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# Charge collection and capacitance–voltage analysis in irradiated n-type magnetic Czochralski silicon detectors

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**Abstract**

The depletion depth of irradiated n-type silicon microstrip detectors can be inferred from both the reciprocal capacitance and from the amount of collected charge. Capacitance voltage (*C–V*) measurements at different frequencies and temperatures are being compared with the bias voltage dependence of the charge collection on an irradiated n-type magnetic Czochralski silicon detector. Good agreement between the reciprocal capacitance and the median collected charge is found when the frequency of the *C–V* measurement is selected such that it scales with the temperature dependence of the leakage current. Measuring *C–V* characteristics at prescribed combinations of temperature and frequency allows then a realistic estimate of the depletion characteristics of irradiated silicon strip detectors based on *C–V* data alone.


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*Keywords:* Silicon detectors; Radiation effect; Charge collection measurement

## 1. Introduction

The main operational parameter of a silicon microstrip detector is the bias voltage dependence of the charge collected at the electrodes when a particle is traversing the device. For a minimum ionising particle (mip), the number of electron/hole pairs is generated uniformly in the detector with 73 e/μm [1], and thus the most probable charge generated is linearly proportional to the thickness of the depleted region. For this reason, the profile of the collected charge for *mips,* evaluated as a function of the applied reverse voltage (CC($V$)), should exhibit the same trend as the reciprocal of the capacitance vs. voltage ($C^{-1}(V)$), since the capacitance of a parallel-plate capacitor varies inversely with its thickness. (This is strictly true only as long as trapping effects can be neglected, which become very important at fluences above $10^{15}\,n_{eq}/cm^2$ [2]).

Predicting the voltage dependence of the charge collection of irradiated sensors from straight-forward electrical measurements facilitates the planning of experiments, and for many years *C–V* measurements have been used for that purpose, as the measurement of the CC($V$) is quite time consuming and experimentally more difficult with respect to a $C^{-1}(V)$ analysis. However, in order to be able to quantify this comparison, it is very important to determine the experimental conditions for which the charge collection CC($V$) can be derived from the capacitance–voltage (*C–V*) characteristics. This is true in particular after fast hadron irradiation at high fluence, when detectors need to be

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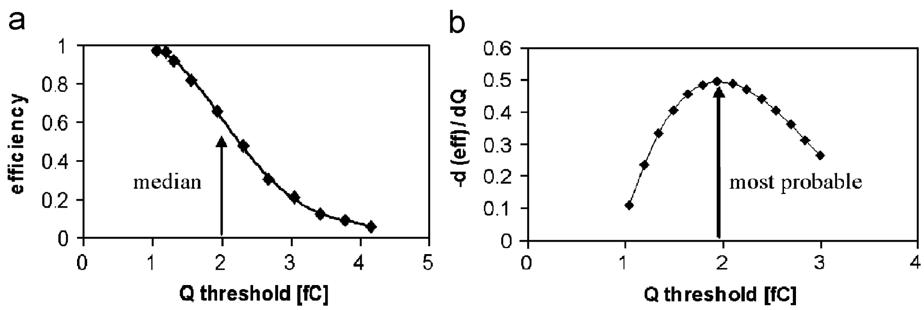


Fig. 1. (a) Efficiency vs. threshold charge for a n-type MCz Si microstrip detector irradiated with 26 MeV protons up to the fluence of $1.7\times10^{14}\,\mathrm{cm}^{-2}$ (5 min annealing at 60 °C) at 80 V and −10 °C. (b) Pulse height spectrum obtained by differentiation.

operated cold to sufficiently decrease the leakage current $I$ generated during irradiation:

$$\frac{I}{Volume}=\alpha\Phi \tag{1}$$

where $\alpha=4\times10^{-17}$ A/cm for 1 MeV neutrons (measured at 20 °C after canonical annealing) [3]. The decrease in leakage current is required to permit higher operating voltage, decrease the noise and avoid self-heating effects. The current dependence on the absolute temperature $T$ is:

$$I(T)\alpha T^2\exp\left(-\frac{E}{kT}\right) \tag{2}$$

where $k$ is the Boltzmann constant. The leakage current is mainly originated by the presence of generation-recombination deep levels close to midgap. Experimentally we find that the activation energy $E$ is close to 0.6 eV for irradiated detectors [4]. It is well known that, after irradiation, radiation-induced deep traps are responsible for a strong dependence of the capacitance on the frequency and temperature. This work presents a simple and efficient method to quantitatively compare $C$–$V$ at different temperatures with CC($V$) analyses at low temperature.

In Section 2 the experimental set-up is described, and the theoretical framework of the correlation between temperature and frequency in $C$–$V$ measurements is explained in Section 3. In Section 4 measurements on an irradiated p-on-n Magnetic Czochralski (MCz) Si detector are used to compare the charge collection with the inverse capacitances at different frequencies and temperatures.

## 2. Experimental set-up

Measurements have been performed with microstrip detectors produced at IRST, Trento within the INFN SMART project [5]. They are processed on 300 μm thick n-type MCz Silicon wafers of about 1 kΩ cm resistivity, with 4.5 cm length and 50 μm pitch. The irradiation was performed at the Forschungszentrum Karlsruhe Cyclotron with 26 MeV protons up to 1 MeV neutron equivalent fluences in the range $10^{14}$–$10^{15}\,\mathrm{cm}^{-2}$.

The measurement of the collected charge on microstrip detectors has been performed at SCIPP, UC Santa Cruz. The CC($V$) investigations have been carried out with a $^{90}$Sr source, using a small scintillator to trigger the binary data acquisition system (DAQ) [6] with a 200 ns shaping time. The $C$–$V$ 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 1000 V). Voltage sourcing and current monitoring are performed through a computer controlled Keithley 2410. In order to reduce the leakage current noise, CC(V) measurements have been carried out close to -10 °C. Low temperature is obtained by 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. Extraction of analogue information from the binary electronic read-out is accomplished by performing efficiency vs. threshold curves, which give the integral of the pulse height spectrum. The following parameters are determined: the efficiency at a fixed threshold of 1 fC, used for example in ATLAS SCT, the median of the pulse height spectrum, i.e. the 50% efficiency point, and the most probable pulse height in the pulse height spectrum, obtained from the threshold curve by differentiation. The method is illustrated in Fig. 1 for an irradiated n-type MCz Si microstrip detector. More details on the experimental system are given in Ref. [6].

## 3. Frequency dependence of the capacitance in irradiated detectors

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 mostly removed or de-activated [3]. 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, $E_t$:

$$e_n\alpha T^2\exp\left(-\frac{E_t}{kT}\right). \tag{3}$$

During the $C$–$V$ measurement an ac test signal is superimposed on the constant applied bias. Due to this ac signal, those deep traps that are close to the edge of the depletion region 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 frequency of the test signal is sufficiently low, i.e. comparable 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 insensitive 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.

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: $f \sim e_n$ [7]. Based on this principle, the proper frequency $f(T)$ to be used at the temperature $T$ can be scaled from the room temperature frequency $f(\mathrm{RT})$ using the respective emission coefficients $e_n$:

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

Since in irradiated silicon the traps with energy levels close to midgap are the main contributors to the radiation damage of the detector, the value of the activation energy in Eq. (3) is approximately the same as in Eq. (2), and the ratio of emission coefficients at two different temperatures in Eq. (4) simply becomes the ratio of leakage currents measured at those two temperatures. Thus Eq. (4) becomes

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

allowing to scale the frequency correctly when a change in the operational temperature is applied.

As a caveat, it is important to note that even before irradiation, $C$–$V$ measurements on microstrip detectors exhibit a frequency dependence of the capacitance [8]. An example of frequency dependence of the capacitance observed before irradiation is shown in Fig. 2 for a microstrip detector, manufactured with n-type MCz Si. The measurements employ the usual algorithm of the LCR meter which represents the microstrip detector simply as one capacitance and one resistance in series. A wide plateau is observed in the range 0.5–100 kHz. In the figure the behaviour of the capacitance as a function of the frequency has been simulated by adding a term inversely proportional to the frequency, with a constant which scales with the observed resistance. A different value for the resistances of implants and the bulk will modify the measured frequency dependence of the capacitance. This effect is not due to the presence of radiation-induced defects in the material, but it is an artefact of the measurement procedure performed on the detector through the LCR meter, and can be corrected for by treating the strip detector correctly as a network of coupled distributed resistors and capacitors [8]. When occurring simultaneously, the two effects should be properly disentangled before proceeding to a correct comparison between the CC($V$) and $C^{-1}(V)$ profiles.

Our study will be focussed on the plateau range of frequency where only the effect of deep traps is relevant. As a recent standardisation of experimental measurement within the High Energy Physics Community has fixed the test signal frequency of a $C$–$V$ characteristics to 10 kHz [9], we will consider this as the reference parameter at room temperature. The $C^{-1}(V)$ profile of a heavily irradiated detector measured at 10 kHz will appear considerably flattened going from room temperature to a lower temperature such as $-10\,^{\circ}\mathrm{C}$, as an effect of the frozen out of the carriers in the deep traps. As an example, Fig. 3 shows the $C^{-1}(V)$ for a proton irradiated n-type MCz Si detector ($1.7 \times 10^{14}\,\mathrm{cm}^{-2}$ 1 MeV neutron equivalent): the shape of the curves measured at RT (22 °C) and low temperature (−10 °C) are indeed quite different.

The average ratio of the leakage current of this detector measured at different voltages and at two different temperatures ($T_\mathrm{R} = 22.4\,^{\circ}\mathrm{C}$ and $T_\mathrm{L} = -11\,^{\circ}\mathrm{C}$) is $I(T_\mathrm{R})/I(T_\mathrm{L}) = 20.3 \pm 2.0$ (further details can be found in

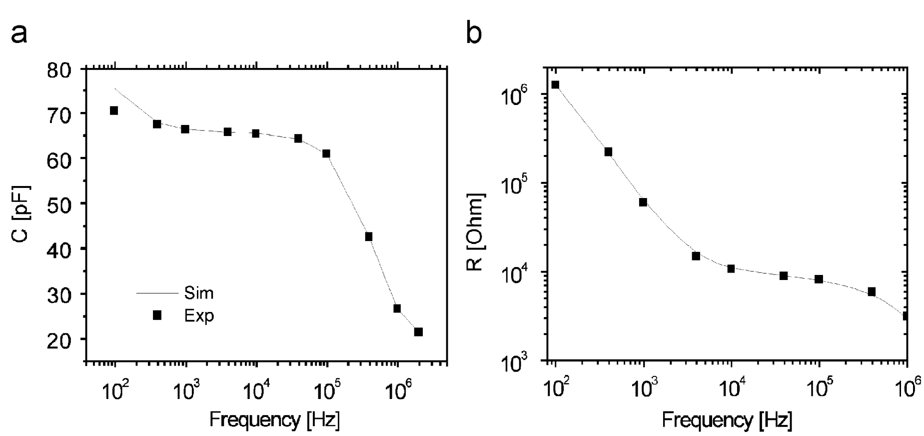


Fig. 2. Capacitance (a) and resistance (b) measured at room temperature in $C_\mathrm{s}R_\mathrm{s}$ mode at 300 V for a p-on-n microstrip detector before irradiation.

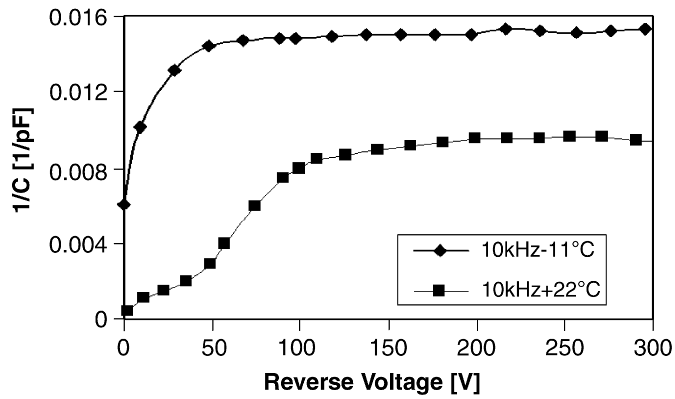


Fig. 3. Reciprocal of the capacitance vs. voltage measured at 22 °C and −11 °C on a p-on-n irradiated MCz Si microstrip detector with a 10 kHz test signal frequency. The fluence of the irradiation was $1.7\times10^{14}\,\mathrm{cm}^{-2}$ (1 MeV $n_{eq}$), with no annealing performed after irradiation.

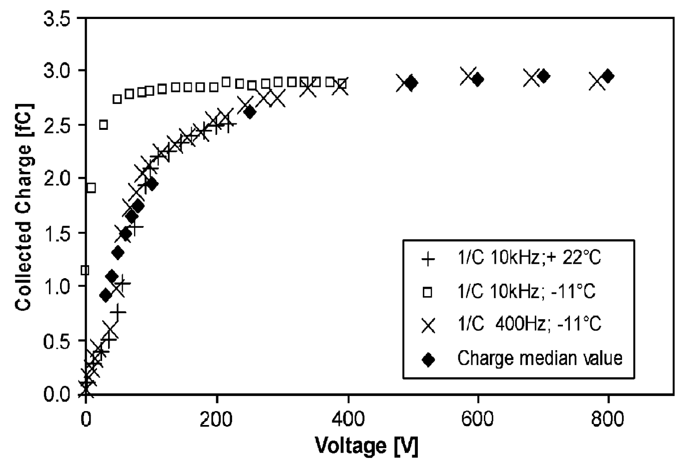


Fig. 4. Median value of the collected charge in an irradiated n-type MCz Si microstrip detector W187-S2 (Fluence of irradiation $1.7\times10^{14}\,\mathrm{cm}^{-2}$ 1 MeV $n_{eq}$), after 5 min annealing at 60 °C, compared to the reciprocal capacitance normalised on the collected charge measured at different temperatures with test signal of different frequencies.

Table 1
Frequency to be used at temperature $T$ to best approximate the 10 kHz RT $C$–$V$ characteristics

| $T$ (°C) | Frequency (Hz) |
|---|---|
| 20 | $10^4$ |
| 10 | $4\times10^3$ |
| 0 | $1.5\times10^3$ |
| −10 | 450 |
| −20 | 200 |
| −30 | 50 |

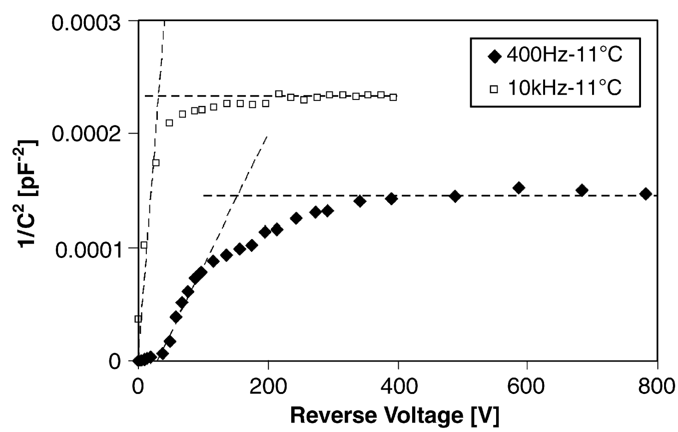


Fig. 5. $1/C^2$ vs. voltage for the irradiated microstrip detector W187-S2 measured with different experimental parameters. Dashed lines are shown to demonstrate the standard method to determine the full depletion voltage.

Ref. [10]). This scaling factor corresponds to an activation energy $E=0.60\pm0.02\,\mathrm{eV}$ in Eq. (3), in agreement with previous literature [4]. Table 1 lists the correct frequency to be used at low temperature T to best approximate a $C$–$V$ characteristic measured at 10 kHz and room temperature (Eq. (5)).

## 4. Comparison between charge collection and capacitance measurements in irradiated detectors

We are ultimately interested in comparing the $C^{-1}(V)$ with the charge collection CC($V$) measurements performed at low temperature. The CC($V$) curve obtained for a n-type MCz Si microstrip detector irradiated with 26 MeV protons up to the 1 MeV neutron equivalent fluence of $1.7\times10^{14}\,\mathrm{cm}^{-2}$ (after 5 min annealing at 60 °C) is shown in Fig. 4. In the high voltage range the inefficiency of the detector is about 10%. We have superimposed the collected charge with the data of three normalised $1/C$ vs. $V$ measurements taken at the following pairs of frequency and temperature: 400 Hz and −11 °C; 10 kHz and 22 °C; 10 kHz and −11 °C. We observe that: (a) the 10 kHz curve at −11 °C is much too flat to describe the charge collection profile over any voltage range; (b) the 10 kHz curve at +22 °C is in agreement with the charge collection profile up to approximately 200 V, (for higher voltages the leakage current exceeds the limit of the $C$–$V$ measurement system, and thus cannot be measured and compared with the CC($V$)); (c) the low frequency $C^{-1}(V)$ curve measured at −11 °C and 400 Hz is fitting the charge collection profile much better over the entire voltage range.

An important parameter usually extracted from the $C$–$V$ characteristics is the full depletion voltage $V_{fd}$, corresponding to the bias required to maximise the charge collected in the detector. In a detector characterised by a uniform doping, such that the effective doping concentration $N_{eff}$ is constant, the $1/C^2$ vs. voltage curve is a straight line for $V<V_{fd}$ and then is a constant for $V>V_{fd}$. In irradiated detectors, $V_{fd}$ is usually determined as the intersection point of the two linear curves in the $1/C^2$ vs. voltage profile

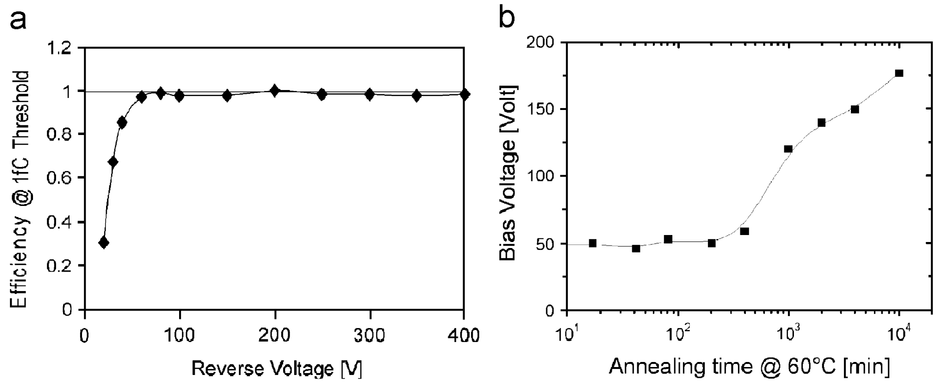


Fig. 6. (a) Efficiency vs. reverse voltage at 1 fC threshold on W187-s4 microstrip detector measured at −10 °C (5 min annealing at 60 °C); (b) Bias voltage required for a 90% efficiency as a function of the annealing time at 60 °C.

best fitting, respectively, the low range, where the sample is under-depleted, and the high voltage where over-depletion occurs. The $C^{-2}(V)$ curve for the irradiated microstrip detector is shown in Fig. 5 for two experimental combinations of the parameters $(f,T)$: (10 kHz; −11 °C) and (400 Hz; −11 °C). Using the standard procedure for evaluating $V_{fd}$ one obtains 48 and 140 V at high and low temperature respectively, quite different. Using Fig. 4, we find first that these values corresponds to about the 45% and 80% of the maximum collected charge, while the maximum CC is actually achieved for $V \approx 350$ V. This indicates that this standard method gives flawed results for the actual full depletion voltage at any frequency, but certainly at 10 kHz. Moreover, when performing $1/C$ measurements at the correct combination of frequency and temperature, the fraction of collected charge at any bias can be predicted.

The strong non-linearity of the $C^{-2}(V)$ at low $T$ could be caused by a non-uniform doping of the device after irradiation. Although this analysis cannot reveal the nature of the radiation-induced deep traps responsible of this strong doping non-uniformity, we suppose that this effect is related to the occurring of a double junction in the irradiated detector [11]. Further analysis of this effect is in progress.

For application as a tracking detector, the efficiency of the sensor at a fixed threshold (usually 1 fC as in the ATLAS-SCT) is of ultimate interest. The efficiency of the CC($V$) for 1 fC threshold is shown in Fig. 6a for the n-type MCz sensor of Figs. 4 and 5. The detector reaches a 100% efficiency in the charge collection already at 100 V, even though the full depletion voltage is 350 V as mentioned before. One of the attractiveness of the Czochralski bulk is the expectation that there is much less reverse annealing than in float zone material [12]. We have performed an accelerated annealing study at elevated temperature (60 °C), where anneal times are a factor of about 700 shorter than at room temperature. To increase the stability of the result, we show in Fig. 6b the bias voltage required for 90% efficiency, since it can be determined much more reliably than the voltage for 100% efficiency. A remarkable result is that this voltage value is almost independent of the annealing time up to 400 min, corresponding to about 200 days at room temperature. At longer anneal time, this voltage increases by about a factor 3 after about 10,000 h. A similar, but less pronounced annealing behaviour is seen in the median pulse height. This time structure is similar to anneal studies using $C$–$V$ data [12].

## 5. Conclusions

We have analysed the $C$–$V$ curves of a n-type Si detector irradiated with 26 MeV protons up to $1.7 \times 10^{14}$ $n_{eq}/cm^2$ at different temperatures and frequencies, and have determined the correct scaling of the test signal frequency for capacitance measurements at low temperature to best reproduce the voltage dependence of the collected charge. The best agreement in the entire voltage range is achieved when the $C$–$V$ measurement is done at low temperature and low frequency ("LTLF"). The value of the required frequency can be determined by a proper scaling through the temperature dependence of the leakage current of the device. The $C^{-1}(V)$ profile done at LTLF can be used to evaluate the voltage required to maximise the collected charge. From the analysis of the median charge determined through an efficiency vs. threshold plot this value is achieved for $V \approx 350$ V, while to reach 100% efficiency at 1 fC threshold (as in the ATLAS-SCT ) the required voltage is about 100 V. The collected charges and efficiencies are practically independent of the annealing time up to 400 min at 60 °C.

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