ATLAS Internal Note
INDET-NO-176
22 July 1997

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} 1MeV neutrons per cm^2. We observe that signals from minimum ionising particles are produced with high charge collection efficiency (CCE~70%) at relatively low forward bias voltages.The more usual reverse bias requires ~10 times larger voltage to produce similar CCE.

PACS: 07.77.-n; 85.30.-z. Keywords: irradiated silicon detectors; forward bias.

As shown recently [1] the forward I-V characteristictics of Si diodes after irradiation by more than 10^{14} 1MeV neutrons/cm^2 are close to ohmic. Such behaviour was predicted for GaAs devices by a model based on relaxation semiconductors [2,3] and confirmed experimentally[4]. Irradiated Si is expected to be similar to GaAs[5].

The major limitation to the use of Si detectors in high radiation environments is the rise in the full depletion voltage with irradiation dose[6]. Typically a reverse bias of several hundred volts is required to make a Si detector fully sensitive to minimum ionising particles (MIPs) after heavy irradiation. In a forward biased detector the electric field is expected to be nearly uniform in the main part of the bulk while near the contacts the field may be attenuated [3,7]. The larger current under forward bias can play a beneficial role in filling the traps and so increasing the carrier lifetime[5,8].

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[*] To be published in Nuclear Instruments and Methods (1997).

We have investigated two p-i-n diodes with sensitive area 5x5 mm^2 and 300μm thickness made of detector grade n-type Si. Before irradiation the full depletion voltage was measured to be 34V and 15 V for the diodes #1 and #2, respectively. The diodes were irradiated by neutrons with energy ~1 MeV at ISIS at RAL[9]. The fluence equivalent to that of 1MeV neutrons[10] was 1.1 10^{14} cm^{-2} for diode #1 and 2.8 10^{14} cm^{-2} for diode #2. After irradiation the diodes were kept for several days at room temperature until their depletion voltages ceased to decrease. The minimum depletion voltage achieved in this way was 143V for diode #1 and 386V for diode #2 as determined from CV measurements at 10kHz frequency and 273K temperature. Afterwards the diodes were always kept cool and all the measurements were made at temperatures below 283K to prevent reverse annealing[6].

The charge collection efficiency (CCE) was measured for MIPs from a ^{90}Sr β-source and for α-particles from an ^{241}Am source using a preamplifier with 25ns peaking time. A coincidence between two scintillator counters was used for the MIP trigger while for α-particles the trigger was provided by the detector signal itself. MIP spectra were fitted by a Landau distribution and the most probable energy deposition was used for the CCE calculation. The details of the experimental set-up and procedures are published elsewhere[11,12].

Fig.1 shows the MIP CCE for detector #2 under reverse (positive) and forward (negative) bias applied to the n$^+$ contact. For reverse bias the CCE grows linearly with voltage as shown by the fit made to the points with U_{bias} < 400V. Such a dependence can be understood on the basis that: a)the geometrical CCE is proportional to d^2 - the square of depletion thickness[8], which in turn is proportional to U_{bias}; b)the trapping in a partially depleted detector is constant because the effective collection time is proportional to d^2/U_{bias} and therefore does not change with U_{bias}.. The α-particle signals measured under reverse bias also support this model. Simultaneously they show that the depletion region is adjacent to the n$^+$ contact because of radiation induced type inversion (see Ref.[6] and references therein). More data on and more detailed discussion of the CCE under the reverse bias may be found in Ref.[12].

As was shown above, the α-particle data imply that the geometric CCE is not more than 70%. Therefore trapping does not exceed 15% for $U_{bias} > 0.1U_{dep}$. This is less than the trapping at full depletion voltage under reverse bias (see above). But the carrier collection time is about 10 times larger for the 10 times lower bias voltage. Therefore the carrier lifetime due to trapping must be at least 10 times longer in the detector under forward bias than in the same detector under reverse bias. This could be due to trap filling by the large current under forward bias. Such effects were predicted e.g. in Ref.[5,8].

In all the points presented in Fig.3 the quality of the Landau fit was good. The sigma of the gaussian smearing found in the fits was equal to that of the noise determined from the pedestal measurements. The noise sigma grew proportionally to the square root of the dark current as expected from shot noise.

In conclusion we have demonstrated that Si detectors irradiated by more than 10^{14} n/cm^2 can be successfully operated under forward bias and that they give the same MIP signal as that for ~10 times larger reverse bias voltage. This mode of operation looks especially suitable for detectors with small area sensitive elements such as pixels for which the current per element will be low even under forward bias. It should be noted that the MIP CCE values observed here apply to planar diodes and may be different for finely segmented detectors. As shown in Ref.[14] the insensitive layer adjacent to the detection plane affects the signal much more strongly than the same layer near the back plane. The data presented in Fig.2 show that the low field layer is thinner near the p^+ electrode in the forward biased detector. Thus standard p^+ on n detector technology seems to be a natural choice for this mode of operation.

One possible application to a real experiment would be to pre-irradiate Si detectors by a fluence ~10^{14} n/cm^2 and then forward bias them up to the maximum current tolerable by the front-end electronics and cooling abilities of the system (the use of a current rather than a voltage power supply for detector bias seems to be more natural). The data from Ref.[1] show that when the fluence grows up to 10^{16} n/cm^2 the ohmic behaviour of the forward biased Si detectors becomes more pronounced, while the

At 400V reverse bias the CCE reaches 70%. Since at this voltage the detector is fully depleted the remaining 30% deficiency is due to carrier trapping in agreement with earlier observations[13]. The trapping can be further diminished by an increase of the bias above the depletion voltage.

Under forward bias the CCE grows with voltage much faster and reaches ~70% at 50V. Assuming (on the same grounds as above) that the geometric efficiency is proportional to the square of the active (non-zero electric field) region thickness one can conclude that the minimum active thickness (calculated assuming zero trapping) is $\sqrt{0.7}=0.84$ of the total detector thickness i.e. ~250μm.

Fig.2 shows the CCE for α-particles measured with forward bias under the same conditions as for the data in Fig.1. Illumination from the p+ side produces larger signals than that from the n+ side, but both are rather small (the lower signal limit is set by the trigger threshold) even for the largest bias voltage used. The small α-particle signals can be attributed to the attenuation of the electric field near the contacts as was predicted in some simulations[3,7].

Since the range of α-particles in Si is ~25μm one concludes that there exists a low field area adjacent to each electrode that is responsible for the low CCE values shown in Fig.2. As a result the active thickness cannot exceed the detector thickness minus twice the α-particle range i.e. ~250μm. This in turn results in geometric efficiency for MIPs being not more than $(250/300)^2 = 0.7$.

Fig.3 shows the MIP CCE under forward bias for each diode at temperature 249K and for diode#2 at 272K as a function of the bias voltage normalised to the corresponding depletion voltage. The maximum voltage in each case was limited by the current through the detector sensitive region reaching ~6μA/mm^2. This limit was chosen because of the increase of the noise in the preamplifier and the danger of detector thermal runaway. All 3 sets of data show practically the same voltage dependence. For U_{bias} above $0.1U_{dep}$ the CCE is larger than 60%.

conductivity gradually decreases with fluence. Thus forward bias operation could become more appropriate with the growth of fluence. Probably the charge trapping will ultimately become the major limiting factor as was found to be the case for the GaAs detectors[15].

We wish to thank B.K.Jones and J.Santana for helpful discussions.

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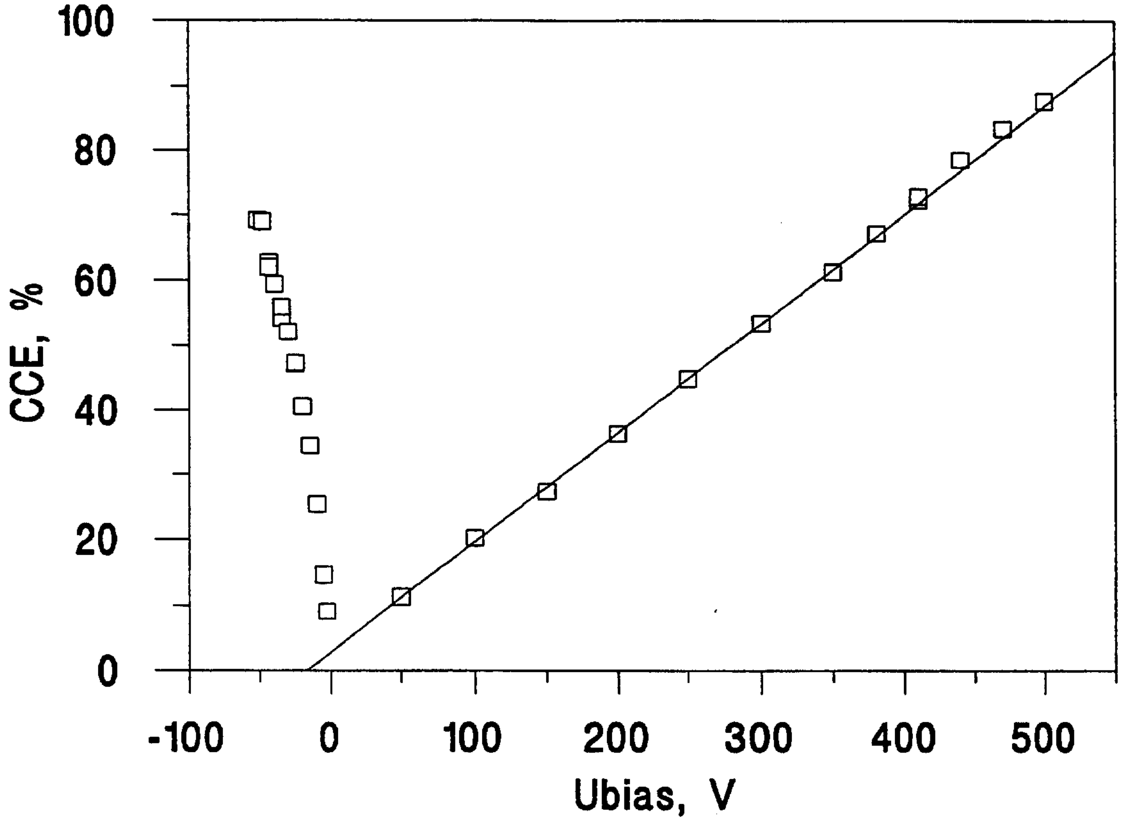
FIGURE CAPTIONS

Fig.1. MIP CCE for diode #2 measured at 249K for reverse (+) and forward (-) bias.

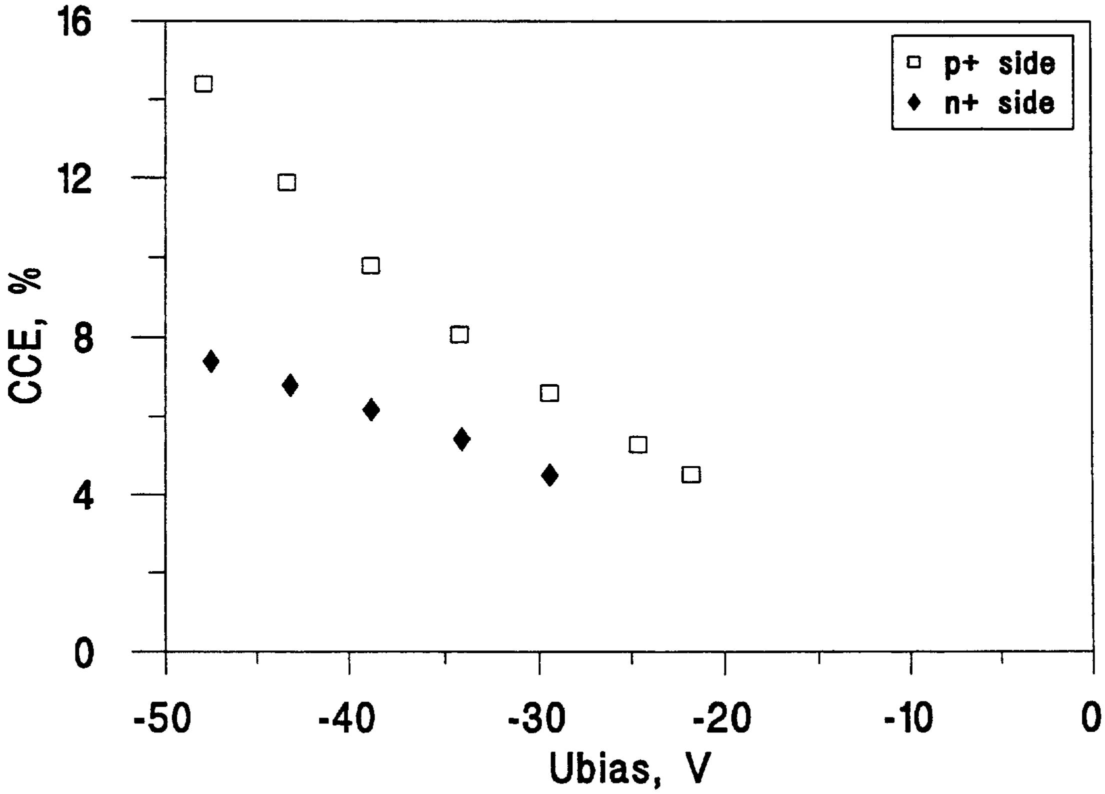
Fig.2. CCE for α-particle illumination from the different sides of the forward biased diode#2 at 249K.

Fig.3. MIP CCE for both diodes at 249K and for the diode #2 at 272K vs. bias voltage normalised to the corresponding depletion voltage.



CCE, %
100
80
60
40
20
0
-100
0
100
200
300
400
500
Ubias, V

Fig.1



CCE, %
16
12
8
4
0
-50
-40
-30
-20
-10
0
Ubias, V
□ p+ side
♦ n+ side

Fig.2

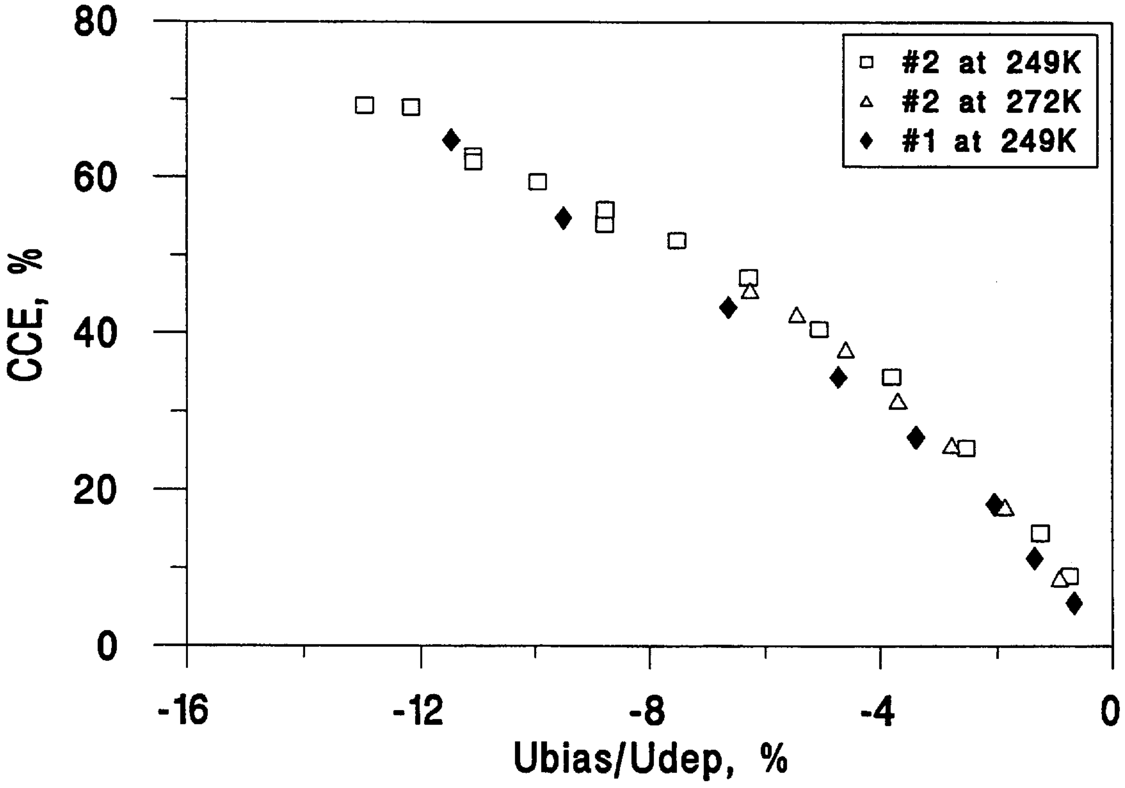


Fig.3