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Carrier Mobilities in Irradiated Silicon

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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 10^{14} n/cm^2 . 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^2.

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 10^{14} n/cm^2 and a prediction is made that a fluence of at least of ~10^{15} n/cm^2 is necessary to affect carrier drift mobilities significantly. On the other hand a clear decrease in mobilities by ~20% for electrons and by ~10% for holes was observed in [3] already for a fluence of ~0.5 10^{14} n/cm^2. Data for fluences well above 10^{14} n/cm^2 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 5x5 mm^2 and thickness of ~300μm. 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 1MeV 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 (<1ns) light pulse from one of two lasers with the wavelength of 675 or 830 nm. The absorption length λ in Si for these wavelengths is 3.8 ± 0.5 and 13 ± 2 μm, 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 ± 0.5) 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 σ 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 ~0.03ns (statistical) and 0.1ns (systematic). The smearing σ for the leading edge was found to be always ~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 ~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 λ. 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 μ 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 γ values in Table 2 are either close to or fixed at 1. The parameters μ and v_s are correlated with γ. Therefore for the study of their relative variations with fluence it is necessary to keep γ fixed, but its exact value is not important. In the present analysis we have chosen γ=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:

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

For fitting the data the starting point was put at the absorption length λ 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 μ 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 χ^2/N_{df} either became ~1 or ceased to improve. In the latter case the fit errors were increased by $(\chi^2/N_{df})^{0.5}$. 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 λ (see section 2) and ± 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 $(\chi^2/N_{df})^{0.5}$. The systematic error for the average takes into account uncertainties in the detector thickness 298 ± 3 μm, 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_{eff} grows linearly with x from 0 at the p^+ electrode to N_{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:

$T_c=(x_2-x_1)/v_s+(bw^2/3\mu U_d)\,[\mathrm{arctg}(bx_2/w)-\mathrm{arctg}(bx_1/w)]$, (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_{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_{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_{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} cm^{-3} [1] while the space charge density even for U_d=400 V is ~6 10^{12} 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 10^{14} 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

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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^2 (1MeV equivalent)	0	0.58 ± 0.02	2.39 ± 0.16
U_{dep}, V	134.1 ± 1.0	41 ± 6	385 ± 15

Table 2.

Reference	[1]	[13]	[2]
γ_e	1.04	1.27	1.00
μ_e ,cm^2/(V s)	1927	1726	1928
v_{se} ,10^7cm/s	1.16	1.09	1.18
γ_h	1.19	1.10	1.00
μ_h ,cm^2/(V s)	571	618	635
v_{sh} ,10^7cm/s	0.876	0.772	0.782

Table 3.

Parameter	μ_e		v_{se}		μ_h		v_{sh}	
Units	$cm^2/(V\ s)$		$10^7 cm/s$		$cm^2/(V\ s)$		$10^7 cm/s$	
λ, 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
σ_{fit}	39	60	.011	.010	3.3	2.7	.007	.006
σ_{full}	39	60	.042	.045	5.1	11.7	.021	.026
Average	1988		1.094		615		0.793	
σ_{stat}	33		.030		9.6		0.036	
σ_{syst}	41		.012		13.5		0.009	
Final result	1988 ± 53		$1.094 \pm .032$		615 ± 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
σ_{fit}	17	14	.007	.008	2.3	3.7	.006	.007
σ_{full}	18	25	.042	.046	2.4	4.8	.023	.026
Average	1901		1.112		617		0.812	
σ_{stat}	14		.031		2.1		0.017	
σ_{syst}	46		.013		15.1		0.013	
Final result	1901 ± 48		$1.112 \pm .033$		617 ± 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
σ_{fit}	141	127	.015	.015	6.5	11.9	.013	.029
σ_{full}	141	133	.039	.042	6.5	12.0	.039	.048
Average	2010		1.040		464		1.027	
σ_{stat}	97		.029		5.7		0.030	
σ_{syst}	63		.011		15.8		0.021	
Final result	2010 ± 116		$1.040 \pm .031$		464 ± 17		$1.027 \pm .037$	

Table 4.

Parameter	μ_e		v_{se}		μ_h		v_{sh}	
Units	$cm^2/(V\ s)$		$10^7 cm/s$		$cm^2/(V\ s)$		$10^7 cm/s$	
λ, 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
σ_{fit}	18	16	.006	.008	3.1	5.5	.006	.010
σ_{full}	19	27	.040	.043	3.2	6.0	.021	.025
Average	2007		1.086		649		0.778	
σ_{stat}	15		.029		2.8		0.016	
σ_{syst}	69		.017		21.9		0.019	
Final result	2007 ± 71		$1.086 \pm .034$		649 ± 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
σ_{fit}	49	71	.008	.007	5.6	8.1	.008	.017
σ_{full}	50	90	.038	.037	5.6	8.1	.031	.037
Average	2249		1.030		566		0.950	
σ_{stat}	178		.027		9.0		0.024	
σ_{syst}	201		.018		46.9		0.052	
Final result	2249 ± 268		$1.030 \pm .032$		566 ± 48		$0.950 \pm .057$	