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Capacitance-Voltage analysis at different temperatures in heavily irradiated silicon detectors

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1. Introduction

The main operational parameter of a silicon detector is the charge collected at the electrodes when a particle is impinging on the device. The collected charge should reach its maximum when the detector is fully depleted. Thus it is of major importance to determine the full depletion voltage of the detector before and after irradiation with fast hadron fluence (Φ). The measurement of the full depletion voltage is usually performed by capacitance-voltage analysis (C-V). Standardization of the procedure within RD50 has fixed the test signal frequency of a C-V measurement to 10kHz [1]. Measurements of non-irradiated silicon detectors are usually done at room temperature RT, while after exposure to large fast hadron fluence detectors need to be operated cold to sufficiently decrease the leakage current I (to permit higher operating voltage and dcrease the noise):

$$\frac{I}{Volume} = \alpha \cdot \Phi \qquad (1)$$

where $\alpha = 4 \cdot 10^{-17}$ A/cm for 1MeV neutrons (measured at 20°C after canonical annealing) [2]. As the leakage current is mainly originated by the presence of generation-recombination deep levels close to mid-gap the current dependence on the absolute temperature T is:

$$I(T) \;\alpha\; T^2 \exp(-\frac{E_g}{2KT}) \qquad (2)$$

with E_g =1.12eV the silicon band gap. It is very important to choose the best experimental conditions to make a reasonable comparison of the C-V analysis with charge collection (CCE) measurements performed at low temperature. This work presents a simple and efficient method to quantitatively compare C-V at different temperatures with CCE analyses at low temperature.

2. Experimental Set-Up

Measurements have been performed with micro strip detectors produced at IRST, Trento within the INFN SMART project. They are processed on 300µm thick n- and p-type MCz Silicon wafers of 1-10kΩcm resistivity, with 4.5cm length and 50µm pitch. Detectors have been irradiated at Karlsruhe with 26MeV protons up to the fluence of 4×10^{14}cm^{-2}. More details are given in [3].
The C-V measurements have been performed at SCIPP, UC Santa Cruz. The experimental set-up is based on a HP 4284A LCR meter coupled with the HP 16065A text fixture (modified to permit biasing with voltages up to 1000V). Voltage sourcing and current monitoring are through a Keithley 2410

source/electrometer. The temperature is controlled manually by flushing nitrogen vapour or spilling liquid nitrogen at the bottom of a thermally insulated box containing the sample holder. The temperature is sensed with a Pt resistor (Pt100) to a fraction of 1°C.

3. Experimental Procedure and Results

After heavy irradiation the silicon detector is highly compensated by the radiation-induced traps, and the shallow dopants (mainly P or B) initially present in the material are essentially de-activated [2]. In this situation, the space charge of the device is essentially due only to the deep traps formed by irradiation. The emission coefficient e_n of these radiation induced traps is thermally activated through a Boltzmann factor depending on the distance in energy between their energy level and the edge of the conduction or valence band, E_t:

$$e_n \ \alpha \ T^2 \exp(-\frac{E_t}{KT}) \qquad (3)$$

During the C-V measurement an AC test signal is superimposed on the constant applied bias. Due to this a.c. signal, those deep traps that are close to the interface continuously switch between the depleted and the neutral regions. In the depleted region they are supposed to be empty and so contribute to the space charge of the device, while in the neutral region they are filled with charged carriers and thus neutral. If the test signal frequency is sufficiently low, i.e. compared with the emission constant of the trap, this process of filling and re-emptying the traps will be measured by the device. Conversely, at sufficiently high test signal frequencies the measurement will be blind to the presence of the deep traps, so the material will appear essentially intrinsic. As a result, a flattening of the capacitance voltage measurement will be observed (Fig.1).

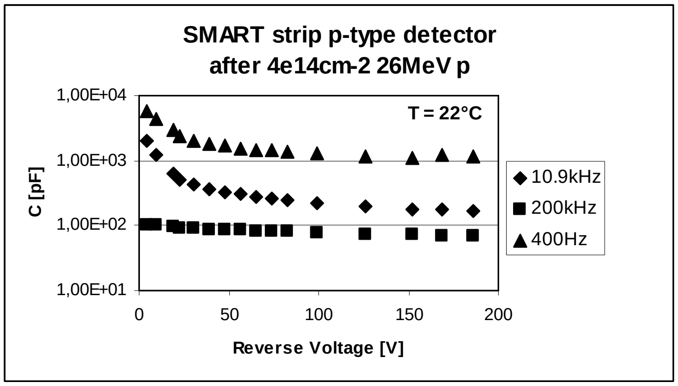

Fig. 1 Capacitance vs. voltage (C-V) for different test signal frequencies measured at room temperature (22°C) on an n-on-p irradiated SMART MCz Si micro strip detector.

As the emission coefficient is thermally activated (see eq.3) the test signal frequency f where this flattening is occurring depends on the temperature through: f ~ e_n [4]. Thus the capacitance voltage characteristic of an heavily irradiated detector measured at 10kHz will appear considerably flattened going from room temperature to low temperature. As an example, fig. 2 shows results for an irradiated n-type MCz Si detector: the shape of the curves measured at RT (22°C) and low temperature (-10°C) are indeed quite different. Since our ultimate interest will be to perform a comparison between C-V analysis and charge collection studies, from now on we are showing the reciprocal capacitance as a function of the reverse voltage, since it should be a measure of the depth of the depleted region.

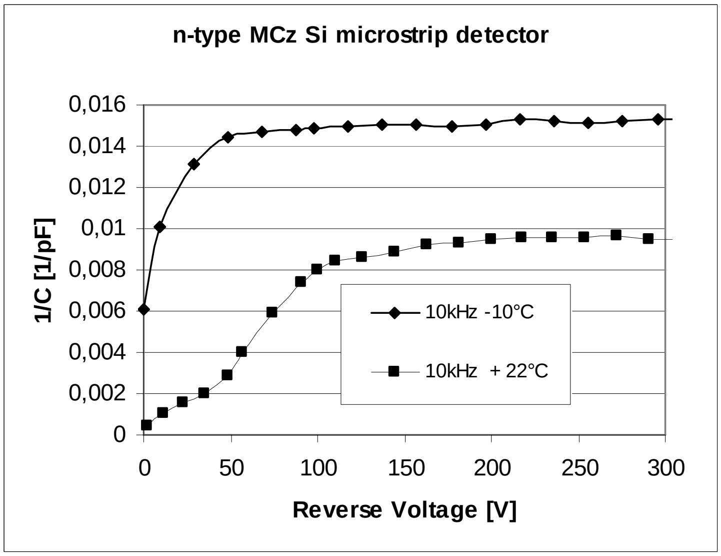

Fig. 2 Reciprocal of the capacitance vs. voltage measured at 22°C and -10°C on p-on-n irradiated SMART MCz Si microstrip detector with a 10kHz test signal frequency.

Based on this principle, the correct frequency f(T) to be used at the temperature T to correctly scale the room temperature frequency f(RT) is:

$$f(T) = \frac{e_n(T)}{e_n(RT)} f(RT) \tag{4}$$

To determine the frequency at low temperature we need thus know the value of the activation energy of the main radiation-induced traps (eq. 3). Actually, it is well known that in irradiated silicon, those traps with energy levels close to midgap are the main contributors to the radiation damage of the detector. Thus, by directly comparing eqs. 2 and 3, we observe that we can easily express the ratio of the emission coefficients at two different temperatures as the ratio of the leakage current measured at those two temperatures. Thus:

$$f(T) \approx \frac{I(T)}{I(RT)} f(RT) \tag{5}$$

Before testing the validity of this approach with measurements let us mention an important experimental detail that can affect the search of the best frequency at low T. Due to the high leakage current flowing in the heavily irradiated silicon detector, self-heating of the detector under test may occur at room temperature when high voltages are applied. A test has been carried out using a Pt100 temperature sensor in the sample holder during a C-V measurement up to 350V in air. During the measurement cycle, the temperature was seen to change from 22.2°C to 32°C due to the self-heating effect. As a consequence the current is seen to increase super-linearly with the voltage, especially at high voltage. A second measurement has been carried out by maintaining the temperature constant to 22.2°C by means of a continuous nitrogen flux in the measurement box. Results are shown in fig. 3.

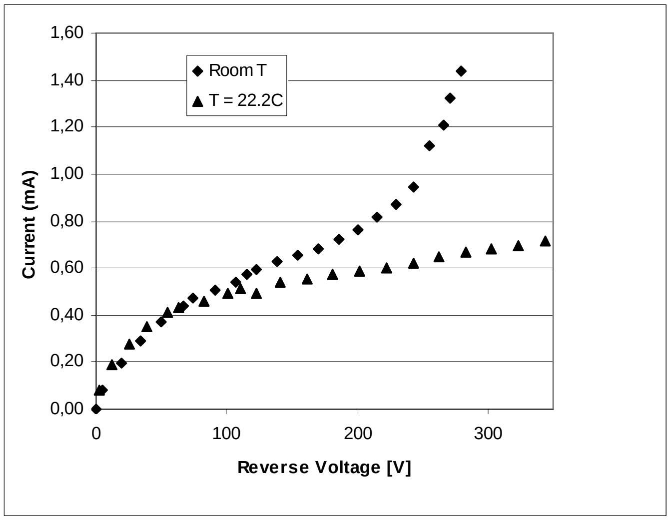

Fig. 3 Leakage current vs. voltage as measured during a C-V measurement on a p-on-n irradiated SMART MCz Si micro strip detector. One curve was measured without keeping the temperature constant ("Room T"), the other while maintaining T constant at 22.2°C by flowing nitrogen in the sample holder.

Moreover, the increase of temperature and leakage current has a non-negligible effect on the value of the capacitance measured at high voltage. An additional complication arises from the fact that the test fixture includes a series resistance of R_S = 100kΩ, which requires the correction of the reverse voltage actually applied to the sample for the voltage drop due to the current flowing in that resistance. Fig. 4 shows the effect of self-heating on the reciprocal of the capacitance vs. voltage curve.

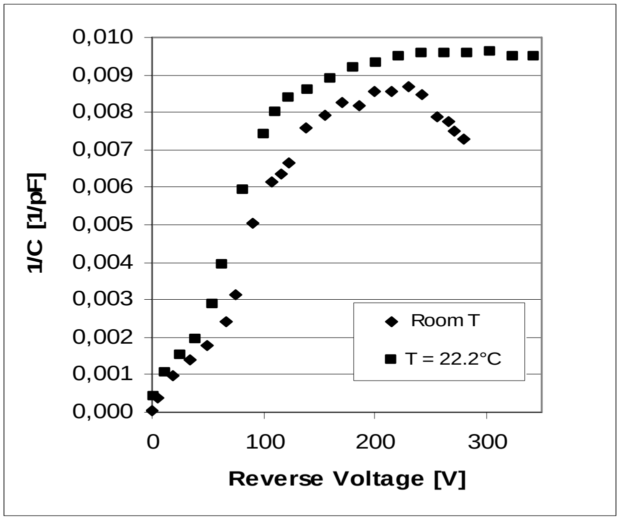

Fig. 4 Reciprocal of the capacitance vs. voltage measured without keeping the T constant (Room T) and maintaining T constant at 22.2°C by flowing nitrogen in the sample holder. Measurements performed on a p-on-n irradiated SMART MCz Si microstrip detector with a 10kHz test signal frequency.

Fig. 5 shows the ratio of the current measured with the same detector at different voltages measured at two different temperatures: T_R = 22.4°C and T_L = -11°C. From eq. (2) the ratio of the leakage currents at these two temperatures is predicted to be $\frac{I(T_R)}{I(T_L)} = 20.3$.

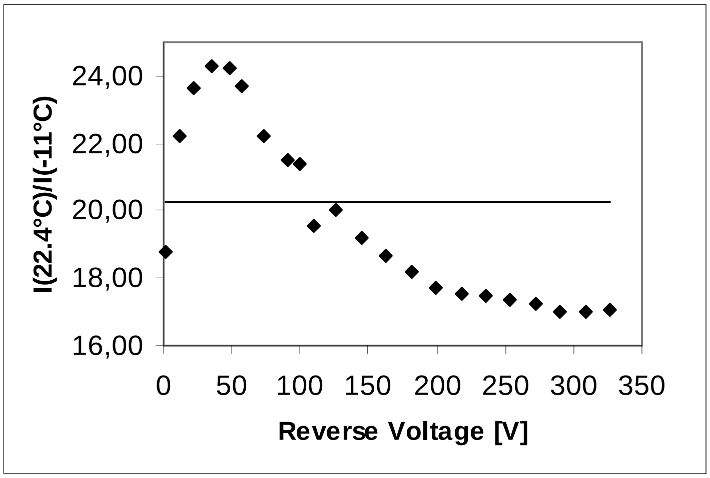

Fig. 5 Ratio of the leakage currents measured at 22.4°C and -11°C as a function of the reverse voltage. The line is the ratio as calculated with eq. (2).

We attribute the fluctuation of this parameter to the fact that the leakage current shows small deviations from the law $I \;\alpha\; \sqrt{V_{rev} + V_{bi}}$ (see fig. 6).

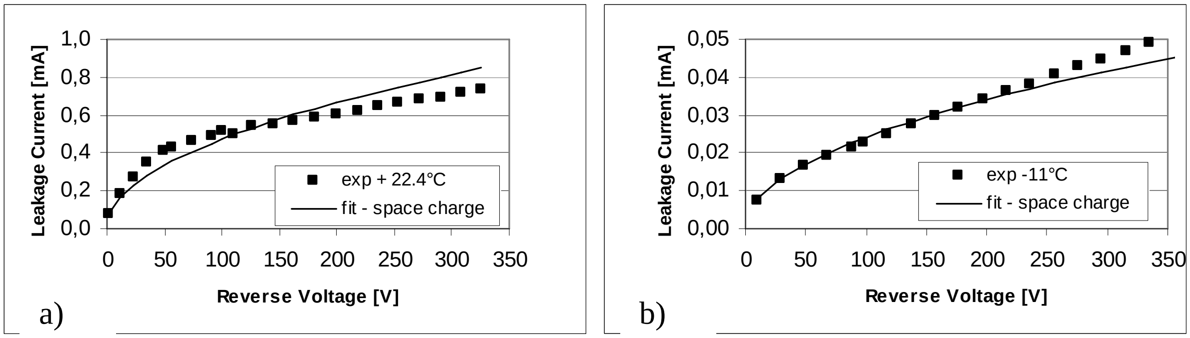

Fig. 6 Leakage current vs. voltage of an irradiated SMART detector (micro strip p-on-n MCz Si) as measured during a C-V measurement at (a) 22.4°C and (b) -11°C. The curves have been fitted using a square root dependence on the reverse voltage, as expected in the development of a rectangular p-n junction space charge region.

We can now calculate the frequency to be used at low T to best approximate a C-V characteristic measured at 9.6kHz and 22.4°C. Fig. 7 shows the best-frequency curve to perform C-V measurements at -11°C, corresponding to Fig. 5. Fig. 8 shows the comparison of the reciprocal capacitance vs. reverse voltage as measured at RT with 9.6kHz and at -11°C with low frequency.

The comparison shows good agreement up to nearly 200V. For higher voltages, the reciprocal of the capacitance still increases with the voltage at low T, while at RT the 1/C vs. V curve is saturating. It is not possible to perform this comparison to higher voltages, because the leakage current at room temperature at this irradiation fluence will exceed the compliance of the power supply.

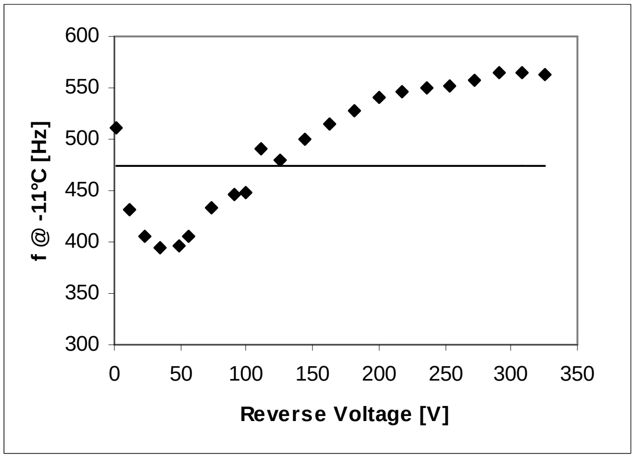

Fig. 7 Best low temperature frequency as determined by the ratio of the leakage currents measured at 22.4°C and -11°C. The line shows the frequency calculated from the temperature ratio with eqs.2 and 5.

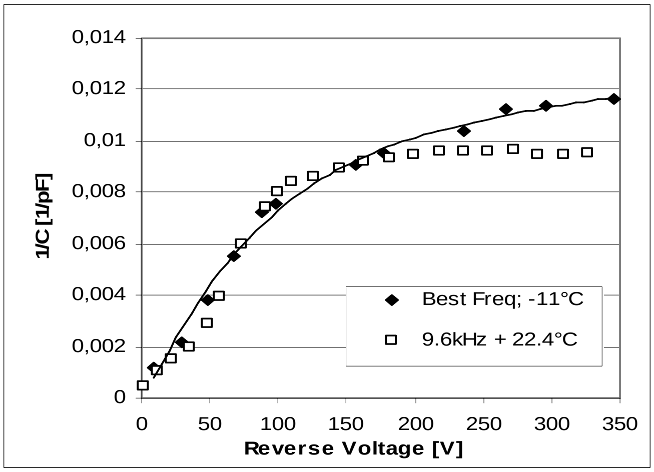

Fig. 8 Comparison of the reciprocal capacity 1/C vs. V at low frequency and -11°C and with 9.6kHz, 22.4°C.

We are ultimately interested in comparing the 1/C vs. V curves with the charge collection (CCE) measurements performed at low temperature. We thus show in fig. 9 the median value of the charge as a function of the reverse voltage. This measurement is performed using a ^{90}Sr beta source and an electronic read-out with 200ns shaping time, as described in Ref. [5]. We have superimposed the collected charge with the data of several normalised 1/C vs. V measurements taken at the following pairs of frequency and temperature: low frequency LF (500Hz) and -11°C; 9.6kHz and 22.4°C; 9.6kHz and -11°C. We observe that: (a) the 9.6kHz curve at -10°C is much too flat to describe the charge collection profile over the entire voltage range; (b) the 9.6kHz curve at +22°C is in agreement with the charge collection profile up to approximately 200V, then it saturates, while the CC is still increasing; (c) the low frequency 1/C curve at -11°C is fitting the charge collection profile well over the entire voltage range.

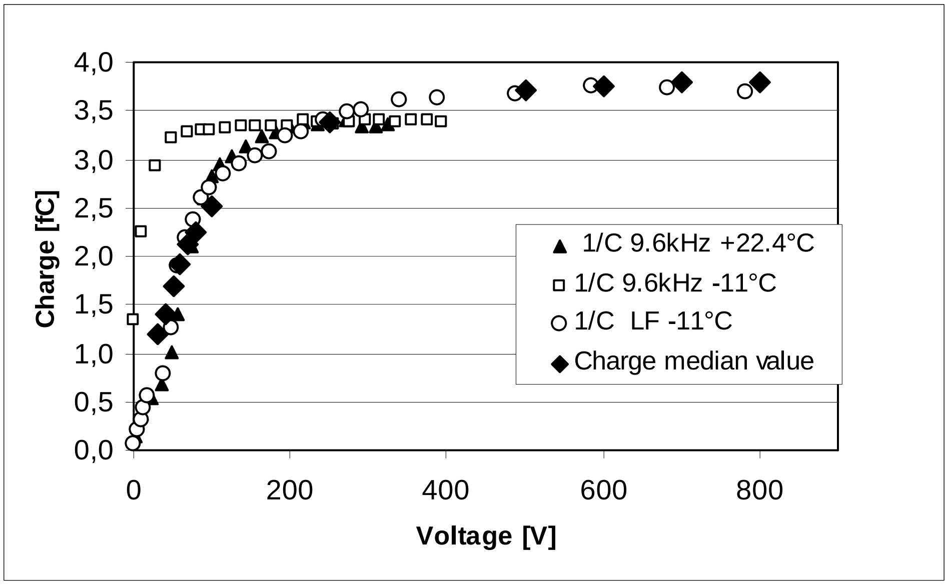

Fig. 9 Median value of the collected charge in an irradiated n-type MCz Si micro strip detector [5] compared to the normalised reciprocal capacitance measured at different temperatures with test signal of different frequencies.

Conclusions

We have analysed the C-V curves of Si detectors irradiated with 26MeV protons up to 4x10^{14}cm^{-2} at different temperatures and frequencies. We have determined the right scaling of the test signal frequency when the temperature is decreased from room temperature RT (22.4°C) to -11°C. Comparing the charge collection profile vs. reverse voltage with the normalised reciprocal capacitance measured at room T and 9.6kHz we observe fair good agreement up to approximately 200V. For higher voltages the C-V curve is flat, while the charge collection still increases. The best agreement in the entire voltage range is achieved when the C-V measurement is done at lowered temperature at low frequency. The value of the frequency, close to 500Hz, is determined by scaling 9.6kHz with the ratio of the leakage current as measured at -11°C and at RT.

References

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