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Forward bias operation of irradiated silicon detectors

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2. Forward bias IV characteristics
3. CCE under forward and reverse bias
4. Conclusion

1. Introduction

We had first demonstrated the possibility to operate heavily irradiated silicon detectors under forward bias in 1997: NIM A399, pp.35-37.

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Operation of heavily irradiated silicon detectors under forward bias

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Abstract

Test diodes made of detector grade Si have been irradiated by fluences up to 2.8×10^{14} 1 MeV neutrons per cm^2. We observe that signals from minimum ionising particles are produced with high charge collection efficiency (CCE$\sim$70%) at relatively low forward bias voltages. The more usual reverse bias requires $\sim$10 times larger voltage to produce similar CCE.

Further details were published in:

- L.Beattie, A.Chilingarov and T.Sloan, “Forward Bias I-V Characteristics for heavily irradiated Silicon diodes”, ROSE Technical Note ROSE/TN/98-1, March 1998;
- L.Beattie, A.Chilingarov and T.Sloan, “Forward-bias operation of Si detectors: the way to work in high-radiation environment”, NIM **A439** (2000) 293-302.

Our interest to forward bias (FB) was inspired by a substantial flattening of the FB IV curves for irradiated diodes. This was already well known at that time. The main question was: what charge collection efficiency (CCE) one could achieve for practically accessible bias voltages. The answer was very encouraging: CCE of ~**70%** was reached at ~**15%** of the nominal depletion voltage.

This high CCE value can be explained only if the trapping time of the carriers for the FB mode is significantly longer than for the standard reverse bias (RB) mode. Exactly this was expected theoretically. In several publications: e.g. G.Lutz, NIM **A377** (1996) 234; B.K.Jones et al., NIM **A395** (1997) 81, different methods of the trap filling were proposed including **FB**.

Our results were obtained with a moderate cooling: at temperatures between -29^{o} and 0^{o}C. The decrease of temperature expanded the range of possible bias voltage but did not change the CCE. The current decrease with temperature followed the usual exponential pattern. Further cooling clearly looked very advantageous.

The CCE dependence for a wide temperature range is difficult to predict. On the one hand the current filling the trapping centres exponentially decreases with temperature. On the other hand the emission time of the traps increases exponentially with temperature decrease. The exact balance between these two competing phenomena with opposite and rather sharp temperature dependences is sensitive to minor details of the irradiated Si properties.

The later studies by **RD-39** proved the usefulness of the **FB** mode for the temperatures down to 77K. At these temperatures the CCE of **~90%** was reached for the diode irradiated by $5 \bullet 10^{14}$ n/cm^2 and of **~60%** for the diode irradiated by $2 \bullet 10^{15}$ n/cm^2 (K.Borer et al., NIM **A440** (2000) 5-16).

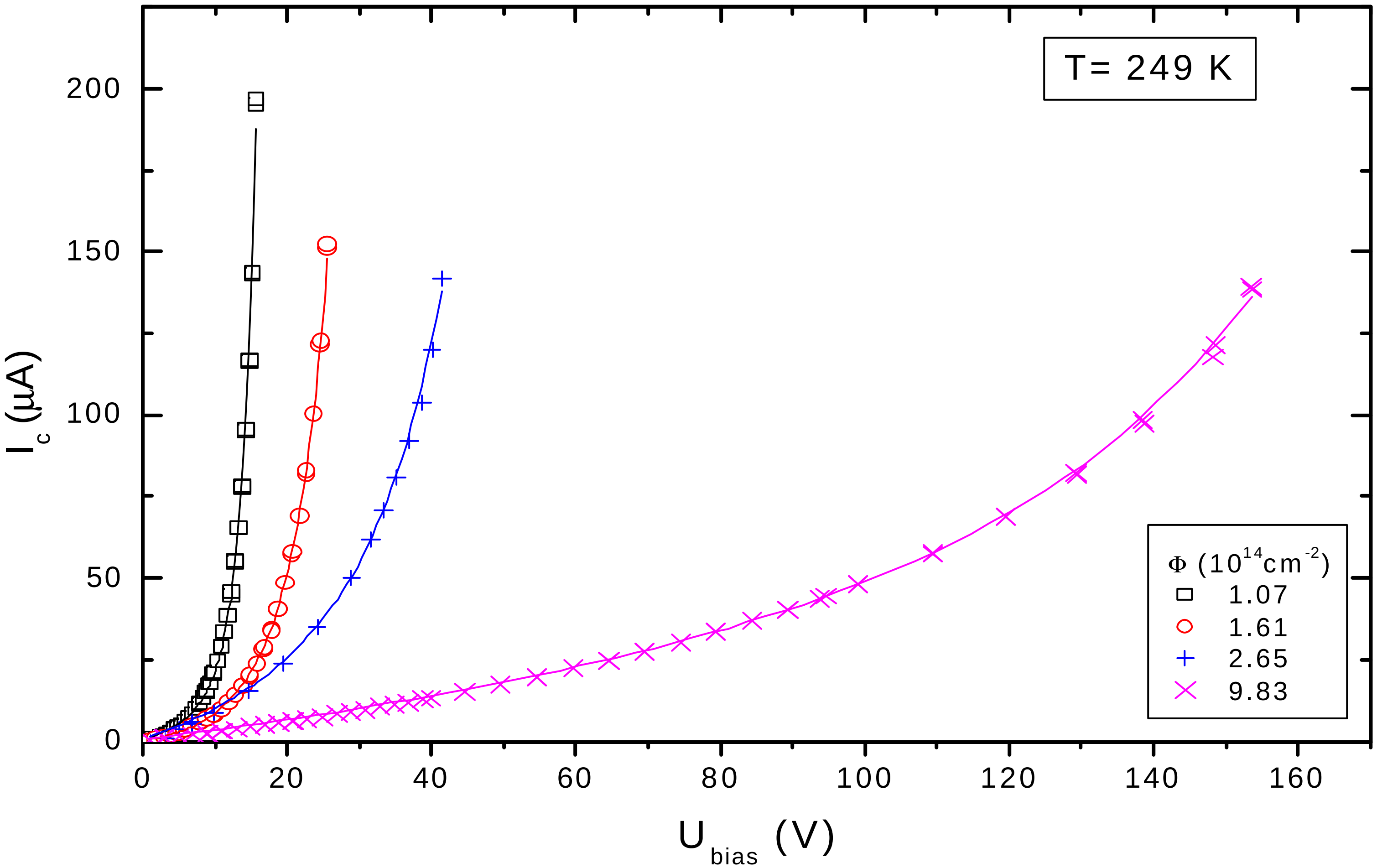
2. Forward bias IV characteristics

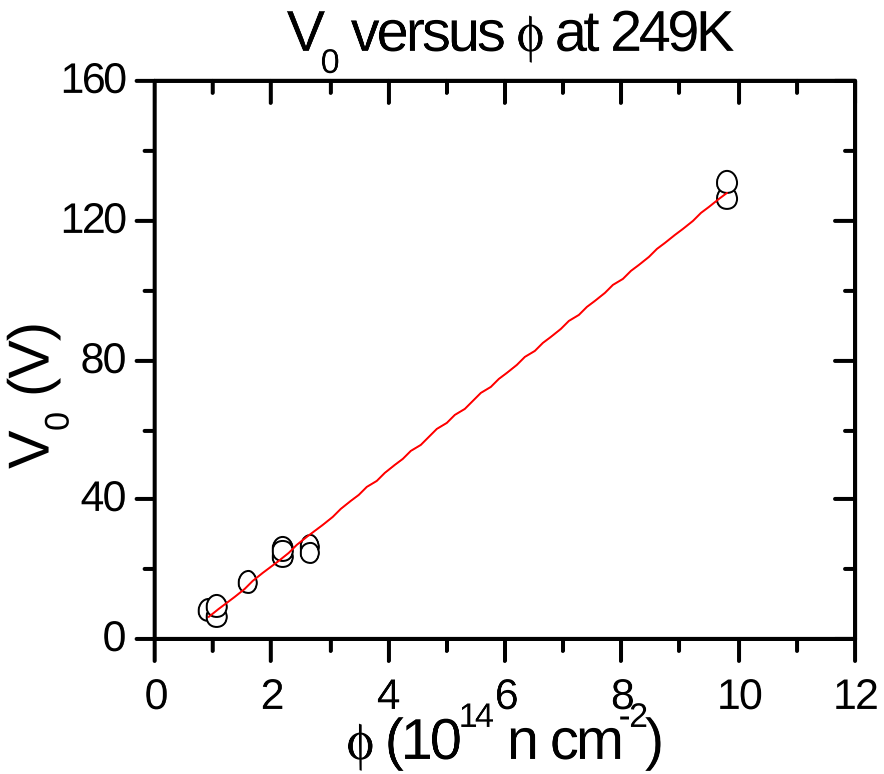
We have investigated IV characteristics for 12 diodes irradiated by fluences in the range (1-10)10^{14} n/cm^2. The temperature range of the measurements was $-29^o - 0^o$C or 244-273 K.

The standard FB IV dependence $I=I_0[\exp(V/V_0)-1]$ with two free parameters I_0 and V_0 did not fit the experimental data very well. A much better fit was obtained with an empirically found 3-parameter function: $I=G_0V+I_0\{\exp[(V/V_0)^2]-1\}$.

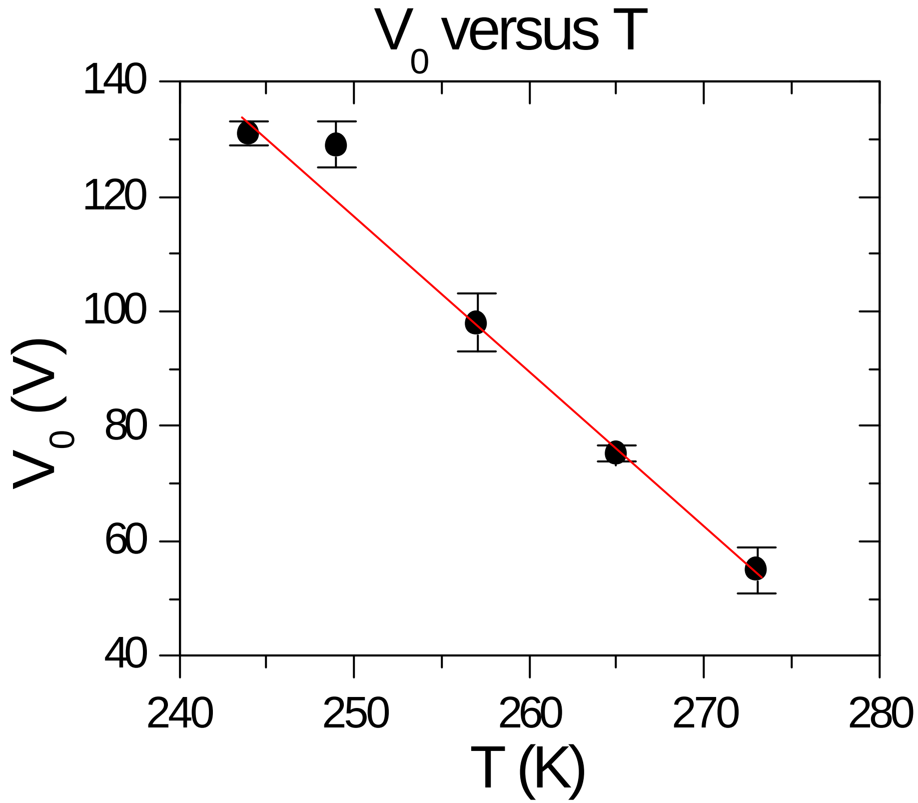
The major parameter defining the rise in the current is V_0. Its value sets a scale for a reasonable achievable bias voltage. This parameter was found to grow ~ linearly with fluence and with a decrease in temperature (within our limited temperature range). Thus to extend the bias range in the FB mode one needs <u>to irradiate the detector and to operate it cool.</u>

IV for different irradiated diodes with fit curves



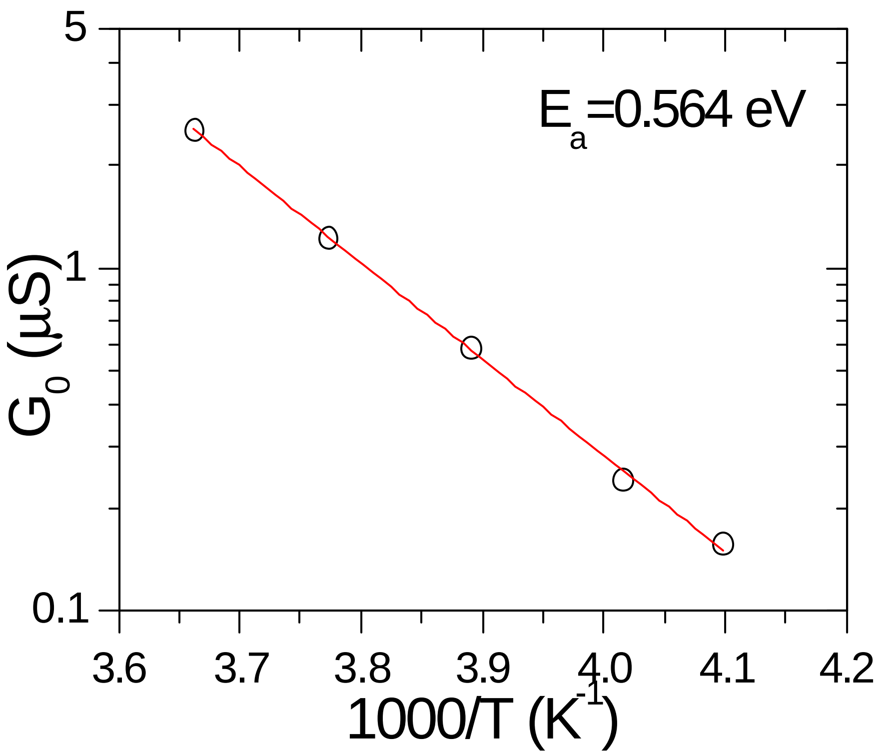


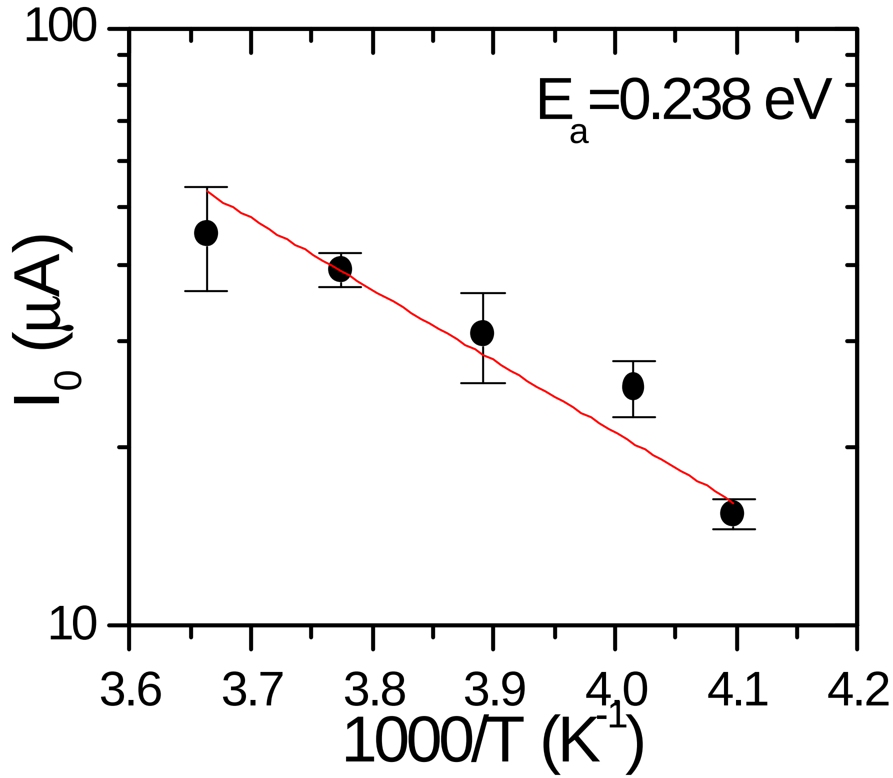
V0 versus φ at 249K
V0 (V)
φ (10^14 n cm^-2)
0
40
80
120
160
0
2
4
6
8
10
12



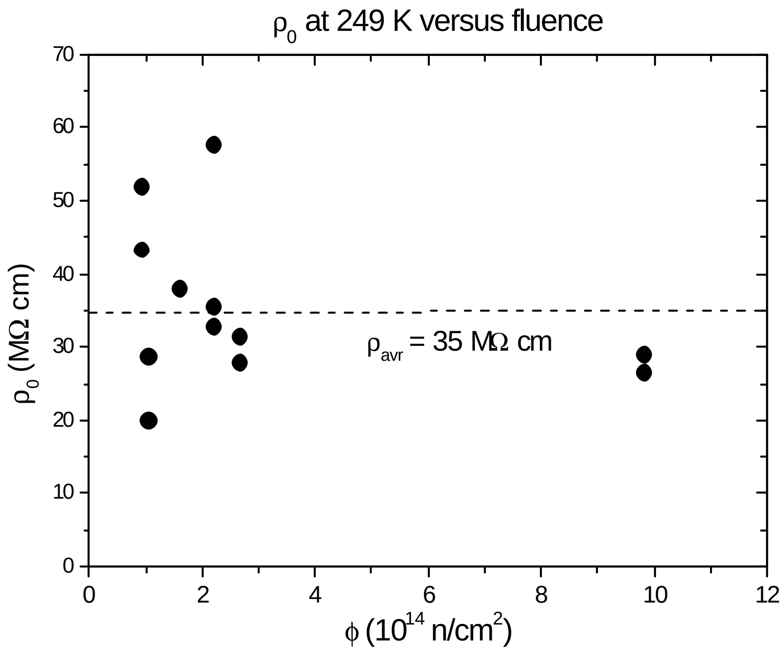
V0 versus T
V0 (V)
T (K)
40
60
80
100
120
140
240
250
260
270
280

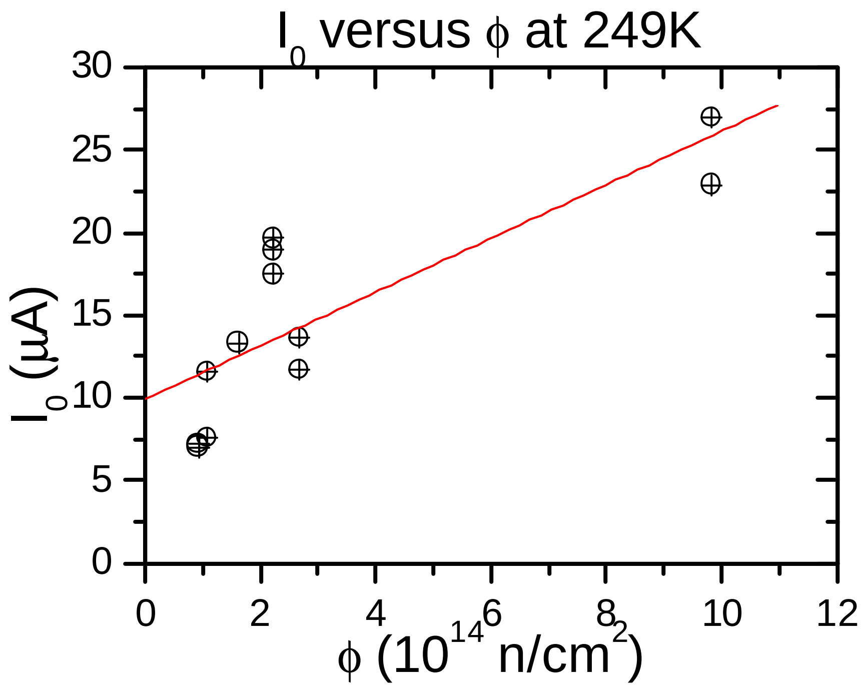
Parameters G_0 and I_0 change with temperature by a standard dependence: $\exp(-E_a/kT)$.





Ohmic conductivity G_0 does not depend on fluence, while I_0 grows with fluence, but rather slowly.





For this plot G_0 was converted to specific resistivity ρ_0 from the relation: G_0=Area/(ρ_0*thickness).

The average value is comparable with the resistivity of intrinsic Si at this temperature.

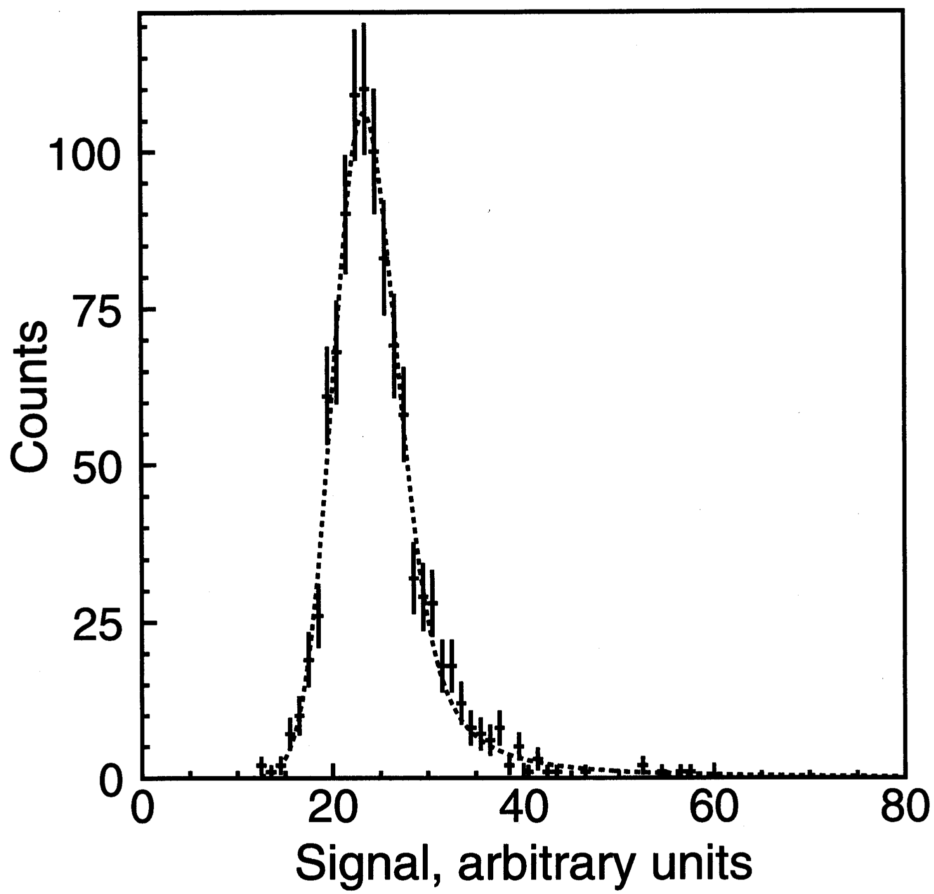
3. CCE under forward and reverse bias

The CCE was measured with a fast amplifier with a shaping time of ~25 ns. Minimum Ionising Particles (MIPs) were emulated by b's from ^{90}Sr source. The MIP spectra were fit by the Landau curve with most probable energy deposition Δ_{mp} and Gaussian smearing σ_G left free in the fit. The fit quality was good for both reverse and forward bias modes.

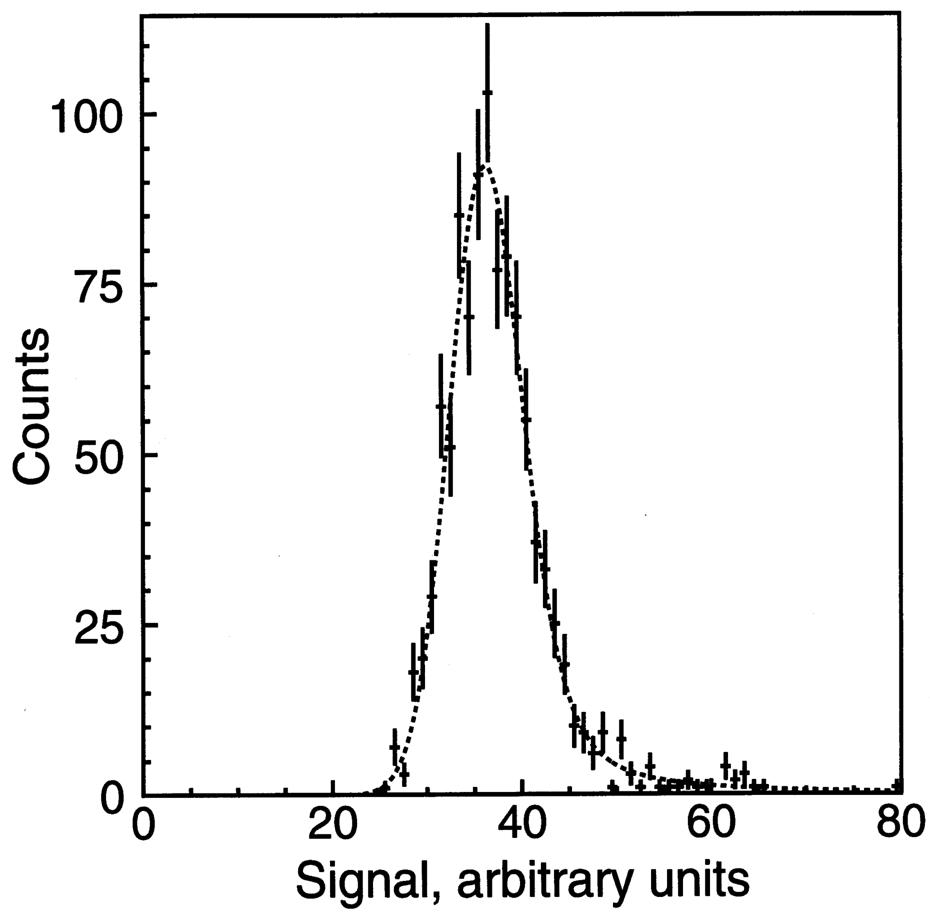
For the FB the width of Landau peak was typically larger than for the RB because of the higher noise related to the larger dark current. Since the Δ_{mp} in the fit was found for the **pure Landau curve before the smearing**, the noise broadening **did not affect the CCE** defined as the ratio of the Δ_{mp} to its value in the same detector before the irradiation.

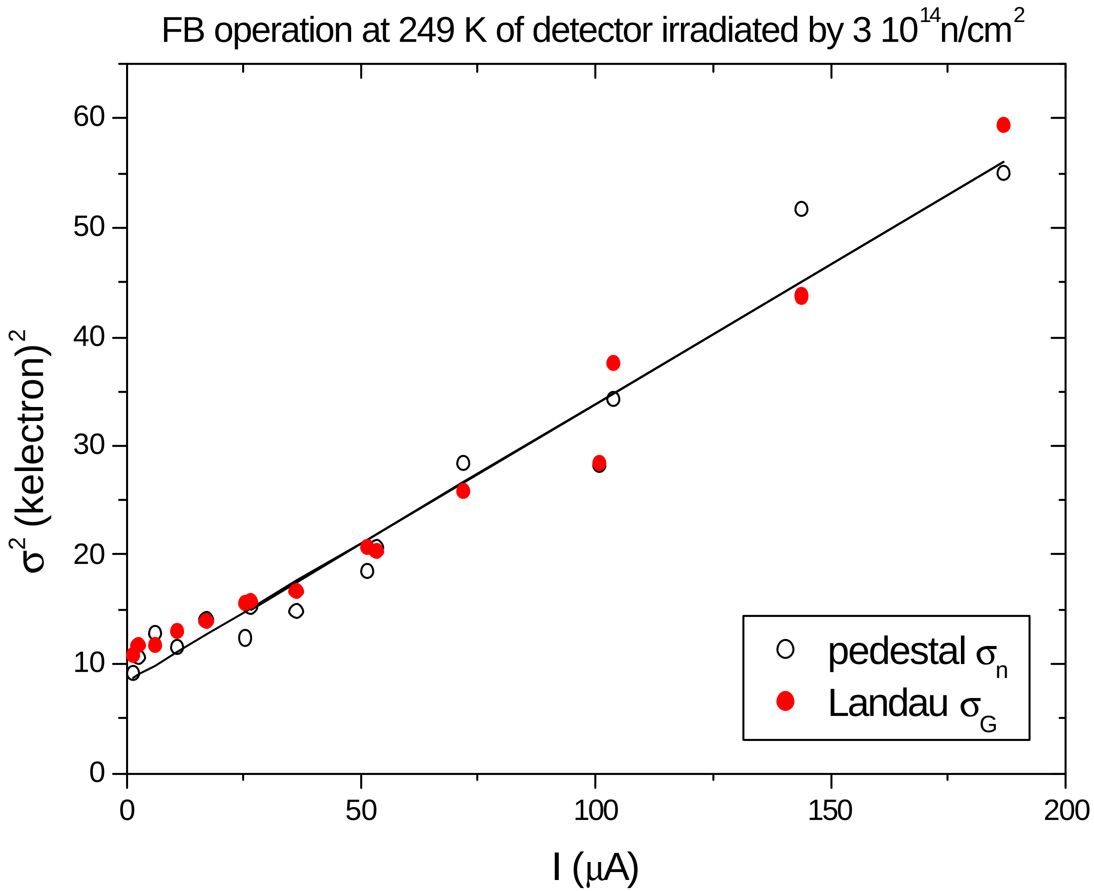
Below there are two examples of the Landau distributions measured at -24^{o}C for the detector irradiated by 10^{15} n/cm^2.

Reverse bias, 700 V



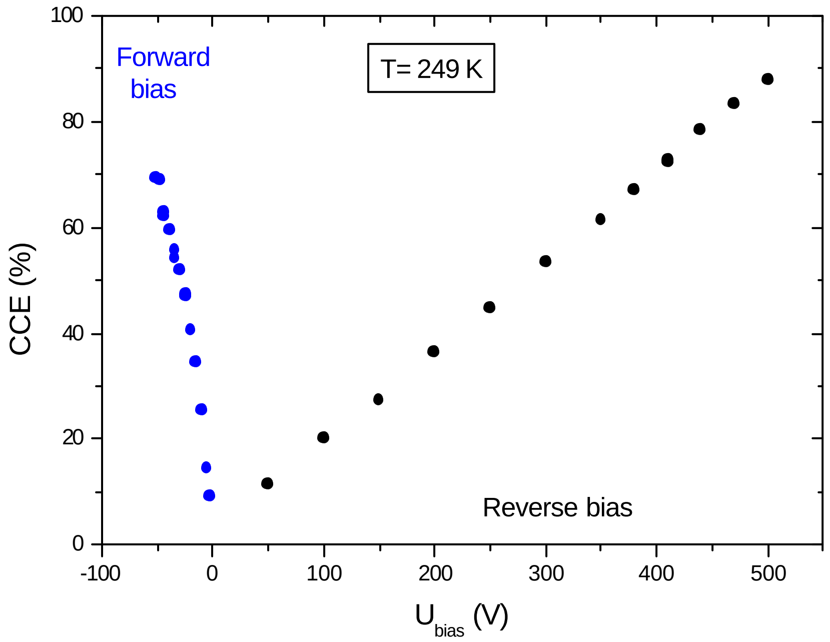
Forward bias, 90 V

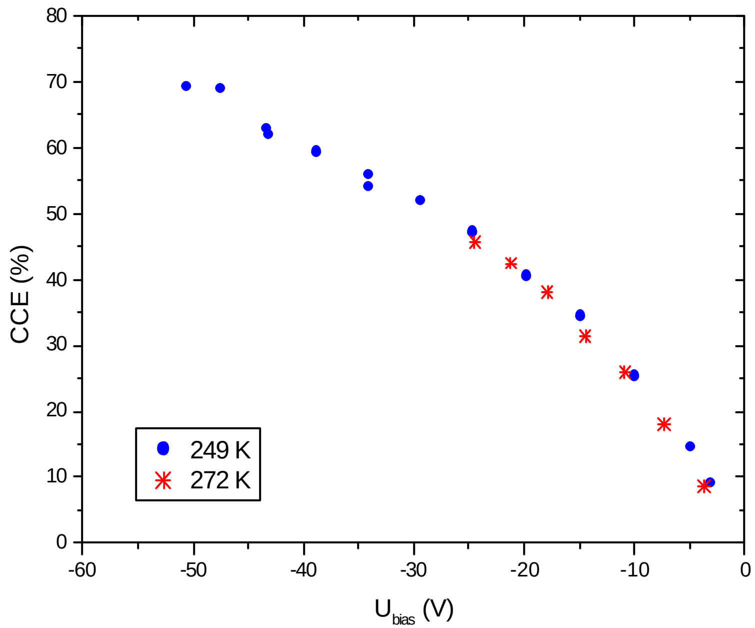




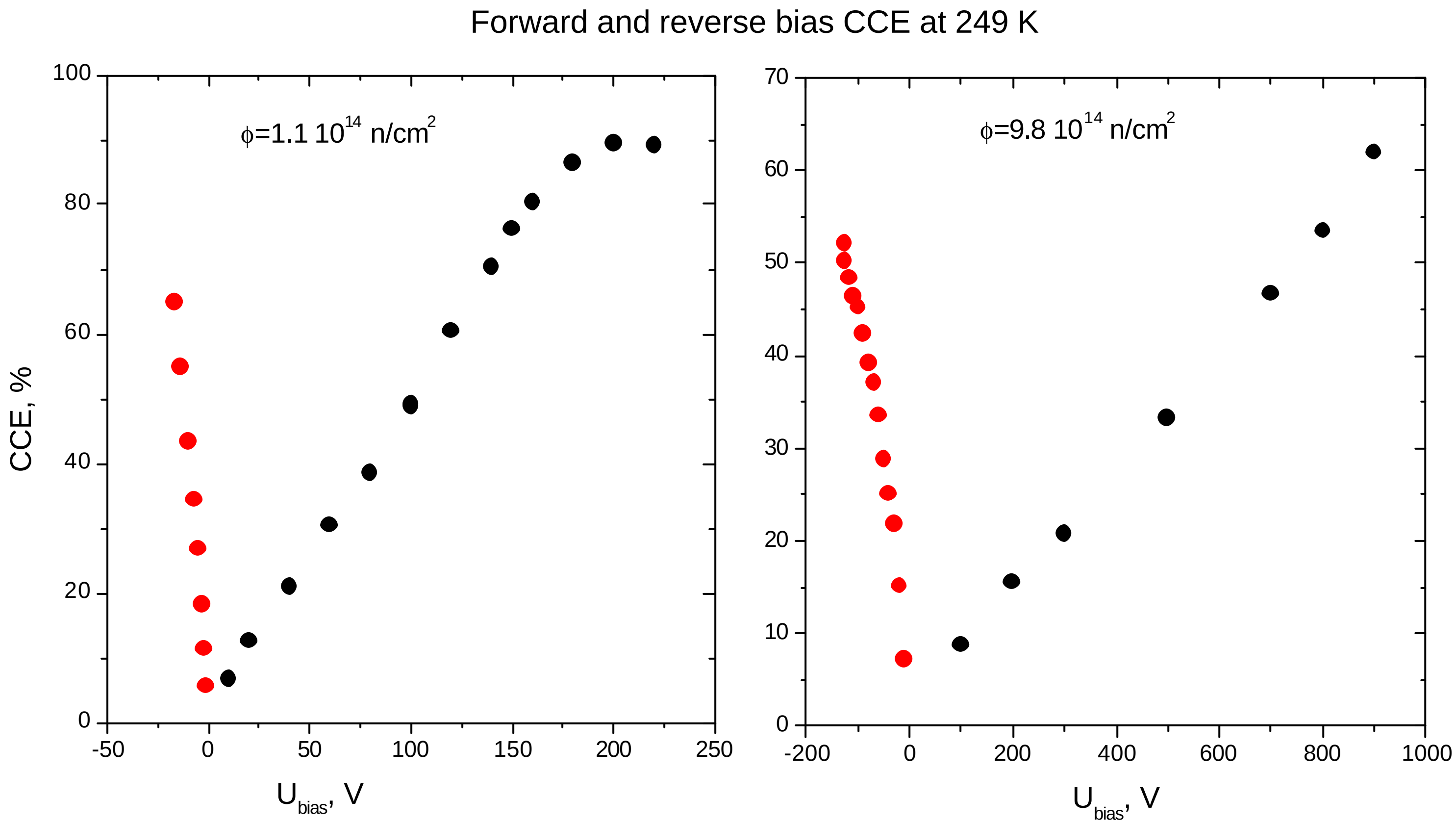
The Gaussian smearing from the Landau fit σ_G agrees well with the noise sigma σ_n found from the pedestal measurements. Both are growing proportionally to the square root of the current proving that this is standard shot noise. The slope corresponds to the shaping time of the electronics.

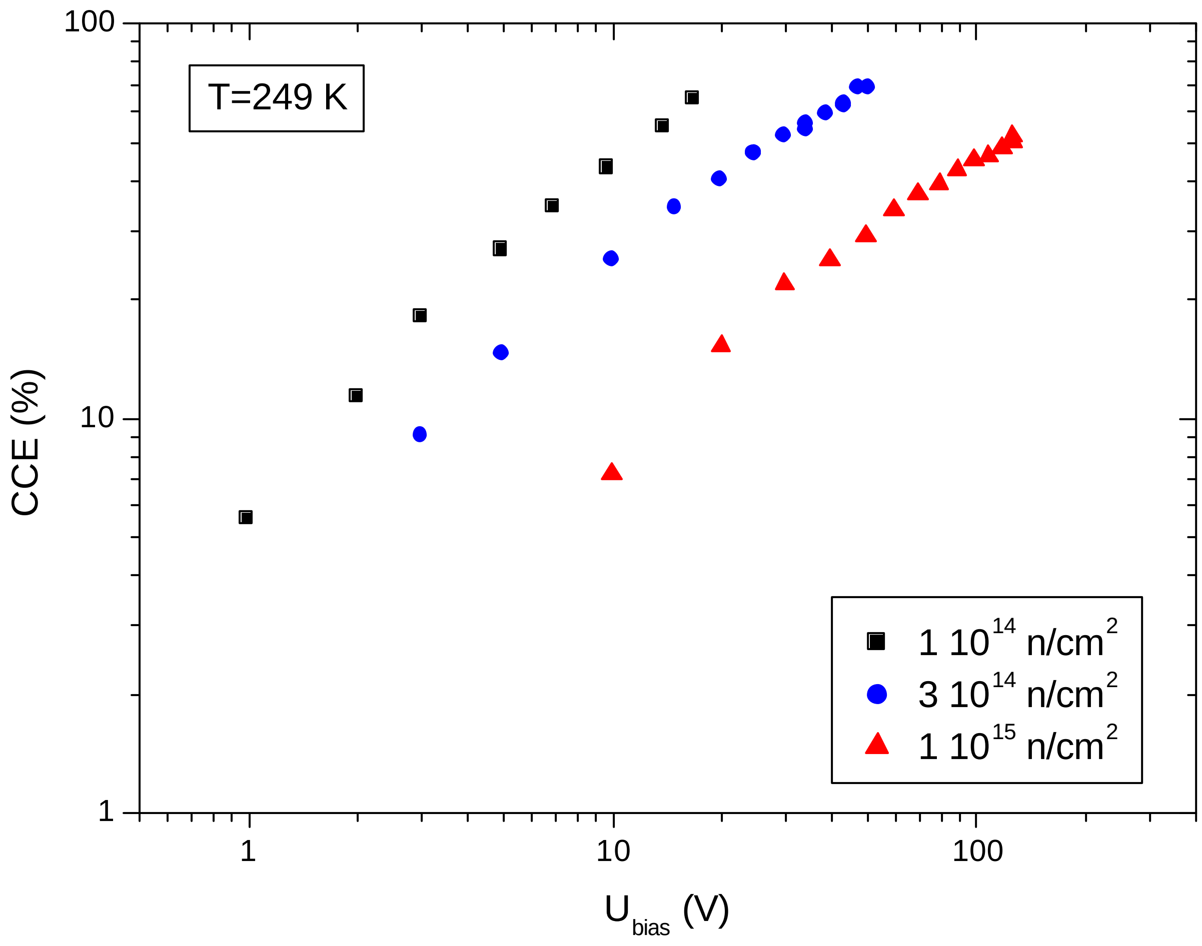
For the FB the CCE grows with voltage much faster than for the RB. Within our temperature range the CCE is independent of temperature. Here are the data for the diode irradiated by $3*10^{14}$ n/cm^2.





A similar pattern is repeated for other detectors irradiated above 10^{14} n/cm^2.





The FB CCE in our data shows no sign of saturation with bias voltage. The U_{bias} in our case was always limited by maximum tolerable current through the detector, which we had chosen as ~6 μA/mm^2. Clearly a further decrease of temperature would allow higher U_{bias} and hence higher CCE. The shape of the CCE dependence roughly scales with the depletion voltage.

As expected the carrier trapping time under the FB is considerably larger than that under the RB due to the filling of the trapping centres by the high dark current. Numerically this can be estimated as follows.

For detectors irradiated by $1*10^{14}$ and $3*10^{14}$ n/cm^2 the RB CCE at the depletion voltage U_{dep} is ~70%. Under the FB such CCE is achieved at ~1/8 of U_{dep}. The CCE loss by the carrier trapping is a function of the ratio between the carrier collection time t_{col} and trapping time τ. With no saturation t_{col} is inversely proportional to the U_{bias}. If in the FB mode the whole detector thickness is fully sensitive, then neglecting carrier velocity saturation and non-uniformity of the field distribution one can conclude that the trapping time under FB is by ~8 times longer than under the RB.

If under the FB a part of the detector thickness is insensitive then the FB CCE loss is partially due to the geometric effects. This makes the estimations more complicated but the result remains approximately the same.

RD39 obtained similar results with standard diodes operated in FB mode at cryogenic temperatures. For the 400 μm thick detector irradiated by 10^{15} n/cm^2 efficiency of ~50% was reached at the field corresponding to the maximum bias in our sample. Note that at higher voltages CCE saturates at ~55% level.

K. Borer et al. / Nuclear Instruments and Methods in Physics Research A 462 (2001) 474–483 **RD39**

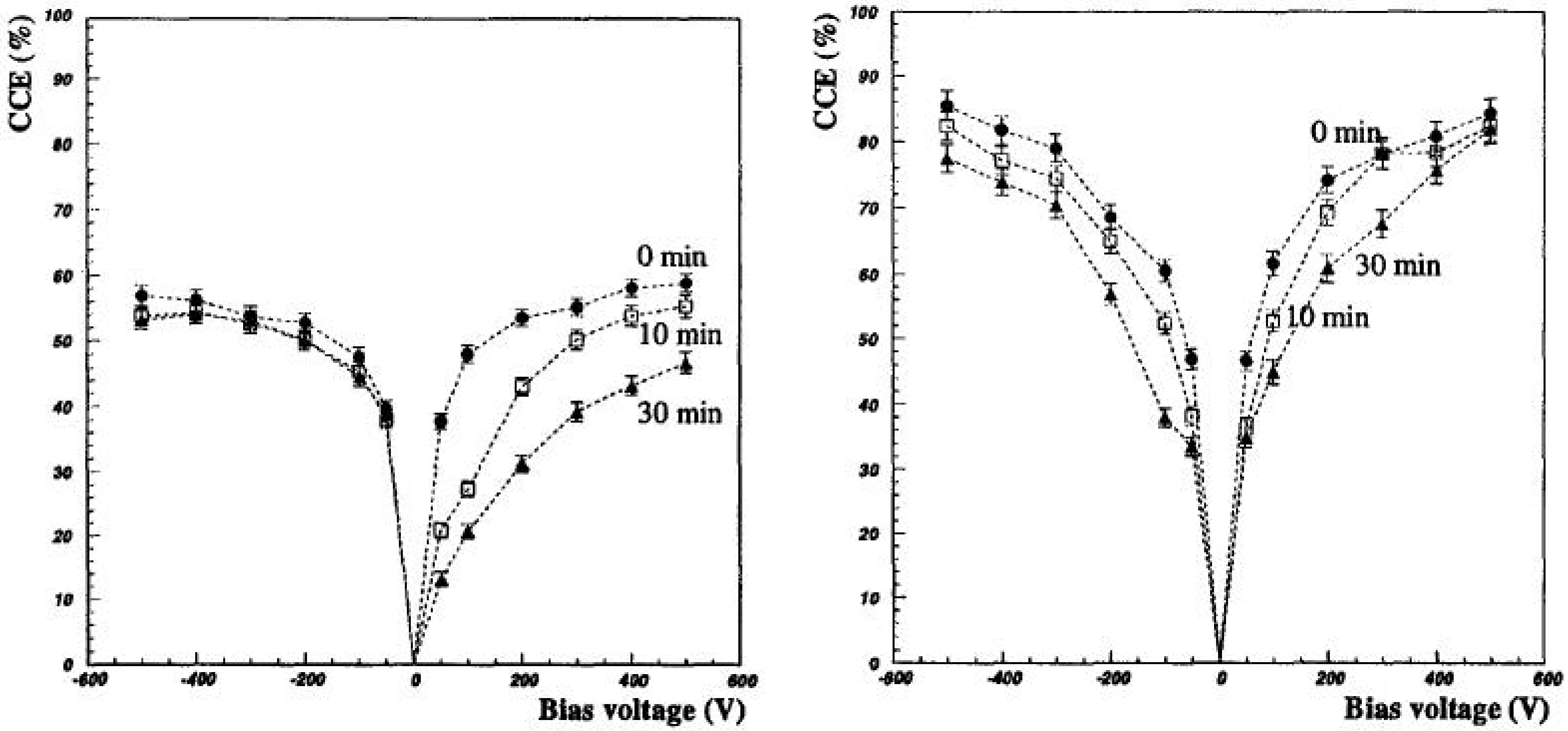


Fig. 7. CCE as a function of the bias voltage at several time intervals after voltage turn-on for the standard (left) and the double-p (right) detectors. In both cases the temperature was 130 K.

Temperature dependence of the CCE in the range 77-200K is complicated but rather weak. The samples 2, 3 and 4 were irradiated by fluences 0.5, 1 and 2 10^{15} n/cm^2 respectively. The CCE for the diode #4 (with 300 μm thickness) does not saturate up to 250 V bias.

K. Borer et al. / Nuclear Instruments and Methods in Physics Research A 440 (2000) 5–16 **RD39**

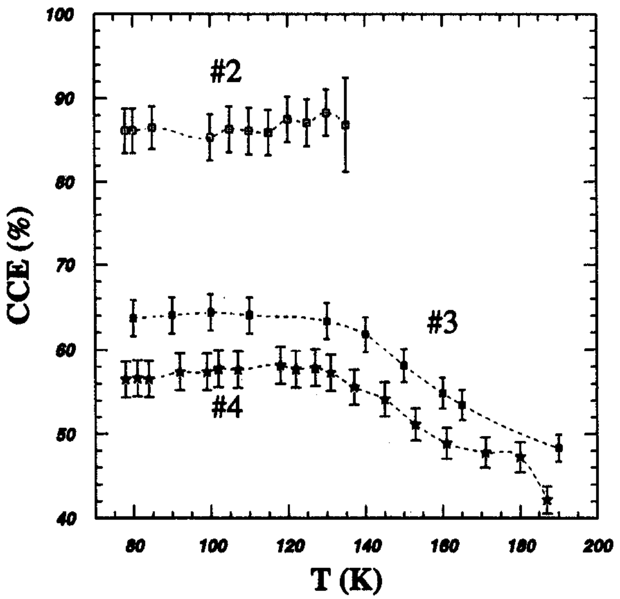


Fig. 7. Temperature dependence of the CCE for detectors #2, #3 and #4. All three detectors were operated at a forward bias voltage of 250 V. Note that the zero of the vertical axis is offset in this plot.

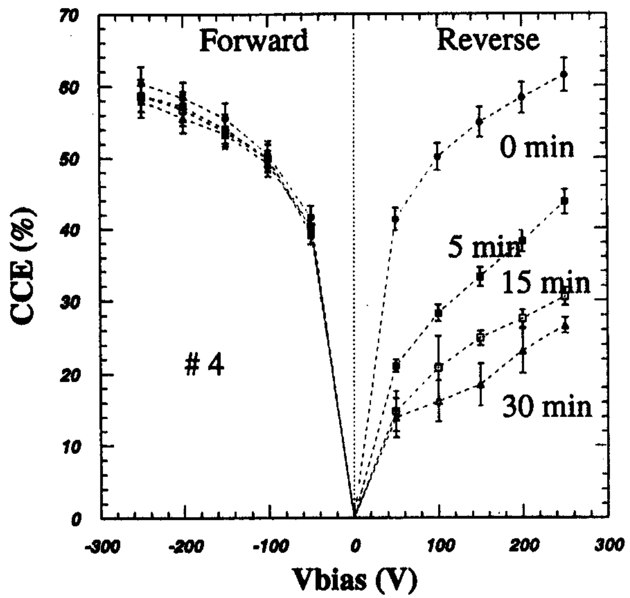


Fig. 8. Voltage dependence of the CCE of detector #4 in the extended voltage range allowed by the forward bias operation. Measurements at different time intervals after HV turn-on are shown.

4. Conclusions

1. The forward bias is a useful mode of operation when the fluence expected in the experiment well exceeds 10^{14} n/cm^2. Under the **FB** the major limitation is the **detector current**, which can **easily** be controlled **by** the operating **temperature**. In the standard **RB** mode the major limiting factor is **depletion voltage**, which is **much less sensitive to the temperature**.

2. With a **moderate cooling** the FB can be used only with irradiated detectors. In a real experiment one can **pre-irradiate** the detectors with ~10^{14} n/cm^2 fluence before using them. Alternatively the **switch from the reverse to forward bias** can be made after high enough detector irradiation. This however requires truly bipolar front-end electronics and looks more complicated.

3. For the FB mode a **current source** can be used to bias detectors instead of the voltage source. It is more natural for this mode and simultaneously **eliminates** the problem of the **thermal runaway**, because the **positive** feed back loop in the system with a fixed voltage on the detector (higher temperature – higher current – higher power dissipation – higher temperature) is replaced by the **negative** feed back in the system with the fixed current through the detector: higher temperature – lower voltage – lower power dissipation – lower temperature.

4. The results of RD-39 have demonstrated the applicability of the FB mode down to cryogenic temperatures. Therefore one can **optimise operating temperature within a wide range** designing a realistic detector system based on the forward bias mode.