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Dependence of Depletion Voltage and Capacitance on Temperature and Frequency in Heavily Irradiated Silicon Diodes

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Abstract

The dependence of the depletion voltage and capacitance on the temperature and frequency used for the measurement has been studied for heavily irradiated silicon diodes made from detector grade silicon. It was observed that a logarithmic increase of frequency produced the same capacitance change as a linear decrease in temperature at a fixed bias voltage. The depletion voltage was found to depend on the frequency and the temperature. In some cases the depletion capacitance was found to differ from the value measured before irradiation. Hence, care must be exercised in defining exactly what is meant by the depletion voltage for an operational detector.

1 Introduction

For silicon detectors to be used in the ATLAS experiment at the Large Hadron Collider (LHC), the main considerations are the operating conditions expected. The tracking detector is expected to be bombarded with $\sim 10^{13}$ particles cm^{-2} $year^{-1}$. It will be operated in the temperature range 263-273K. The major limiting factor is the increase of the depletion voltage with fluence.

CV measurement is a standard way to find out the full depletion voltage of a semiconductor diode. At full depletion the diode has full sensitivity to detect particles. The depletion voltage is normally defined as the bias voltage required so that the region depleted of free carriers reaches through the whole of the semiconductor bulk. Typically the measurement is performed at a frequency of 10kHz, and at room temperature.

The aim of this work was to study variations of the depletion voltage and capacitance with frequency and temperature for silicon diodes irradiated by 1-3 x 10^{14} n cm^{-2}. It is well known that after irradiation CV characteristics have a strong dependence on measurement frequency [1, 2] and that there is a deviation from the $1/V^{\frac{1}{2}}$ dependence of C seen before irradiation.

A prediction for the temperature dependence of depletion voltage [3] is that a 30% decrease in depletion voltage will be observed when the temperature is lowered from 300K to 270K for a strongly type-inverted detector. Previous data appears to support this prediction over the temperature range 273-315K [4], all measured at 10kHz. The present study concentrates on the temperature range 257-305K, using the measurement frequencies 1, 10, 20 and 100kHz.

A characteristic time, related to any process in a normal semiconductor, depends on temperature as:

$$\tau \propto \exp\left(\frac{Ea}{kT}\right) \qquad (1)$$

therefore a linear decrease in temperature should correspond to a logarithmic decrease in frequency.

2 Experimental Details

The test structures were p-i-n diodes with 5x5mm^2 sensitive area (surrounded by a guard ring) and with 300μm thickness. They were manufactured using n-type material by Micron Semiconductor. The mask design was created by the Liverpool University HEP group. The diodes were extensively tested at room temperature (around 295K), and usually at 10kHz to extract the depletion voltage and capacitance, before the irradiation.

Irradiation took place at two facilities: at ISIS (Rutherford Appleton Laboratory), by 1MeV neutrons, and at PSI (Zurich), by 300MeV/c pions. All irradiations were performed at room temperature and without bias.

The test diodes were stored at room temperature and tested daily until minimum depletion voltage was reached. Afterwards they were stored at 273K to ensure that the reverse annealing process did not take place.

Capacitance was measured using a HP4263A Precision LCR meter. A Melcor SealTEC ST 1.4-127-045L Peltier device was used to control the temperature of the diode during the measurements.

Two methods typically used to find depletion voltage were compared. The first uses the crossing of two straight lines fitted in the logC-logV plot, while the second, uses the crossing point of one straight line with a level fixed at C_o - the capacitance measured before irradiation.

3 Results and Discussion

3.1 CV Characteristics

Preliminary tests were performed on a non-irradiated diode, at room temperature, at 4 different frequencies from 0.1 to 100kHz. As expected we found no dependence of the CV characteristics on the measurement frequency used. After irradiation however, a strong frequency dependence is observed at every fixed temperature within our range (fig. 1 shows logC-logV at 273K). It is assumed that this is a consequence of the finite reaction time of the deep traps which should respond less effectively to high frequency AC signals as they do to signals at a lower frequency. The zoomed region in the plot clearly shows that the depletion capacitance is less than C_o (9pF in this case) at the lowest frequency. Fig. 2 shows the temperature dependence of the CV characteristics at a fixed frequency of 10kHz. By comparing figs. 1 and 2 one can see the similarities between the temperature and frequency dependences of the CV characteristics. A logarithmic change in frequency gives the same pattern of CV's as a linear change in temperature. The data for 289K in fig. 2 shows clearly a change in the level of the depletion capacitance from the level seen at lower temperatures, and this change is also noted in other independent data [5]. Shown on this plot is a typical fit with two straight lines, where the absolute gradients are marked as $|S1|$ and $|S2|$ respectively. Note that, in the irradiated diodes the slope of the second part of the curve $|S2|$ may not be equal to zero, whereas before irradiation we observed zero slope. For non-irradiated diodes, the first part of the CV curve obeys a power law relation C = a V^b with b=0.5. In the irradiated diodes $|S1|$ deviates from this behaviour.

As the CV curves change, so $|S1|$ and $|S2|$ are expected to vary with temperature and frequency, and their variations are illustrated in figs. 3 and 4. $|S1|$ is plotted versus T in 3a, and versus period in 3b. In 3a the level of $|S1|$ increases with decreasing frequency, and there is a tendency for $|S1|$ to grow with temperature. Variation with period is very similar, but on a logarithmic scale. Again the link between temperature and frequency is displayed.

The behaviour of $|S2|$ is more complex (fig. 4). Almost stable around zero at lowest temperatures and shortest periods in our range, $|S2|$ grows as either the temperature or the period increases. This behaviour becomes strongest for high temperature and long period.

3.2 Depletion Voltage

The depletion voltages shown in fig. 5 are derived from the intersection of the two fitted straight lines in the logC-logV plot. Measurements are made at frequencies 1, 10, 20 and 100kHz. We observe that the general level increases as frequency decreases. At 1kHz and 10kHz there is a 15-20% increase of the depletion voltage over the temperature range 255-305K. It is somewhat less than the 30% predicted in [3] for the range 270-300K. At 100kHz there is no obvious temperature dependence of depletion voltage.

At all temperatures except for 257K there is a 15-20% increase in depletion voltage when frequency changes from 10kHz to 1kHz. This may possibly be explained by the presence of a transition region between the space charge region and the neutral bulk in heavily irradiated silicon (in non-irradiated silicon diodes this transition is abrupt). The variation of depletion voltage with frequency may then be attributed to probing different parts of this transition region by different frequency signals. Further investigations into the existence of this phenomenon are being undertaken by the Lancaster group. At the lowest temperature no clear period dependence is observed, similar to results at 100kHz versus temperature.

All the above measurements were made with the diode irradiated by 1.1 x 10^{14} n cm^{-2}. Complications arose when testing more heavily irradiated diodes. Even at the lowest measuring temperature the current through the diode was so large that it caused thermal runaway at high bias voltage. This made capacitance measurement difficult and sometimes impossible with our system. Depletion voltages for these diodes are $\sim$350-400V and with our limit on bias voltage 500V it became difficult to distinguish the characteristic "kink" in the CV curve, appearing when the diode reaches full depletion. Data is shown, in fig. 6, for a diode irradiated by a total fluence of 2.7 x 10^{14} π cm^{-2}. In general they are similar to those presented in fig. 5a, except for the larger values of depletion voltage due to the higher radiation fluence.

There exists data on temperature dependence of the depletion voltage measured at 10kHz for similar but less heavily irradiated diodes [4, 5]. Fig. 7 contains data (normalised to the average value obtained below 280K in each case) from two of our diodes irradiated by 1.0 x 10^{14} n cm^{-2} and 2.7 x 10^{14} π cm^{-2}, from a diode tested by Lancaster Semiconductor group irradiated by 0.3 x 10^{14} n cm^{-2} [5], and from a diode irradiated by 0.5 x 10^{14} p cm^{-2} [4]. Five percent errors are assumed on all of the data. All data are in good agreement and follow the same trend, being almost stable below 280K, and rising at higher temperatures.

3.3 Depletion Capacitance

The depletion capacitance for an irradiated diode, as mentioned previously, may vary from the value measured before irradiation. Fig. 8a illustrates that at our very highest frequency the variation from C_o=9pF is very small, but at low frequency, especially as the temperature rises, this variation becomes much larger. This effect can be seen also in fig. 8b . At low temperatures the variation of C_o with period is very small (corresponding to the nearly flat temperature dependence for high frequency).

The depletion capacitance for two diodes (at 1.0 and 2.7 x 10^{14} particles cm^{-2}) is compared at both 1kHz and 10kHz as a function of temperature in fig. 9. The values of C are systematically higher for the more heavily irradiated diode, but the dependence on temperature is approximately the same for both measurement frequencies.

We have compared the results where depletion voltage is extracted from (i) two straight lines, and (ii) the crossing of one straight line with a level fixed at C_o, in the logC-logV plot (fig. 10). The second method gives a much steeper slope, closer to the predicted $\frac{1}{3}$ increase in the range 270-300K than given by the first method. It is clear that two methods typically used to extract depletion voltages give noticeably different results, and hence great care must be taken over how we define depletion voltage.

4 Conclusions

Measurements for diodes irradiated by more than 1 x 10^{14} particles cm^{-2} show that CV characteristics are dependent not only on frequency but also on measurement temperature. An increase in temperature has a similar effect on the CV as a decrease in measurement frequency. The slopes of the two parts of the CV curves are also dependent on frequency and temperature, becoming steeper as temperature increases or as frequency is decreased. Our results are seen to agree with the theoretical prediction made in equation (1), that a linear decrease in temperature is equivalent to a logarithmic increase in measurement frequency.

The depletion voltage extracted using fitting of two straight lines in the logC-logV plot was seen to vary with temperature and period. The variation with temperature was only a 15-20% effect for a 50K temperature change, not the 30% for 30K effect predicted in reference [3]. The systematic increase of depletion voltage at a fixed temperature with the period of the measurement AC signal indicates the existence of a systematic effect influencing the value of depletion voltage extracted from the CV measurements.

The depletion capacitance was found to differ from C_o in several cases. For more heavily irradiated diodes the change in level becomes significant, and this may cause a noticeable difference between the results obtained by the two methods of depletion voltage measurement.

It is clear that further investigations are necessary to understand better the proper definition of the depletion voltage for heavily irradiated diodes, examining the possible existence of a transition region between the space charge region and undepleted silicon in the diode. Then we may know the correct way by which we can define the depletion voltage and extract its value from the CV measurements.

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Figure Captions

Fig. 1. LogC-logV at 273K for a diode irradiated by 1.1 x 10^{14} n cm^{-2}

Fig. 2. LogC-logV at 10kHz for a diode irradiated by 1.1 x 10^{14} n cm^{-2}

Fig. 3. (a) $|S1|$ versus T for a diode irradiated by 1.1 x 10^{14} n cm^{-2}
(b) $|S1|$ versus period for a diode irradiated by 1.1 x 10^{14} n cm^{-2}

Fig. 4. (a) $|S2|$ versus T for a diode irradiated by 1.1 x 10^{14} n cm^{-2}
(b) $|S2|$ versus period for a diode irradiated by 1.1 x 10^{14} n cm^{-2}

Fig. 5. (a) Depletion voltage versus T for a diode irradiated by 1.1 x 10^{14} n cm^{-2}
(b) Depletion voltage versus period for a diode irradiated by 1.1 x 10^{14} n cm^{-2}

Fig. 6. Depletion voltage versus T for diode irradiated by 2.7 x 10^{14} π cm^{-2}

Fig. 7. Comparison of depletion voltage data from various sources, all measured at 10kHz (Lanc1 = Lancaster HEP group, Lanc2 = Lancaster Semiconductor group, USA = reference [4], all fluences in 10^{14} particles cm^{-2})

Fig. 8. (a) Depletion capacitance versus T for a diode irradiated by 1.1 x 10^{14} n cm^{-2}
(b) Depletion capaciatnce versus period for a diode irradiated by 1.1 x 10^{14} n cm^{-2}

Fig. 9. Depletion capacitance versus T compared for diodes irradiated by 1.1 and 2.7 x 10^{14} particles cm^{-2}

Fig. 10. Comparison of depletion voltages extracted from two different fitting methods. Slope from crossing with level at 9pF is 1.2V/K, and from intersection of two straight lines slope is 0.6V/K.