

5<sup>th</sup> Conference on Position Sensitive Detectors, London, 13-17.9.99

## Carrier Mobilities in Irradiated Silicon

**T.J.Brodbeck, A.Chilingarov, T.Sloan**  
Lancaster University, UK

**E.Fretwurst, M.Kuhnke, G.Lindstroem**  
University of Hamburg, Germany

**On behalf of the ROSE (RD-48) Collaboration**

### Abstract

Using laser pulses with <1ns duration and a 500 MHz digital oscilloscope the current pulses were investigated for p-i-n Si diodes irradiated by neutrons up to 1 MeV equivalent fluences of  $2.4 \cdot 10^{14}$  n/cm<sup>2</sup>. Fitting the current pulse duration as a function of bias voltage allowed measurement of mobility and saturation velocity for both electrons and holes. No significant changes in these parameters were observed up to the maximum fluence. There are indications of a non-uniform space charge distribution in heavily irradiated diodes.

### 1.Introduction

Carrier mobility, and more generally the dependence of drift velocity on electric field, is an important characteristic of semiconductor detectors. For Si it has been extensively studied (for a comprehensive review see [1]). However little is known about the carrier transport properties in Si after heavy irradiation. This information is important because in many future experiments Si detectors have to work after 1 MeV neutron equivalent fluences of  $>10^{14}$  n/cm<sup>2</sup>.

In [2] no significant changes were observed in the transport properties of both electrons and holes up to 1 MeV neutron fluences of  $0.5 \cdot 10^{14}$  n/cm<sup>2</sup> and a prediction is made that a fluence of at least of  $\sim 10^{15}$  n/cm<sup>2</sup> is necessary to affect carrier drift mobilities significantly. On the other hand a clear decrease in mobilities by  $\sim 20\%$  for electrons and by  $\sim 10\%$  for holes was observed in [3] already for a fluence of  $\sim 0.5 \cdot 10^{14}$  n/cm<sup>2</sup>. Data for fluences well above  $10^{14}$  n/cm<sup>2</sup> are clearly needed to clarify the situation.

## 2. Experimental details

The measurements were made with 3 planar Si diodes produced from almost standard n-type <111> material as part of the RD-48 (ROSE) Collaboration Project [4]. The diodes have sensitive area  $5 \times 5 \text{ mm}^2$  and thickness of  $\sim 300 \mu\text{m}$ . Two diodes were irradiated by neutrons from a Be(d,n) source [5] with an average energy 5.2 MeV. The fluences corrected to the equivalent for 1 MeV neutrons are shown in Table 1. After irradiation the diodes were annealed to allow the depletion voltage to reach a minimum. Depletion voltages were defined from CV measurements at room temperature and at 10 kHz frequency. The  $U_d$  errors in Table 1 include the uncertainty in depletion voltage measurement for heavily irradiated diodes [6].

The signal in the detector was produced by a short ( $< 1 \text{ ns}$ ) light pulse from one of two lasers with the wavelength of 675 or 830 nm. The absorption length  $\lambda$  in Si for these wavelengths is  $3.8 \pm 0.5$  and  $13 \pm 2 \mu\text{m}$ , respectively (the errors reflect the spread in the published data [7-10]). Current pulses from the detector were measured, digitised and averaged by a 500 MHz oscilloscope and then stored in a computer. During the measurements the diodes were kept at a temperature of  $(273 \pm 0.5) \text{ K}$ . Either side of the diode could be illuminated via optical fibers. The laser pulse frequency was 100 Hz. Further details of the set-up can be found in [11]. Typical current pulses are shown in Fig.1. In the non-irradiated detector #76 (Fig.1a) the high field is near the  $p^+$  electrode, while in the irradiated detector #81 (Fig.1b) it is near the  $n^+$  electrode. This is the well known “type-inversion” which in our case happens for both irradiated diodes.

## 3. Collection time measurement

The carrier transport properties were determined from measurements of the carrier collection time ( $T_c$ ) defined as the interval between the beginning and the end of the current pulse, as a function of the detector bias voltage. This is the well known Time-of-Flight (TOF) method [12] but applied to the case of a rather non-uniform electric

field. The relatively high depletion voltage of the non-irradiated detector allowed us a cross-check of such an analysis.

For each pulse the leading (trailing) edge was fitted with the exponential  $A \exp[k(t-t_0)]$  starting (ending) at time  $t_0$  and folded with a Gaussian. The parameters  $A$ ,  $k$ ,  $t_0$  and Gaussian  $S$  were free parameters of the fit. Generally the fit quality was good as shown in Fig.1. After detailed optimisation the fit range for the leading (trailing) edge was chosen as  $-1.2\sigma \div 2.4\sigma$  ( $-3.0\sigma \div 0.8\sigma$ ) around the estimated  $t_0$ . The collection time  $T_c$  was defined as the difference between the  $t_0$  values (shown in Fig.1 by crosses) for the trailing and leading edges. Since the laser and the oscilloscope were triggered by the same pulse generator the leading edge  $t_0$  for all bias voltages were averaged to get the common start time. The resulting  $T_c$  errors were  $\sim 0.03$ ns (statistical) and 0.1ns (systematic). The smearing  $\sigma$  for the leading edge was found to be always  $\sim 0.5$  ns, which is the system resolution. The broadening of the observed pulse by this resolution is  $< 0.1\%$  even for the shortest collection time of  $\sim 3$  ns and therefore was neglected.

Under the same conditions the  $T_c$  value for the 830 nm laser was always shorter than that for the 675 nm laser because of the longer absorption length  $\lambda$ . Otherwise the data for the two lasers were very similar. The values of  $T_c$  as a function of bias voltage for all diodes and both side illumination by the 675 laser are presented in Fig.2. The errors are smaller than the symbol sizes. The curves in this plot are the result of the fit discussed in the next section.

#### 4. Fit of the collection time results

The standard parameterisation of the drift velocity  $v = \mu E / [1 + (\mu E / v_s)^\gamma]^{1/\gamma}$  was used, where  $\mu$  is the carrier mobility and  $v_s$  is the saturation velocity. Typical values of these parameters for electrons and holes from the literature are presented in Table 2. All the data in this Table correspond to a temperature of 273K (except for the saturation velocity from ref. [2] where only average values for the temperature range 110-300K are quoted). The  $\gamma$  values in Table 2 are either close to or fixed at 1. The parameters  $\mu$  and  $v_s$  are correlated with  $\gamma$ . Therefore for the study of their relative variations with

fluence it is necessary to keep  $\gamma$  fixed, but its exact value is not important. In the present analysis we have chosen  $\gamma=1$  for the sake of simplicity.

For a detector with thickness  $w$ , applied bias  $U$ , depletion voltage  $U_d$  and the electric field growing linearly with coordinate  $x$  the drift time between the points  $x_1$  and  $x_2 > x_1$  can be written as:

$$T_c = (x_2 - x_1) / v_s + (w^2 / 2\mu U_d) \ln[(U - U_d + 2U_d x_2 / w) / (U - U_d + 2U_d x_1 / w)] \quad (1)$$

For fitting the data the starting point was put at the absorption length  $\lambda$  from the illuminated electrode and the end point at the coordinate of the other electrode. Eqn. (1) was fitted to the measured  $T_c$  values with  $\mu$  and  $v_s$  as free parameters. Typically with all points included the fit quality was not satisfactory. One by one the lowest bias points were excluded from the fit until the  $C^2/N_{df}$  either became  $\sim 1$  or ceased to improve. In the latter case the fit errors were increased by  $(C^2/N_{df})^{0.5}$ . The same fit range was always used for the two lasers to avoid additional systematic error in laser comparison. The fit curves are shown in Fig.2.

The results of the fit for both lasers are presented in Table 3. For each parameter and laser it shows: the optimal value, the fit error and the full error including in quadrature the systematic errors in  $\lambda$  (see section 2) and  $\pm 0.1$  ns in  $T_c$ . The results for the two lasers are averaged according to their full errors. If these results do not agree within their errors the statistical error of the average is increased by the corresponding  $(C^2/N_{df})^{0.5}$ . The systematic error for the average takes into account uncertainties in the detector thickness  $298 \pm 3$   $\mu\text{m}$ , and depletion voltage (see Table 1) which are common for both lasers. The statistical and systematic errors added in quadrature give the final error.

For the most heavily irradiated diode #81 a reasonable fit was possible only through the points from 650 V upwards. To overcome this difficulty the assumption was made that the space charge density  $N_{\text{eff}}$  grows linearly with  $x$  from 0 at the  $p^+$  electrode to  $N_{\text{max}}$  at the  $n^+$  electrode (a possible reason for this is discussed later). In this case the electric field becomes a quadratic function of  $x$ :  $E = (U - U_d) / w + 3U_d / w (x/w)^2$ . The  $T_c$  calculated for the same conditions as in eqn.(1) is:

$$T_c = (x_2 - x_1) / v_s + (bw^2 / 3\mu U_d) [\text{arctg}(bx_2/w) - \text{arctg}(bx_1/w)], \quad (2)$$

where  $b = [3U_d / (U - U_d)]^{0.5}$ . This equation fits the data for diode #81 starting from 490 V. Fits using both functions are shown in Fig.3 for the 830 nm laser data. The results for the quadratic field fit are presented in Table 4. For completeness we also included the fit by eqn. (2) for the diode #79. The curves for detector #81 in Fig.2 are the fits by eqn. (2).

## 5. Discussion and conclusion

When  $U_{\text{bias}}$  is close to  $U_d$  the collection time is due mainly to the carrier drift through the low field region at one side of the detector and is extremely sensitive to the exact details of this field. This explains the poor fit quality when the lowest bias points are included in the fit. The results for the 675 and 830 nm lasers agree well. The 675 nm light gives more compact initial ionisation deposition which corresponds better to our  $T_c$  calculation for a point-like charge, but simultaneously these data are more sensitive to the details of the electric field near the  $p(n)^+$  electrodes resulting e.g. from the doping edge profile. Averaging the results from the two lasers with quite different systematic errors increases the reliability of our measurements.

The results for the non-irradiated detector #76 are in a reasonable agreement with the published data (see Table 2). This confirms the applicability of our analysis for the measurement of the carrier transport parameters. The data for the diode #79 can be equally well fitted by the linear and quadratic field functions (the low  $U_d$  makes these data not very sensitive to the field profile). For diode #81 the quadratic field seems to describe the data better. A possible reason for the linear rise of  $N_{\text{eff}}$  with  $x$  may be the linear rise in the density of the thermally generated bulk current for the carriers moving in the  $x$  direction (electrons in our case). If  $N_{\text{eff}}$  is mainly due to trapped electrons it may be proportional to the electron current density and hence to the  $x$  coordinate.

The mobility and saturation velocity for both carrier types in the irradiated detectors agree with those for the non-irradiated detector within the errors which are usually less than 10%. The only exception is the most heavily irradiated diode #81 with the linear field fit (Table 3). In this case for holes the mobility is lower by 25% and the saturation

velocity is higher by 30% compared to the non-irradiated diode data. The agreement becomes reasonable if the quadratic field is used (Table 4). Insensitivity of the carrier transport properties to irradiation up to the fluence studied here is not surprising. On the one hand it was theoretically predicted in [2]. On the other hand the known mobility dependence on impurity concentration in Si flattens for concentrations below  $10^{16} \text{ cm}^{-3}$  [1] while the space charge density even for  $U_d=400 \text{ V}$  is  $\sim 6 \cdot 10^{12} \text{ cm}^{-3}$ .

In conclusion, we have extended the study of carrier transport properties for irradiated Si detectors up to the equivalent 1MeV neutron fluence of  $2.4 \cdot 10^{14} \text{ n/cm}^2$ . In agreement with expectations there is no change (within 5-10% errors) in mobility or saturation velocity for both electrons and holes. There are indications that in heavily irradiated diodes the space charge density is non-uniform.

### **Acknowledgments**

Financial support from the BMBF to the Hamburg group under contract 05 7HH17I is acknowledged.

### **References**

1. C.Jacoboni et al., Solid-State Electron. 20 (1977) 77.
2. V.Eremin and Z.Li, NIM A362 (1995) 338.
3. C.Leroy et al., NIM A426 (1999) 99.
4. RD48 Status Report, CERN/LHCC 98-39, 21 October 1998.
5. H.J.Brede et al., NIM A274(1989)332.
6. L.J.Beattie, PhD thesis, RAL-TH-1998-015, November 1998.
7. W.C.Dash and R.Newman, Phys.Rev. 99 (1955) 1151.
8. H.R.Philipp, J.Appl.Phys. 43 (1972) 2835.
9. R.Hulthen, Physica Scripta 12 (1975) 342.
10. H.A.Weakliem and D.Redfield, J.Appl.Phys. 50 (1979) 1491.
11. V.Eremin and Z.Li, IEEE Trans.Nucl.Sci. NS-41 (1994) 1907.
12. C.Canali et al., J.Phys.Chem.Solids 32 (1971) 1707.
13. The fit of the experimental data from ref.[12] in H.Feick, PhD thesis, 1997, Internal Report, DESY F35D-97-08, Appendix A, p.181.

## Table Captions

Table 1. Detectors and their irradiation.

Table 2. Published data on the drift velocity parameters for electrons and holes.

Table 3. Fit results for linear electric field.

Table 4. Fit results for quadratic electric field.

## Figure Captions

Fig.1. Current pulses for illumination from both sides: of detector #76 by the 830 nm laser (a); of detector #81 by the 675 nm laser (b). The bias voltage and the main carrier type are indicated on the plots. The curves are the result of the fit described in section 3. The crosses on the curves mark the  $t_0$  values found in the fit.

Fig.2. Collection time vs bias voltage for 675 nm laser data. The curves are the results of the fit described in section 4. Data for detectors #76 and #79 are fitted by the linear field model and for detector #81 by the quadratic field model. The curves are solid inside the fit range and dotted outside it.

Fig.3. Collection time vs bias voltage for detector #81 illuminated by the 830 nm laser. The curves are the results of the fit by the linear field model through the points at 650-950 V and by the quadratic field model through the points at 490-950 V. The solid lines pass through the points included in the fit. Outside the fit range the curves are shown by dash-dotted line for the linear field fit and by dotted line for the quadratic field fit.

Table 1.

Detector Name	#76	#79	#81
Fluence, $10^{14}$ n/cm <sup>2</sup> (1MeV equivalent)	0	$0.58 \pm 0.02$	$2.39 \pm 0.16$
$U_{\text{dep}}$ , V	$134.1 \pm 1.0$	$41 \pm 6$	$385 \pm 15$

Table 2.

Reference	[1]	[13]	[2]
$\gamma_e$	1.04	1.27	1.00
$\mu_e$ , cm <sup>2</sup> /(V s)	1927	1726	1928
$v_{se}$ , $10^7$ cm/s	1.16	1.09	1.18
$\gamma_h$	1.19	1.10	1.00
$\mu_h$ , cm <sup>2</sup> /(V s)	571	618	635
$v_{sh}$ , $10^7$ cm/s	0.876	0.772	0.782



Table 3.

Parameter	$\mu_e$		$v_{se}$		$\mu_h$		$v_{sh}$	
Units	$\text{cm}^2/(\text{V s})$		$10^7 \text{cm/s}$		$\text{cm}^2/(\text{V s})$		$10^7 \text{cm/s}$	
$\lambda$ , nm	675	830	675	830	675	830	675	830
Detector Name					#76			
Fit bias range, V	200-495				175-495			
Fit value	2010	1936	1.085	1.105	619	593	.764	.838
$\sigma_{\text{fit}}$	39	60	.011	.010	3.3	2.7	.007	.006
$\sigma_{\text{full}}$	39	60	.042	.045	5.1	11.7	.021	.026
Average	1988		1.094		615		0.793	
$\sigma_{\text{stat}}$	33		.030		9.6		0.036	
$\sigma_{\text{syst}}$	41		.012		13.5		0.009	
Final result	$1988 \pm 53$		$1.094 \pm .032$		$615 \pm 17$		$0.793 \pm .037$	
Detector Name					#79			
Fit bias range, V	125-490				125-490			
Fit value	1914	1877	1.099	1.128	617	618	.803	.823
$\sigma_{\text{fit}}$	17	14	.007	.008	2.3	3.7	.006	.007
$\sigma_{\text{full}}$	18	25	.042	.046	2.4	4.8	.023	.026
Average	1901		1.112		617		0.812	
$\sigma_{\text{stat}}$	14		.031		2.1		0.017	
$\sigma_{\text{syst}}$	46		.013		15.1		0.013	
Final result	$1901 \pm 48$		$1.112 \pm .033$		$617 \pm 15$		$0.812 \pm .021$	
Detector Name					#81			
Fit bias range, V	650-950				650-950			
Fit value	2026	1996	1.032	1.049	466	459	1.032	1.020
$\sigma_{\text{fit}}$	141	127	.015	.015	6.5	11.9	.013	.029
$\sigma_{\text{full}}$	141	133	.039	.042	6.5	12.0	.039	.048
Average	2010		1.040		464		1.027	
$\sigma_{\text{stat}}$	97		.029		5.7		0.030	
$\sigma_{\text{syst}}$	63		.011		15.8		0.021	
Final result	$2010 \pm 116$		$1.040 \pm .031$		$464 \pm 17$		$1.027 \pm .037$	

Table 4.

Parameter	$\mu_e$		$v_{se}$		$\mu_h$		$v_{sh}$	
Units	$\text{cm}^2/(\text{V s})$		$10^7 \text{cm/s}$		$\text{cm}^2/(\text{V s})$		$10^7 \text{cm/s}$	
$\lambda$ , nm	675	830	675	830	675	830	675	830
Detector Name	#79							
Fit bias range, V	125-490				125-490			
Fit value	2014	1993	1.077	1.096	650	646	.766	.794
$\sigma_{\text{fit}}$	18	16	.006	.008	3.1	5.5	.006	.010
$\sigma_{\text{full}}$	19	27	.040	.043	3.2	6.0	.021	.025
Average	2007		1.086		649		0.778	
$\sigma_{\text{stat}}$	15		.029		2.8		0.016	
$\sigma_{\text{syst}}$	69		.017		21.9		0.019	
Final result	$2007 \pm 71$		$1.086 \pm .034$		$649 \pm 22$		$0.778 \pm .025$	
Detector Name	#81							
Fit bias range, V	490-950				490-950			
Fit value	2150	2568	1.042	1.019	572	553	.943	.961
$\sigma_{\text{fit}}$	49	71	.008	.007	5.6	8.1	.008	.017
$\sigma_{\text{full}}$	50	90	.038	.037	5.6	8.1	.031	.037
Average	2249		1.030		566		0.950	
$\sigma_{\text{stat}}$	178		.027		9.0		0.024	
$\sigma_{\text{syst}}$	201		.018		46.9		0.052	
Final result	$2249 \pm 268$		$1.030 \pm .032$		$566 \pm 48$		$0.950 \pm .057$	