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Evaluation of Transient Current in Si PIN Photodiode Induced by High-Energy Charged Particles

by

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Abstract

Single Event Transient (SET) current subjects to the Bit Error Rate (BER) degradation of optical data links used in space radiation environments. Here, SET currents induced by heavy ions with energy of several MeV are measured by using the Transient Ion Beam Induced Current (TIBIC) technique. In order to simulate the SET current waveforms using the Transient Charge Technique (TCT) based on Ramo's theorem, correction factors to the low-field mobility are introduced. A reasonable agreement between experiments and simulations is obtained under slight theoretical limit.

Keywords: Single Event Effect, Transient Current, PIN Photodiode, Transient Charge Technique, High Injection

1. Introduction

In recent years, special interest has been paid to high-energy proton induced Bit Error Rate (BER) degradation in optical data links used in harsh radiation environments. Previous workers have shown that photodetectors which are the principle component of an optical receiver are primarily responsible for BER degradation [1, 2]. When high-energy protons traverse a photodiode, both inelastic reactions and elastic collisions are responsible for producing a spectrum of high-energy secondary ions. In silicon, high-energy protons generate nuclear fragments such as He, C, N, O, F, Ne, Na, Mg, Al, Si and P, and Si recoils with energies up to several tens of MeV. The energy-loss of these particles induces a current on the terminal of a photodetector resulting in a Single Event Transient (SET) current, which degrades the BER depending on its height and duration (see Fig. 1) [1].

Analyzing the SET current induced by a high-energy secondary ion in a photodiode is a necessary pre-requisite for reliably estimating and understanding proton induced BER degradation. General theoretical treatments for predicting the SET current are difficult, since charge collection following ionization is a complicated process. To obtain the numerical solution of these mechanisms, Technology Computed Aided Design (TCAD) simulation is typically employed [3-5]. Although these approaches are thought to be accurate, they are computationally intensive, particularly if 3D simulations are performed. Semi-analytical models providing the practical solutions as opposed to complicated and physically inaccessible TCAD simulations are important for reducing computational times when a large number of simulations are required, as is the case here.

In previous works, reasonable agreement between experiment and simple model based on the Ramo's theorem [6, 7] has been achieved for ions with low Linear Energy Transfer (LET) [8] as demonstrated by the establishment of the Transient Charge Technique (TCT) [8, 9]. However, for heavy ions, the injected carrier density is orders of magnitude higher than the carrier density of device, and high-injection effects cause disturbed electric field. Here we attempt to include correctional factors to the standard theories used in TCT to account for influence of high injection effects.

2. Experiments

The devices examined in this work were commercial 1.5GHz (at -3dB) Si pin photodiodes with a diameter of 450μm. The depletion layer width was ~15μm at -20V as measured by cross-sectional Laser Beam Induced Current (LBIC) and Transient Ion Beam Induced Current (TIBIC) at Japan Atomic Energy Agency (JAEA) [10, 11]. The devices were mounted on ceramic chip carriers for high-speed TIBIC measurements. A single ion hit system was employed to reduce the influence of displacement damage effects. The TIBIC measurement configuration is described in Fig. 1. Transient currents are recorded by a 3GHz oscilloscope (Tektronix

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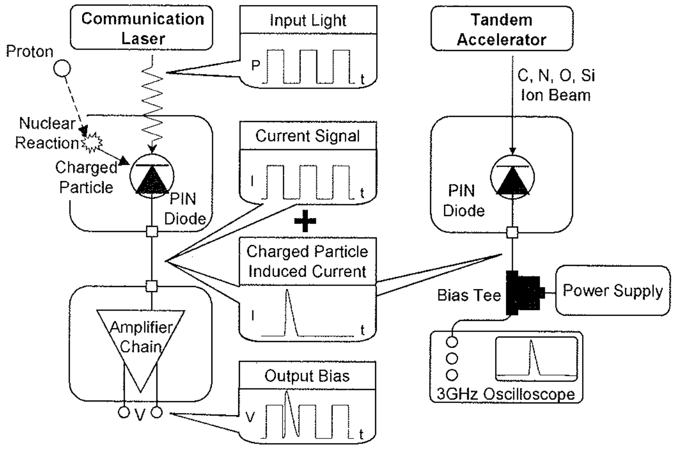
TDS694C). More detailed information of the measurement system is described elsewhere [12, 13].

The JAEA Tandem accelerator and microbeam line were used to deliver focused beams of C, N, O and Si with energies ranging from 6 to 18MeV. These energies and species were chosen due to their predominance in the proton induced particle spectrum. During ion irradiation, a reverse bias of -20V was applied to the photodiode. Since the projected range of all ions is within the depletion layer under this bias condition, both funneling and diffusion from the substrate could be ignored.

3. Results and discussion

Fig. 2 shows typical transient current waveforms for C, N, O and Si irradiation at an applied bias of -20V. These plots indicate that the peak current increases with increasing ion energy for any given ion species. Fig. 3 shows linear-log plots of the transient current waveforms for C. Quite noticeable is that charge collection undergoes a slow decay, followed by a faster one [5]. These different current decay rates are related to the carrier dynamics under the high and low injection levels. In spite of complications, the charge collection dynamics can be simplified into the following three steps: (a) the dipolar separation of the electrons and holes in plasma resulting in a transient capacitance response, (b) the erosion of the plasma edge influenced by ambipolar diffusion and (c) the electric field induced drift of carriers after the initial high-injection plasma has collapsed.



(a) Proton induced Bit Error Rate degradation (b) Measurement Method

Fig.1 (a) BER degradation induced by the high-energy proton induced charged particle irradiation. (b) Measurement system for evaluating charged particle induced transient current.

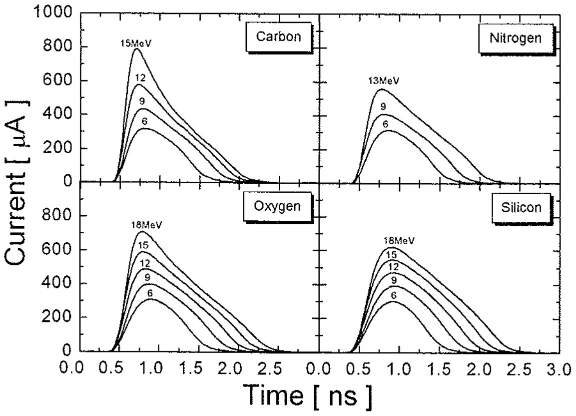


Fig.2 Typical transient current waveforms induced by C, N, O and Si ions. The energies for each ion are also labeled above each transient.

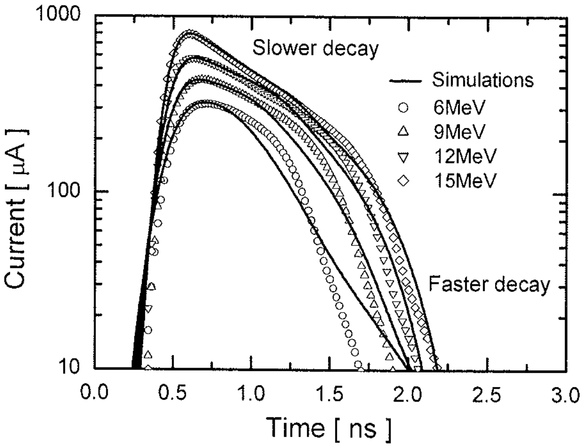


Fig.3 Linear-log plot of transient current waveforms for C ions with various energies. The solid lines are calculated using the correction factors.

3.1 Signal rise-time

The signal rise-time (10-90%) in relation to the transient capacitance response is now discussed. Early investigators studied the signal rise-time of transient currents induced in totally depleted Si surface-barrier detectors with similar structure to the photodiode studied here, in order to identify nuclear fragments by their rise-time signatures [14]. They found empirically that the rise-time of a signal is in proportion to the square root of LET. In this study, Monte Carlo simulation code SRIM2003 (Stopping and Range of Ions in Matter ver. 2003.26) was used to calculate the ion LETs [15]. The experimentally obtained rise-time for various ions as a function of the square root of the energy-loss is shown in Fig. 4. The indicated rise-time is normalized by the system rise-time (~141ps) [4]. It is confirmed that signal rise-times follow the empirical equation with linear fits as shown in Fig. 4. While the slope of each ion seems to be different from fitting line, the approximate rise-time will suffice for this study since we aim to reduce the computational times using semi-analytical methods.

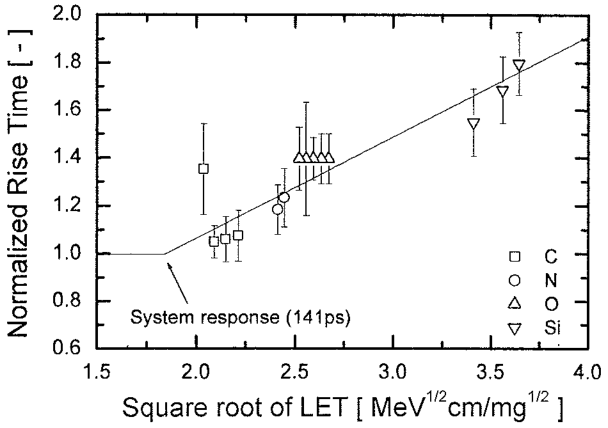


Fig.4 Signal rise-times normalized to the system rise-time as a function of the square root of the average ionizing energy-loss.

After the plasma formation due to ionization, the populations of electrons and holes inside the plasma are immediately accumulated at the edge of the plasma resulting in transient capacitances [5]. The R-C constant consisting of the resistances and capacitances, influences the ideal current response, i.e. the reduction in peak current and extended rise-time. Fig. 4 shows that the signal rise-time induced by high LET ions such as Si is longer than the system rise-time. This experimental result can be explained in terms of an influence of the transient capacitance.

3.2 Transient current

A recent study using carefully controlled experiments and 3D-TCAD simulations demonstrated that the SET current in a photodiode is the sum of the electron, hole, and displacement currents [5]. The contribution of the displacement current to the total transient current is lower by two orders than that of the electron and hole currents when MeV ions penetrate the photodiodes. For simplification the displacement current is neglected here. The remaining component of transient current (electron and hole currents) are calculated by the TCT based on Ramo's theorem which provides a simple theoretical framework with which to calculate the transient current for ions stopping within a junction that generate low injection conditions. The shape of transient current is directly proportional to the drift velocity of the carriers within the electric field. The total current, *i(t)*, is the sum of the electron and hole currents as given by:

$$i(t)=\sum_{e,h} qn_{e,h}(t)A\int E_{W}(t,x)v_{d}^{e,h}(t,x)dx \qquad (1)$$

where, q, $n_{e,h}$, A, E_W and x are the unit charge, the free carrier concentration for electrons and holes, the track column area seen by the electrodes, the weighting field and the depth, respectively [8]. For the drift velocity of both electrons and holes, $v_d^{e,h}$, we use the Canali model including the high field saturation of drift velocity [16].

At the plasma core, the nearly-equal populations of electron and hole result in ambipolar diffusion. Then the ambipolar diffusion coefficient determines the slower component of current as shown in Fig. 3. After the carriers are extracted from the plasma edge, the carriers swiftly drift to the electrodes contributing for the faster component of current [5]. In order to account for this behavior using the simple TCT model, we assume that the effective mobility during the slow and fast phases decreases according to following simple equation:

$$\mu_{s,f}=C_{s,f}\mu_{low} \qquad (2)$$

where, μ_{low} and $\mu_{s,f}$ are the low field mobility and effective mobility for both electrons and holes, respectively. The simple correction factors for both slow and fast terms are $C_{s,f}$. To compare simulations with experiments, we have convoluted the simulated transient currents with the obtained rise-time discussed above. By fitting simulated results to the experimental data shown in Fig. 2, the correction factors at –20V have been calculated for all ions as shown in Fig. 5.

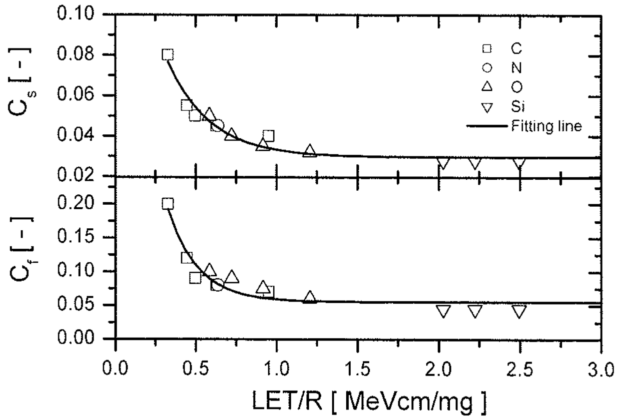


Fig.5 Correction factors as a function of the LET divided by the project range. The solid lines are calculated from the method of least squares.

Fig. 3 represents the simulated transient current waveforms. Quite reasonable agreement is obtained for the 15MeV C ion. While not shown here, this result is in contrast to the calculated results without correction factors, which show the ultra-fast transient current (less than 1ns). As the LET increases and project range decreases, however, the difference increases further, for example 6MeV C ion and Si ions (not shown here). As shown in Fig. 5, the correction factors decrease with increasing the density of e-h pairs which depend on both LET and project range. This fact suggests that the correction factors are strongly related to the carrier injection level.

The most likely reason for the marked difference between experimental and calculated data under ultra high injection condition is that the lateral distribution of plasma (2D or 3D) is not considered. In other words, the correction factors accepted here are insufficient to describe the spatial carrier dynamics which is outside the limits of 1D simulation. It is remarkably suggested that the improved 1D simulation is much better than initial standard model and gives us the practical solutions of SET current from the point of view of engineering, although accepted simple model and correction factors include some theoretical problems,.

4. SUMMARY

High-energy proton induced nuclear reactions and elastic-recoils generate SET currents that trigger bit errors in optical data links used in hash radiation environments. Modeling SET and their influence on bit errors is increasing important. We have measured and analyzed the response of a typical Si photodetector to a variety of MeV heavy ions. It is found that the signal rise-time increasing with LET is caused by the transient capacitance response, which is fast stage of transient current. By applying correction factors to the low-field mobility, the reasonable agreement can be obtained between measurement and prediction under slight theoretical limit.

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