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THE USE OF THE SIGNAL CURRENT PULSE SHAPE TO STUDY THE INTERNAL ELECTRIC FIELD PROFILE AND TRAPPING EFFECTS IN NEUTRON DAMAGED SILICON DETECTORS *

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ABSTRACT

The induced current pulse from ionizing events occurring near contacts on each side of a p^+-n-n^+ silicon junction detector may be used to map the electric field present in the detector. It is of interest to define the operative effects of fast neutron-induced displacement damage in detectors destined for high radiation environments in SSC or LHC. The hole current shape, in particular, has been useful to determine that the field maximum moves to the "rear" n^+ contact as the material apparently changes to p type at 8×10^{12} 1 MeV n/cm². Trapping times for both holes and electrons have been measured as a function of neutron fluence using the current pulse width to measure charge collection time as well as using calculated charge collection times. A clear linear relationship is found for the trapping probability ($1/\tau$) versus neutron fluence. Current pulse shapes have been calculated for representative detector fields and mobility relationships and comparison with measured shapes is reasonable.

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INTRODUCTION

Recently, material type inversion in silicon junction detectors by fast neutron damage has been observed [1]. This change could prove to be a highly deleterious effect of neutron damage in detectors. Type inversion at $\phi > 8 \times 10^{12}$ n/cm² has been confirmed by several groups [2,3] and was initially not confirmed by another [4] when observed by methods which rely on surface type (but later also observed [5]). Experience to date indicates that detectors which have been inverted to p type continue to operate with their leakage current still controlled by the bulk generation current. However, the unpredictability of a detector fabricated and tested as one type base material and expected to operate as another over time requires full understanding of the processes involved.

It must be noted that the inverted material is not compensated by shallow acceptor levels as in a normally B-doped starting material, but is compensated by deep levels near the middle of the b:gap (such as the E center at $E_c - 0.44$ V) which may be crossed by the respective fermi levels as the bands bend near the contacts [6]. This effect modifies the space charge near contacts and could alter the collection field in the detector. It would therefore be of interest to directly measure the electric field in the detector as a function of neutron fluence to assure (aside from carrier trapping) that charge collection will persist at higher fluences.

EXPERIMENTAL METHOD

One means of observing the electric field is through its direct influence on the induced current pulse which is proportional to carrier velocity in turn proportional to the mobility-field product. Current pulse shapes in junction detectors, both damaged and undamaged, have been observed Fretwurst et al [7]. The exact relationship between the current induced on a collecting electrode by the motion of ionization-produced charge has been formulated in terms of the weighting field E_w discussed by Radeka[8] and Gatti and Maifredi[9]. Specifically,

$$i(t) = q \cdot E_w \cdot v(t) \quad (1)$$

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The velocity $v(t)$ contains the product of the electric field and the hole and/or electron mobility; the weighting field E_w is simply $1/d$ for this case, where d is the detector thickness. The particular example of current pulse shapes in a junction detector has been described in [9] and will be discussed later more detail. Although the field $E(x)$ appears in the velocity term, the transformation of position to time giving $E(t)$ imposes somewhat less obvious pulse shapes than if $i(t)$ simply replicated $E(x)$. However, qualitatively $E(x)$ can be inferred from $i(t)$, especially regarding field maxima that may be expected near the rectifying junction contact.

Observation of the current pulse itself, not integrated as collected charge, $q(t)$, also provides an opportunity to directly evaluate trapping through measured charge collection times, which are the current pulse widths. Previous determinations of trapping times, or inverse trapping probabilities, have been made [12] using calculated charge collection times and measured collected charge deficits.

Because the silicon hole mobility is about $1/3$ that of electron mobility, ionization induced near the $n+$ contact, in which holes must make the full detector traversal, will produce longer current pulses which may be more accurately observed with electronics of finite, nsec, response times. Alpha particles stop within $20\text{ }\mu\text{m}$ of each contact and emphasize single carrier collection in a $300\text{ }\mu\text{m}$ thick detector when introduced onto either "front" ($p+$) or "back" ($n+$) contact; in addition they are energetic and supply 220 fC of charge. For the measurements described below, an intense ^{24}Cm source was used in air, collimated to a beam spot of about 1mm^2 . The source to detector distance was kept to within a few mm, giving an incident energy of about 5.5MeV and an estimated energy spread of $<200\text{keV}$.

A hybrid current sensitive preamplifier, BNL IO 354-2, and fast shaping amplifier, BNL IO 553-1, were used and data was taken on a Tektronix Digital Signal Averager DSA 602. The current shape and integrated area were measured. The system response from an injected pulser was found to be 3 nsec (FWHM).

Figure 1 shows the current pulse shapes for alpha particles incident on the front ($p+$) contact and rear ($n+$) contact of a representative undamaged 0.25 cm^2 detector. The left column of Figure 1 is therefore the current shape for electron traversal of an undamaged detector in which the linear electric field is maximum at the front or $p+$ contact. The right column shows the hole current shape starting at 60V bias which is the "depletion" voltage for this detector as determined by the $C(V)$ characteristic. The long term rise and decay indicate that the diffusion of charge from the surface region of the alpha track to the internal field is most influential in determining the hole current shape at biases near and just above the "depletion voltage"--or that voltage derived from the clear break in the capacitance versus applied bias curve. The observation by current pulse shapes of an apparently low field

region near the rear contact, requiring diffusion to introduce charge into the active, linear field region of the detector has been seen and explained previously by Andreev, et al, [10] and Verbitskaya, et al, [11] using a model for alpha collection in which the electric field is screened from the region adjacent to the back contact by the holes produced by ionization at the end of the alpha track. This effect could also be caused by an generally lower resistivity n-type surface layer [12]. At higher biases, the hole pulse shape is clearly rising with time as the holes approach the higher field region towards the front p+ contact. In the top left trace diffusion is clear at longer times in the electron signal as the electrons reach the low to no field region. At depletion, about 60 V, the electrons show a distinct break in the trailing edge of the pulse after reaching the back contact which helps define the collection time. At higher biases, the electron current shape becomes very narrow approaching the system resolution due to the high electron mobility and 300 μ m detector thickness and is not so illustrative of the internal field.

OBSERVED PULSE SHAPES

Figures 2 and 3 represent current shapes for detectors exposed to 1 MeV equivalent fast neutron fluences below and just above the fluence of about 8×10^{12} n/cm² when type inversion has been suggested to occur (over the long term, without correction for self anneal [1]). It is clear from the right column that the highest field still persists at the p+ contact for the detector of Fig. 2 as the hole current rises as the holes traverse the detector, whereas at 3×10^{13} n/cm², shown in Figure 3 the hole current is maximum at the beginning of the pulse and decreases as the holes approach the p+ contact, clearly indicating a reversal of the electric field maximum which is conventionally explained as type inversion. Figure 4 shows the current shapes for a detector irradiated with 8.5×10^{12} n/cm² and measured about six weeks later after the fast time constant room temperature anneals had occurred. The hole current shapes clearly suggest a constant, uniform electric field due to near perfect compensation.

CALCULATED PULSE SHAPES

The induced current on the contact $i(t)$ is directly proportional to the velocity of carriers in the electric field, which in the drift regime is the mobility-electric field product. Equation 1 has been solved for holes and electrons separately in the electric field given by Equation 2:

$$E(x) = \frac{eN_{eff}}{\epsilon\epsilon_0} (x-d) - \frac{(V-V_d)}{d} \pm E_0 \frac{x-d}{d} - E_d \quad (2)$$

where $E_0 = eN_{eff}d/\epsilon\epsilon_0$, V_d is the depletion voltage and E_d is the field at the contact opposite the rectifying contact (or $E(d)$) equal to $-(V-V_d)/d$ for $V > V_d$. Specifically, one uses the drift velocity expression

$$v_d = \frac{dx}{dt} = \mu(E(x)) \cdot E(x) \quad (3)$$

which can be solved for $x(t)$ or $t(x)$. The mobility-field relationship from Sze[15] is used which includes consideration of the saturation velocity. This result is then inserted into (1) transforming $i(x)$ to $i(t)$. These solutions may then be integrated over the range of the incident alpha particle to account for the fact that the charge origin is not simply the front or back contact itself ($x=0$ or d) but a uniform distribution of ionization along the alpha track of $\sim 20\mu\text{m}$ extent from the contact into the detector.

The complete solutions were obtained and essentially agree with Gatti and Manfredi [9]. The calculated current shapes have been convolved with the system response function, a gaussian having $\sigma = 2.5$ nsec. The full analytical details will be published elsewhere. Figure 5 shows the calculated current shapes thusly derived for alpha incidence onto the front and back contact of a detector at a bias just over depletion. It can be noticed that the hole current shape for the junction in the front with alphas incident on the back in this case of just over depletion does not show the clear diffusive effect observed in Figures 1, 2 and to some extent in 3 as well, which is to be expected. Figure 6 gives the comparison of the observed hole current shape of detector 215-28 irradiated with $1.65 \times 10^{13} \text{ n/cm}^2$ with the calculated shape using an effective doping from the C(V) measurement, an origin of alpha ionization of $20 \mu\text{m}$ from the back and a bias over depletion of 75 V. A somewhat reduced hole mobility was used and may effectively include a very short term trapping-detrapping effect. Given the complexity of the system, agreement is considered adequate.

TRAPPING EFFECTS

Figure 7 shows the collected charge from alphas incident on the front and back contacts in detector 206-14, irradiated to $3 \times 10^{13} \text{ n/cm}^2$, as a function of bias, where depletion occurs at about 30 V. The charge loss ΔQ has been defined [13] in terms of the charge collection time t_c and a trapping time constant τ :

$$\Delta \frac{Q}{Q} = a \cdot \frac{t_c}{\tau} \quad (4)$$

where $a = w/2d$ and w is the actual carrier drift length and d is the detector thickness. This result is based on the assumption that $t_c/\tau \ll 1$ and may be modified to describe trapping at higher fluences. The observation of current pulses from alphas incident on the front and back contacts permits direct and accurate observation of the carrier transit time or charge collection time, t_c , for holes and electrons individually. Measurement of the charge loss is derived from the measured values of collected charge, the integral of the current pulse as given by the digital signal analyser. The result is a completely experimental value for the trapping time τ , or the trapping probability $1/\tau$. The value of the transit time t_c is taken as the current pulse width between the half height

values of the rise and fall of the pulse in time. Plotting the data of Figure 7 versus observed pulse width (with the system response time removed in quadrature), one finds a clear linear dependence shown in Figure 8 except for the larger, anomalous values at a bias less than depletion. In this case, the slopes give $\tau_+ = 107 \text{ nsec}$ and $\tau_- = 40 \text{ nsec}$, trapping time constants for holes and electrons respectively.

Having found measured values for τ_+ from alpha measurements, the charge loss for minimum ionizing particles fully traversing the detector may be found[13].

One can also measure the charge decrements using conventional alpha particle spectroscopy for damaged detectors as a function of applied bias and use calculated collection times to derive values of τ . Data from a larger sample of detectors is thus available to augment those damaged detectors for which the current shape has been measured. Using an analytical relationship for the dependence of carrier mobility on the electric field, one can calculate the charge collection time. Two relationships have been used for $\mu(E)$ (for either e or h) taken from Canali et al[14] and Sze[15].

The collection times are then calculated in the same formalism of the induced current shapes and found to be:

$$t_c^e = \frac{v_s}{d} + \tau_e \ln \frac{E(x_i)}{E(x_f)} \quad (5)$$

and

$$t_c^h = \frac{v_s}{d} + \tau_h \ln \frac{E(x_f)}{E(x_i)}$$

for the mobility relationship from Sze [15], where

$$\tau_{e,h} = \frac{\epsilon \epsilon_0}{e \mu_{0,e,h} \cdot N_{eff}}$$

i and f refer to initial and final values of position.

Figure 9 shows the trapping probabilities, $1/\tau$, for holes and electrons as a function of fast neutron fluence that have been derived through charge collection times determined by both methods, direct measurement of the current pulse width and the calculated collection time. There appears to be reasonable agreement between both methods and a clear linear increase in trapping with increasing fluence, as would be expected.

Further calculations of charge collection times have been made using Eq.(6) and comparisons with the observed collection times from current pulse widths are in good agreement. Also, a second

order term has been applied to Eq. (4) for cases when t_c/τ is not $\ll 1$ which better describes the charge decrement at high fluences.

CONCLUSIONS

The observation of hole current pulse shapes for alpha particle irradiations of front (p^+) and back (n^+) contacts that the maximum in the electric field in n-type junction detectors reverts to the back contact after fast neutron fluences $>8 \times 10^{12} \text{ n/cm}^2$ for measurements made weeks post-irradiation, i.e., there being no self anneal correction. Although deep level compensation and removal of shallow donors must be recognized in this process, a comparison of the observed current pulse shapes with calculated shapes is in reasonable agreement implying that the linear electric field profile used in the calculated shapes is still applicable. The observation of hole current shapes for alphas incident on the low field contact, the back contact or source of hole transit, has revealed a slow, diffusive component which may be explained by the shielding of the field by the ionization-produced holes or an anomalously high surface concentration of donors--or both. Trapping times or inverse trapping probabilities can be easily derived from current pulse shapes and agree with other measurements that involve calculated carrier transit times. A linear relationship of trapping probability with neutron fluence is observed, which suggests some caution in assuming little reduction of charge collection for detectors irradiated at fluences above 10^{14} n/cm^2 . Calculated current shapes can also include the effect of trapping and detrapping with results that are not unexpected.

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FIGURE CAPTIONS

Figure 1. Current pulse shapes from an unirradiated, standard ion-implanted detector, 0.25 cm^2 , $\approx 300 \mu\text{m}$ thick. Depletion measured by $C(V)$ occurs at about 60V.

Figure 2. Current pulse shapes from detector 215-22 irradiated with $5 \times 10^{12} \text{ n/cm}^2$ and measured several weeks following the irradiation.

Figure 3. Current pulse shapes from detector 206-14 irradiated with $3 \times 10^{13} \text{ n/cm}^2$ and measured several weeks following the irradiation.

Figure 4. Current pulse shapes from detector 152-2 irradiated with $8.5 \times 10^{12} \text{ n/cm}^2$ and measured six weeks following irradiation.

Figure 5. Calculated current pulse shapes for a representative detector biased just over depletion at 40V. Hole and electron current shapes are shown as results for alphas incident on the back (n^+) and front (p^+) contacts respectively. Solid and dotted traces indicate the front or back position of the rectifying contact.

Figure 6. The comparison between measured and calculated hole current pulse shapes for a detector irradiated above the inversion fluence.

Figure 7. Observed collected charge, both holes and electrons, as a function of bias for detector 206-14, irradiated with $3 \times 10^{13} \text{ n/cm}^2$.

Figure 8. Observed fractional charge loss versus observed pulse width for detector 206-14, irradiated with $3 \times 10^{13} \text{ n/cm}^2$.

Figure 9. Trapping probabilities, $1/\tau$, for both holes and electrons as a function of fast neutron fluence as measured by the observed pulse width (squares) and the calculated charge collection time (circles).

UNIRRADIATED DETECTOR

ALPHAS INTO FRONT

ALPHAS INTO BACK

10 mV/div 10 nsec/div

Figure 1

DETECTOR 215-22

5 e12 n/cm2

Alphas into front

Alphas into back

Figure 2

DETECTOR 206-14

$3 \times 10^{13} \text{ n/cm}^2$

Alphas into front

Alphas into back

Figure 3

DETECTOR 152-2

8.5 e12 n/cm2

Alphas into front

Alphas into back

20 mV/div 10 nsec/div

49 V bias

98 V bias

146 V bias

196 V bias

Figure 4

Alphas incident from the front side

Alphas incident from the back side

Figure 5

CURRENT PULSE SHAPE

JUNCTION ON BACK, ALPHAS INTO BACK

— Calculated

----- Measured

Figure 6

Figure 7

Figure 8

Figure 9

END

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