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Analysis of the transient response of LED-illuminated diodes under heavy radiation damage

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Abstract

The changes of the electrical properties induced by hadron irradiation on silicon detectors have been studied by using the device level simulator HFIELDS. The model of the radiation damage assumes the introduction of radiation-induced acceptor and donor "deep-levels". The electric field profile and the space charge region extension have been calculated for differently irradiated structures. The simulation has been carried out at different biases in order to study the evolution of the space charge region of irradiated detectors as a function of the applied voltages, below and above the full depletion. The time-dependent current responses and the charge collection properties of the structure illuminated by a red LED light have been calculated. The use of the red light results in a shallow (quasi-surface) generation of e–h pairs in silicon, which has been properly taken into account by the simulation. The results of the simulations have been compared to experimental measurements carried out at CERN on samples irradiated with 24 GeV/c protons. The comparison results in a satisfactory agreement, and supports the physical interpretation of experimental data. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The future Large Hadron Collider (LHC) will produce a high luminosity environment that results in a unexperienced radiation doses: this will critically affect the electrical properties of solid-state silicon detectors used in the tracking system. In this work, the general-purpose device simulator HFIELDS [1] has been exploited to model at a physical level the behaviour of progressively irradiated structures. In particular, radiation effects (i.e. charge generation due to a ionising particles) are accounted for by introducing suitable terms into the semiconductor transport equations, whereas

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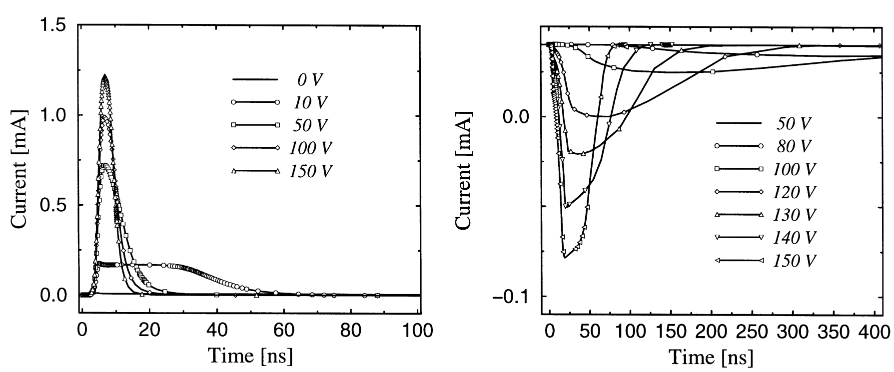
the bulk radiation damage is accounted for by means of two dominant "deep-level" generation/recombination centres, an acceptor level at $Ec - 0.42$ eV and donor level at $Ev + 0.36$ eV [2]. The model is based on generalised Shockley–Read–Hall statistics, and allows for reliable description of radiation-related phenomena, e.g. the so-called *type-inversion* effect and charge collection performance degradation. In order to study the electrical behaviour of irradiated devices, a general p^+nn^+ structure has been adopted, with a bulk concentration of $n = 1.9 \times 10^{12}\ cm^{-3}$ and implant concentration $p^+ = n^+ = 1.0 \times 10^{19}\ cm^{-3}$. A 100 μm width and 284 μm depth are assumed, respectively. The "active behaviour" of the device is predicted by simulating the time-varying current response to a pulse red LED illumination. To this purpose, a given amount of electron/hole pairs have been distributed within the device, accounting for the effect of the LED illumination. Due to the absorption coefficient of the red LED light with a wavelength of 670 ± 50 nm ($\approx 3 \times 10^3\ cm^{-1}$), more than 90% of photons are absorbed in a few μm depth. For simulating purpose, the generated charge has been therefore uniformly distributed in a shallow (quasi-surface) layer, whereas the time distribution of the generated charge follows a Gaussian function.

Simulation results have been compared to experimental measurements carried out at CERN on several n-type silicon diodes (with initial resistivity of 2.2 Ω cm) irradiated in the 24 GeV/c proton beam at CERN PS, with fluences ranging from 1×10^{12} up to $2.9 \times 10^{14}\ cm^{-2}$. The device illumination was performed using a red LED driven by an external pulse generator. The LED is connected to a multimode optical fibre of 0.5 mm diameter which illuminates the detector through a front window (p^+-side) or a rear grid (n^+-side). The detector signal is amplified by two fast current amplifiers (Phillips Scientific model 6954) with a total gain of 1000. The signal pulse shape and the integral of the signal with time were recorded with a 300 MHz LeCroy 9361 oscilloscope.

2. Time-domain response and charge collection analysis

To begin with, a non-irradiated device has been considered, illuminated either from the front (p^+ side) or the back (n^+ side) with a pulsed (15 ns full-width at half-maximum) 660 nm wavelength red LED light. Fig. 1 shows the simulated pulse shape (time-domain response) for different bias voltages in the case of front and back illumination, respectively, whereas the corresponding measured responses are reported in Fig. 2. As expected, sharper current peaks are found with increasing bias voltages, due to larger transit velocity of the mobile charge (which depends on the electric field). Consequently, collecting the generated charge will require a shorter time as well. Differences are found depending on the placement of the light source: by

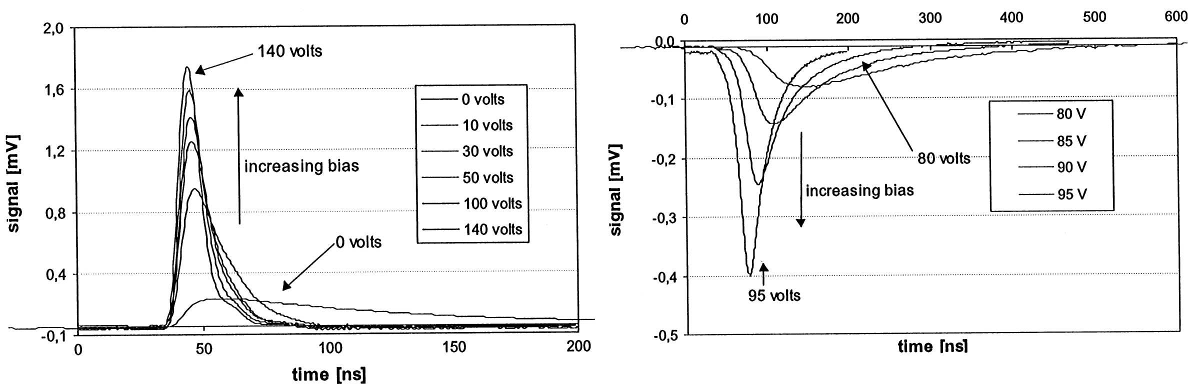


(a) Front Illumination (b) Rear Illumination

Fig. 1. Simulated signal pulse shape for a non-irradiated diode.

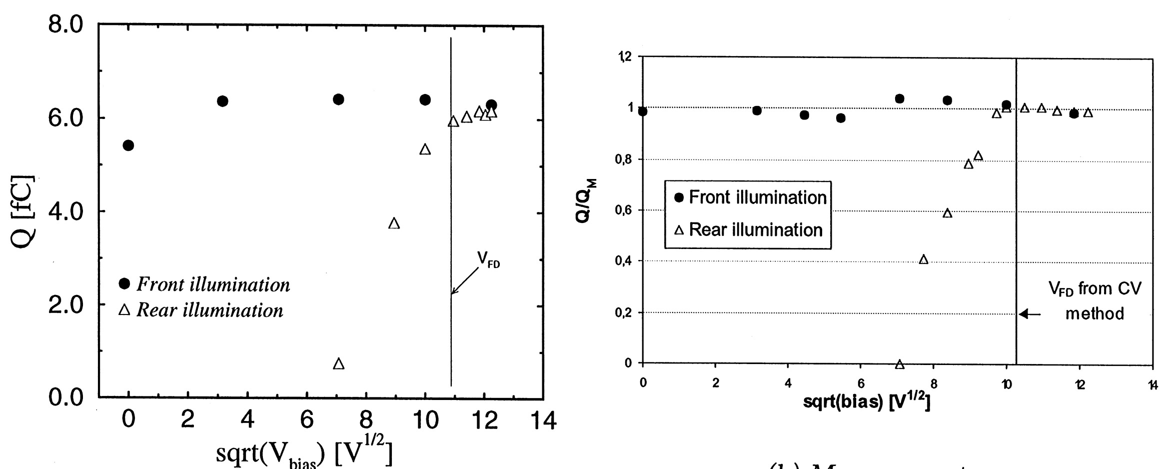
front-illuminating the device, the shallow generation layer falls within the depleted region even at very low bias voltages, so that marked current peaks develop as soon as the device is actually biased. On the contrary, the back-illuminated device needs to attain complete depletion to exhibit similar responses. By integrating current pulses, the amount of collected charge can be estimated: Fig. 3 shows the collected charge, depending on the kind of illumination and on the applied bias.

To investigate the influence of radiation damage on the responses discussed above, structures have been irradiated at different fluences and their response has been measured and compared with simulation. It is customary to introduce the concept of "effective doping" to account for the radiation-induced effects on the device behaviour: i.e. the influence of deep-level traps on the carriers concentration can be, at first order, faked by adjusting the substrate doping concentration. With increasing damage the n-type silicon substrate progressively turns into an "effective" p-type one. An "inversion fluence" can be defined, indicating the fluence at which such a type-inversion occurs.



(a) Front Illumination *(b) Rear Illumination*

Fig. 2. Measured signal pulse shape for a non-irradiated diode.



(a) Simulations *(b) Measurements*

Fig. 3. Collected charge for a non-irradiated diode (the vertical line indicates the full depletion voltage (V_{FD}) as extracted by the capacitance–voltage (CV) characteristic).

This model, however, does not satisfactorily explain the actual behaviour illustrated by Fig. 4. From the above discussion, one should expect that, beyond the inversion fluence, the effective diode junction should move from the p^+ side to the n^+ side and that, consequently, heavily irradiated devices should exhibit a complementary behaviour with respect to the non-irradiated ones. In particular, front-illumination should not induce appreciable response in the irradiated device, unless a large enough bias were applied. However, this is contradicted by the experimental plots shown in Fig. 4. In the low-bias range (Fig. 4a), complete depletion is not actually reached (a depletion voltage of 25 V is extracted for the measured device, irradiated at 5.2×10^{13} p/cm^2). Nevertheless, a sharp peak shows up in this case too, the position of which (on the time-axis) is relatively independent of the applied bias; if therefore cannot be ascribed to diffusion of charge through the non-depleted bulk, but should instead be interpreted as a charge generated within a "depleted layer" still located close to the p^+ contact. By increasing the applied bias (Fig. 4b), a second peak appears, the amplitude and position of which varies with the bias, which could be interpreted as the charge generated at the depleted layer developing from the opposite contact and reaching the p^+-side electrode. As soon as complete depletion is attained, the two peaks tend to merge together, eventually recovering a single-peaked current response. Simulations of a similar structure (depletion voltage is in the order of 50 V in this case) reproduce the same behaviour, as shown in Fig. 5. The same results have been found at higher radiation fluences, with the second peak appearing at higher voltages, as illustrated by Figs. 6 and 7. This behaviour has been explained by supposing the existence of two depletion regions, simultaneously developing from both sides of the device [3–5]. Numerical simulation provides a mean for validating such an interpretation: Fig. 8 shows the computed majority carrier concentration profile within the device, and makes it evident by the actual development of such a twofold depletion layer.

Charge collection properties of irradiated devices have been investigated as well, correlating them to the applied bias. Comparison between simulation predictions and actual measurements show a good overall agreement in this case too (Figs. 9–11): a detailed interpretation of such plots is given elsewhere [6], based on a peculiar distribution of the electric field within the device, characterised by a "soft" switching of the type inversion mechanism. In an intermediate fluence range, the structure cannot be modelled simply as an uniformly-doped silicon substrate, being the occupation probability of deep-level traps non uniform in space; this results in the formation of n^+-side effective junction while the p^+-side junction is still present, and should be witnessed by steep potential barriers (i.e. electric field peaks) at both sided of the device. Again, simulation can be used to validate such an interpretation: the computed electric field profiles are

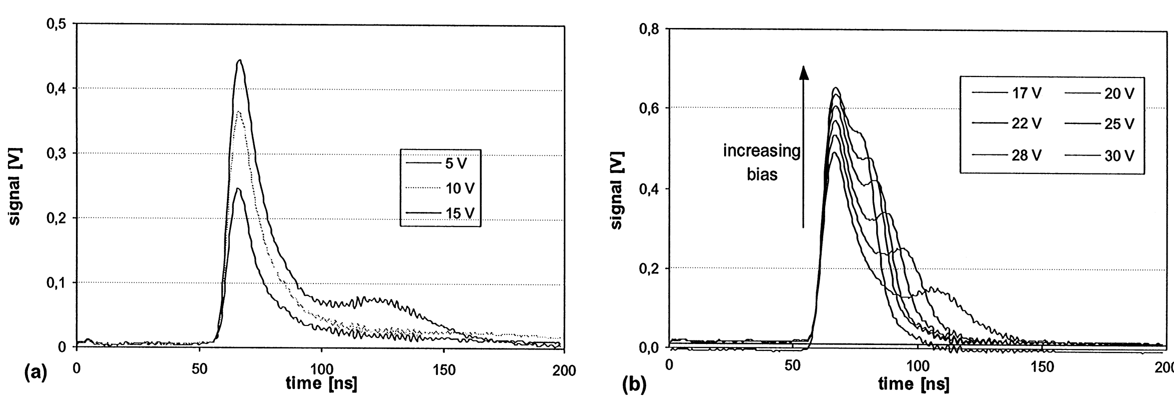


Fig. 4. Measured signal for a diode irradiated at 5.2×10^{13} p/cm^2 – front illumination.

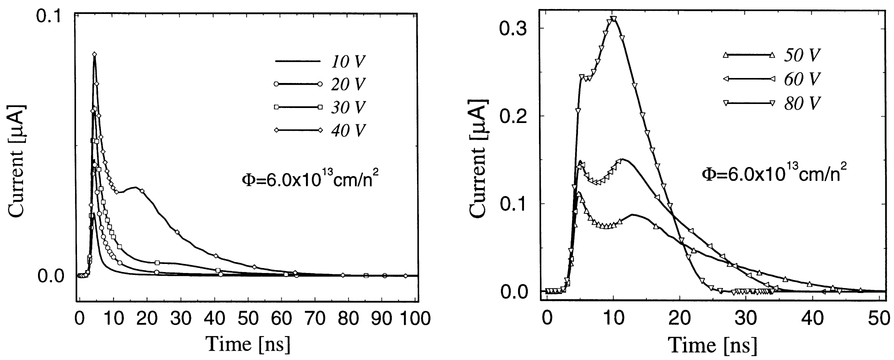


Fig. 5. Simulated signal for a diode irradiated at 6.0×10^{13} n/cm^2 – front illumination.

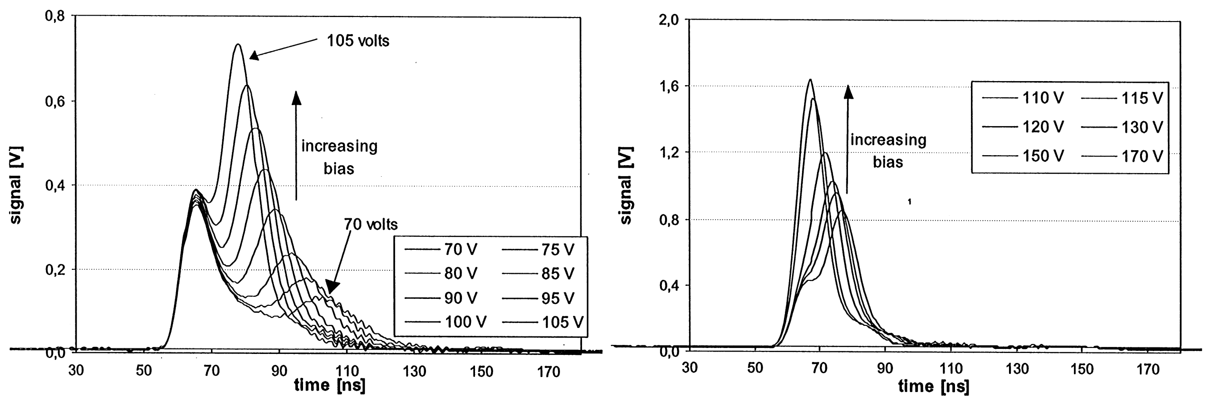


Fig. 6. Measured signal for a diode irradiated at 1.7×10^{14} p/cm^2 – front illumination.

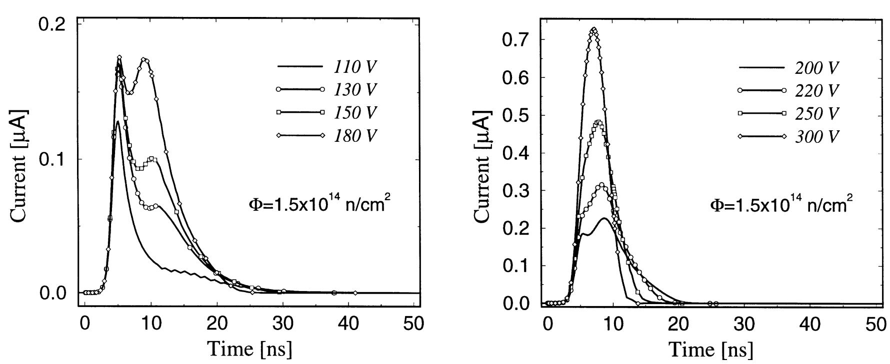


Fig. 7. Simulated signal for a diode irradiated at 1.5×10^{14} n/cm^2 – front illumination.

reported in Figs. 12 and 13, referring to progressively irradiated structures. The triangular field profile at both ends of the structure stand for the depleted regions, and, as expected, a fluence range exists, in which the two layers have comparable extensions.

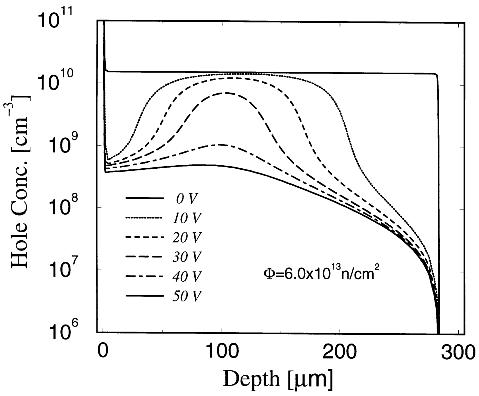
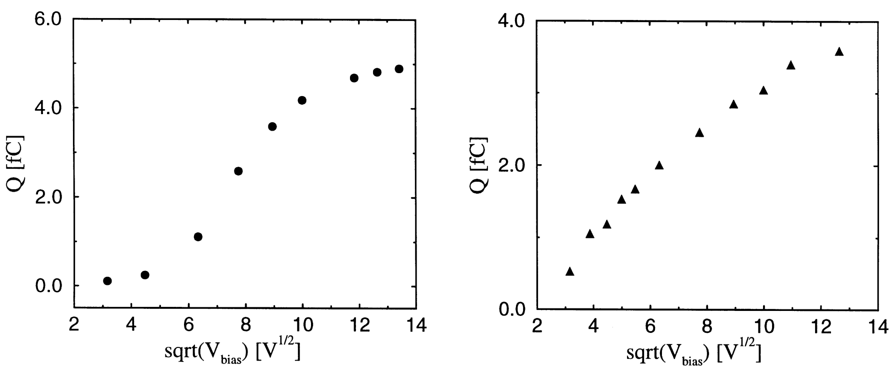


Fig. 8. Majority carrier concentration profile within the device irradiated at 6.0×10^{13} n/cm^2.

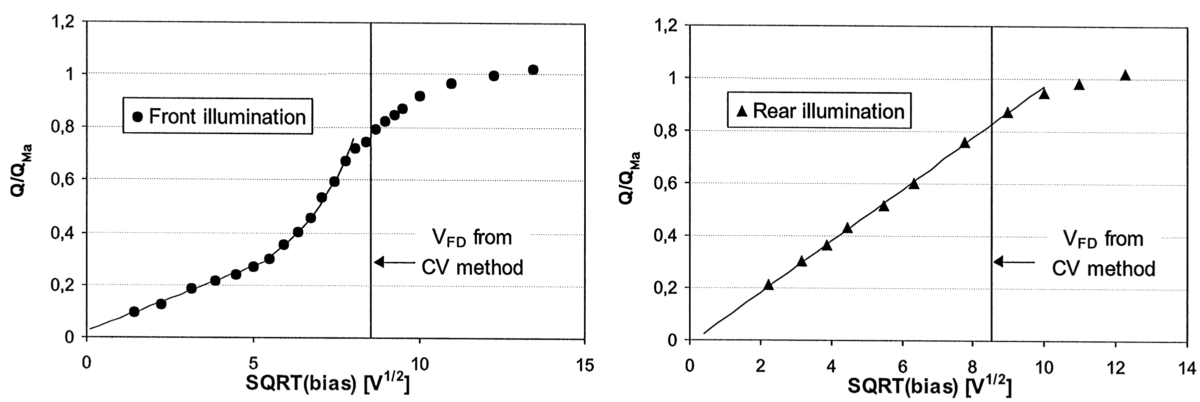
3. Conclusions

An analysis of the behaviour of silicon irradiated diodes has been carried out, focusing on the response to the illumination by a red-light LED. The resulting charge generation in a shallow layer allows to investigate some details on the actual formation of the depletion layer within radiation-damaged devices. Such a study is of clear relevance for the operation of silicon detectors to be implemented in next generation of particle colliders. An extensive comparison between experimental and numerical simulation results has been carried out, allowing for the validation of physical interpretations based on the existence of a dual-sided



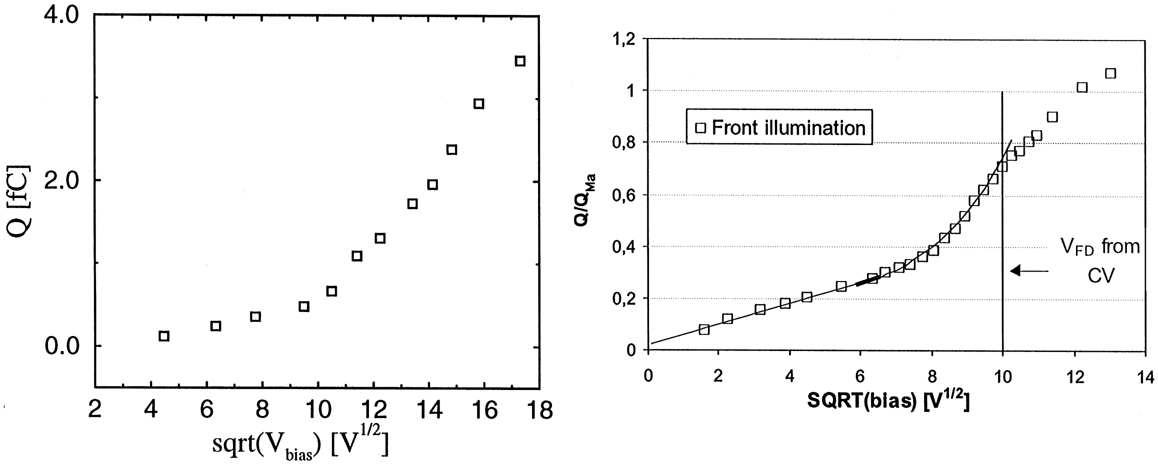
(a) Front Illumination (b) Rear Illumination

Fig. 9. Simulated collected charge for a diode irradiated at 6.0×10^{13} n/cm^2.



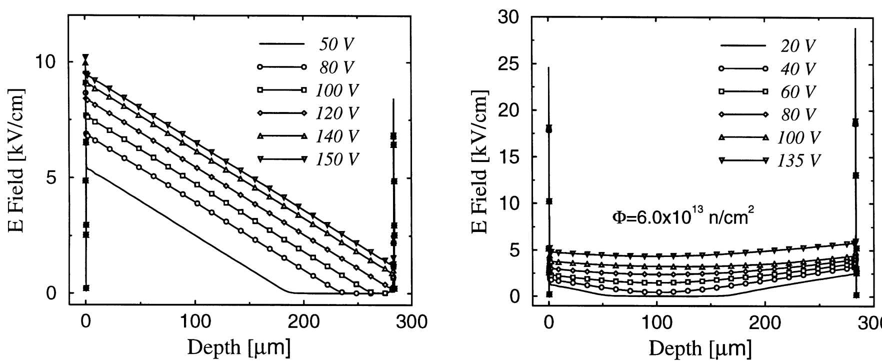
(a) Front Illumination (b) Rear Illumination

Fig. 10. Charge collection efficiency for a diode irradiated at 1.0×10^{14} p/cm^2.



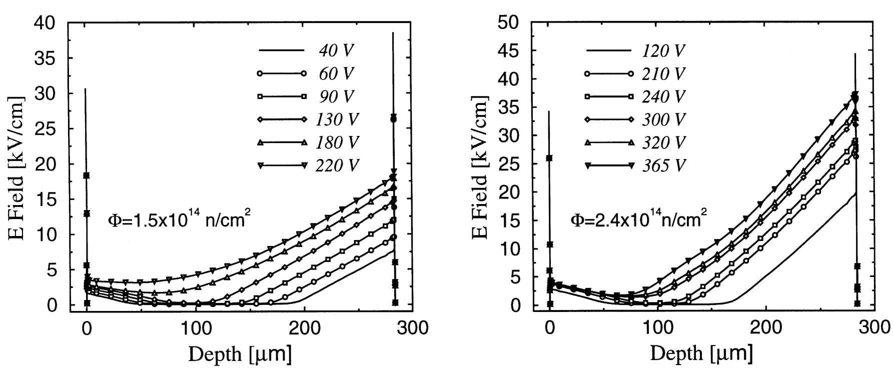
(a) Simulations (b) Measurements

Fig. 11. Collected charge for a diode irradiated 1.5×10^{14} n/cm^2 – front illumination.



(a) Non-Irradiated (b) $\Phi = 6.0 \cdot 10^{13} n/cm^2$

Fig. 12. Electric field evolution for a non-irradiated diode (a) and a diode irradiated at 6.0×10^{13} n/cm^2 (b).



(a) $\Phi = 1.5 \cdot 10^{14} n/cm^2$ (b) $\Phi = 2.0 \cdot 10^{14} n/cm^2$

Fig. 13. Electric field evolution for a diode irradiated at 1.5×10^{14} (a) and 2.4×10^{14} n/cm^2 (b) respectively.

depletion layer. It is worth emphasizing how numerical simulation, apart from predicting charge collection and pulse responses fairly in agreement with experimental data, provides a means for deeper investigations which can hardly be evaluated experimentally. For instance, charge carrier concentration and electric field could be inspected thus providing a significant help in the understanding of many physical details.

References

[1] G. Baccarani, P. Ciampolini, A. Pierantoni, Nucl. Instr. and Meth. A 326 (1993) 253.

[2] E. Fretwurst, C. Dehn, H. Feick, P. Heydarpoor, G. Lindstrom, M. Moll, C. Schutze, T. Schultz, Nucl. Instr. and Meth. A 377 (1996) 258.

[3] D. Passeri, M. Baroncini, P. Ciampolini, G.M. Bilei, A. Santocchia, B. Checucci, E. Fiandrini, IEEE Trans. Nucl. Sci. NS-45 (3) (1998).

[4] L.J. Beattie, T.J. Brodbeck, A. Chilingarov, G. Hughes, S.A. McGarry, Nucl. Instr. and Meth. A 418 (1999) 314.

[5] V. Eremin, Z. Li, I. Iljashenko, Nucl. Instr. and Meth. A 360 (1995) 458.

[6] G. Casse, E. Grigoriev, F. Lemeilleur, M. Glaser, Nucl. Instr. and Meth. A 426 (1999) 140–146.