activation energy of the material and $k_B T$ is the thermal energy. Equation (1) shows that a plot of ln (I) against T^{-1} is a linear relation from which the slope can be used to determine E_a. Figure 2 shows the plots of ln (I) against T^{-1} for the undoped *p*-silicon diodes. The activation energy for diodes 1 is found to be 0.29 eV and 0.24 eV for diode 2. The difference in the quantities is due to the inhomogeneous deposition of gold during the formation of Schottky contact [6].

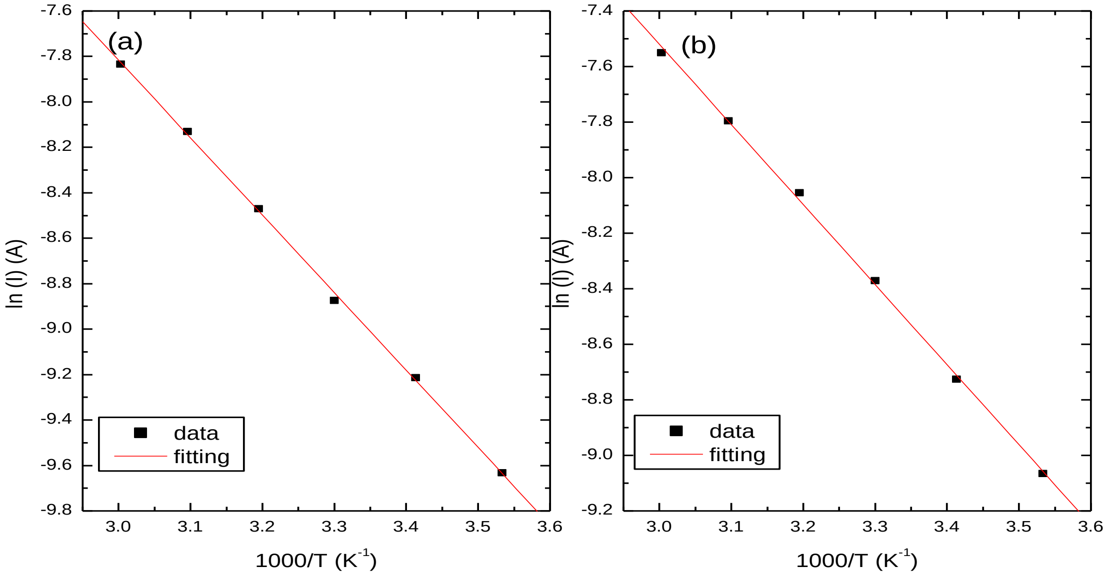

Figure 2. *The plots of ln (I) versus T $^{-1}$ at a constant reverse bias of 0.5 V for the undoped p-silicon diodes.*

Figure 3 shows the forward *I-V* characteristic of the undoped *p*-silicon diodes as a function of temperature. It can be noticed that the forward current increases with temperature for the same voltage. This increase of the current with temperature is not pronounced as that observed in figure 1, for the reverse current. This is because the reverse current is due to the generated carriers while the forward current is due to the diffusion mechanism [4]. The trends are found to be parallel to each other, especially at low voltages to indicate that they are not affected by temperature.

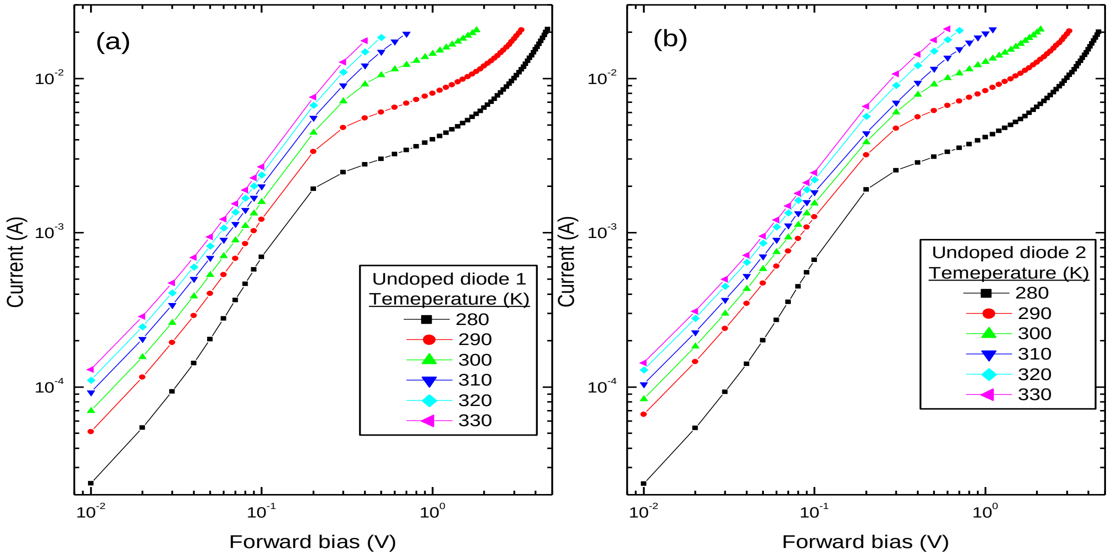

Figure 3. *A variation of the forward I-V characteristic with temperature for the undoped p-silicon diodes.*

Using the forward bias profile, the measurements were used to investigate the variation of the saturation current (I_s), the ideality factor (η) and the Schottky barrier height Φ with temperature. The procedure to determine these parameters have been documented in the literature [5-6]. The temperature measurements were taken on the four diodes fabricated on the same undoped *p*-silicon and the variation of the parameters with temperature was investigated. The average values of the parameters for all diodes were taken and are presented in table 1 for the undoped *p*-silicon diode.

Table 1: A variation of the parameters obtained from the undoped *p*-silicon diodes with temperature.

Temperature (K)	**280**	**290**	**300**	**310**	**320**	**330**
I_s (µA)	32.1	65.8	86.7	115	145	175
η	1.36	1.29	1.24	1.18	1.13	1.04
Φ (V)	0.63	0.63	0.62	0.63	0.62	0.62

The saturation current is a function of temperature [8] and the results obtained show that it increases with temperature. This shows that the amount of carriers withdrawn to the opposite electrodes to contribute to the measured current increases with temperature.

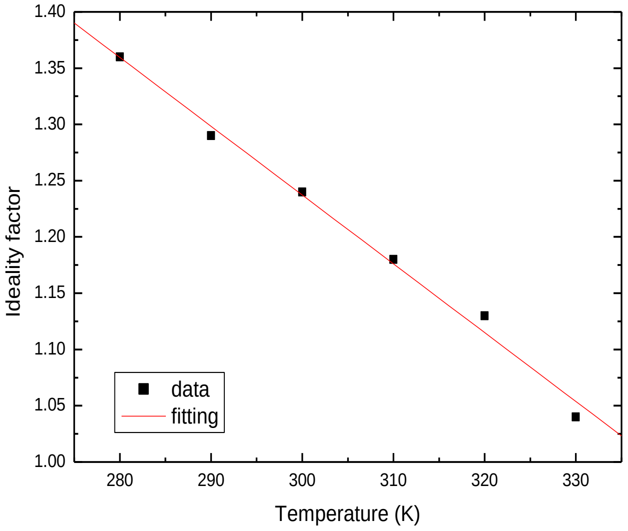

Figure 4. *Temperature dependence of the ideality factor for the undoped p-silicon diode.*

The variation of the ideality factor with temperature is not due to the slope obtained from the plot of ln (*I*) versus V. Since the trends are all parallel to each other the slopes are almost constant. Re-arranging the diode equation that relates the current with voltage [6], it can be noticed that the ideality factor decreases with an increase in temperature at the constant slope. This temperature dependence of the ideality factor for the undoped diode can be seen in figure 4. The linear relation is observed with the slope evaluated as -0.006 K^{-1}.

The results obtained in this work show that the Schottky barrier height is independent of the temperature. This independence disagrees with the results presented in the literature [9] based on the result that were obtained on the diodes fabricated on *p*-Si. The results in that case were interpreted in terms of the metal-semiconductor interface charges. The obtained results, however, agree with those presented in Ref. [10] where tungsten was used for the Schottky contacts on *p*-Si. This independence could be due to the fact that the rate at which the temperature increases is the same as the rate at which the saturation current increases in the logarithmic scale. These rates cancel each other and make the Schottky barrier to be independent of the temperature. These results, thus, also show that the measured current is due to the space charge region not the interface charges since the Schottky barrier height is independent of the temperature.

3.2. Gold-doped p-silicon diodes

The plots of the reverse *I-V* characteristic of gold-doped *p*-silicon diodes were also generated. The plots are not shown here due to the limited size of the paper. Unlike in the case of undoped *p*-silicon diodes, the trends for gold-doped diodes were found to be close to each other to show that effects of temperature have been reduced. The trends were also found to be linear with voltage (Ohmic). This Ohmic behavior of the diodes was discussed in terms of the defect levels that were induced by gold in the energy gap of silicon material [6]. These levels recombine charge carriers and this leads to a reduction of the measured current. As a result, the resistivity of the material increases to show the relaxation behavior [9].

The plots of ln(I) against T^{-1} for gold-doped *p*-silicon diodes were also generated. The linear relations were found and the activation energy for diode 1 was found to be 0.16 eV and 0.18 eV for diode 2. Both activation energies are lower than those obtained from the undoped diodes. It is usual to get the activation of the control sample to be higher than the one of the defect induced samples [7; 10-11]. In the case of Ref.[7], the activation energy of the unirradiated n^+p diode was found to be 0.54 eV and 0.50 eV of the irradiated diode while in the case of Ref.[10] the activation energy of the unirradiated silicon *p-i-n* diodes was found to be 0.87 eV and 0.54 eV for the irradiated diodes. In Ref. [11] the activation energy of the control sample (silicon-germium detector) was found to be 0.43 eV and 0.27 eV for the irradiated detector. A decrease of the activation energy shows that the rate at which the carriers are generated by temperature is reduced by the defect levels induced in the material. These levels recombine the thermal generated carriers as a result, the effects of temperature on the characteristics of the diode are reduced.

The plots of the forward current of gold-doped *p*-silicon diodes were generated (not shown) and found to be Ohmic and independent of the temperature. The independence was found to be more pronounced at high voltages. At the voltages lower than 1 x 10^{-1} V the trends were parallel and very close to each other to show that the effects of temperature were reduced due to the induced defect levels.

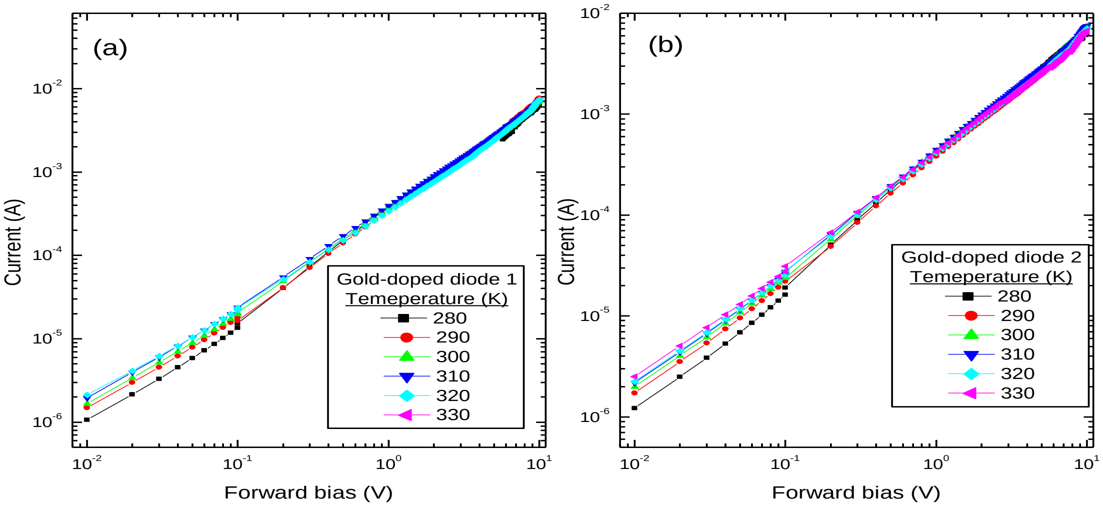

Figure 5: *A variation of the forward I-V characteristic with temperature for the gold-doped p-silicon diodes.*

The forward *I-V* characteristic of gold-doped *p*-silicon diodes shown in figure 5 was also used to determine a variation of the saturation cdurrent, the ideality factor and the Schottky barrier height with temperature. The results are shown in table 2. Similar to the undoped *p*-silicon diodes the saturation current was found to be increasing with temperature. The saturation current has been increased by the factor of 1.4, which is lower than the one obtained from the undoped *p*-silcon diodes (5.0), from that of 280 K to the one of 330 K. The Schottky barrier height, on the other hand, is found to be still independent of the temperature.

Table 2: A variation of the parameters obtained from the gold-doped *p*-silicon diodes with temperature.

Temperature (K)	**280**	**290**	**300**	**310**	**320**	**330**
I_s (µA)	10.2	11.1	11.9	12.6	13.1	13.9
η	1.90	1.87	1.84	1.80	1.76	1.73
Φ (V)	0.68	0.7	0.69	0.68	0.68	0.69

The linear relation of the ideality factor as a function of temperature was observed with the slope of -0.003 K^{-1}. The magnitude of the slope is lower than the one obtained from undoped *p*-silicon diodes (-0.006 K^{-1}) to show that the rate in which the carriers are thermally generated have reduced after doping with gold.

4. Conclusion

At temperatures ranging from 280 K to 330 K the effects of temperature on the *I-V* characteristics of the gold-doped *p*-silicon diodes is found to be reduced. The reduction of these effects can be justified by the reduction in magnitude of E_a after gold doping. This is due to the defects levels that are induced by gold in the energy gap of silicon. The levels recombine the charge carriers that are generated by temperature. These results are similar to those presented for the irradiated diodes under illumination [12]. Similarly, the effects of light were found to be reduced after irradiation. Thus, the gold-doping of is similar to the heavy radiation-damage. They both create defect levels that are responsible for the Ohmic behavior and increase in the resistivity (relaxation behavior) of the material. This relaxation material has been found to be radiation-hard (radiation-resistant) [3].

Acknowledgements

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