Applied Physics Letters

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Citation: Appl. Phys. Lett. **101**, 232104 (2012); doi: 10.1063/1.4769370
View online: http://dx.doi.org/10.1063/1.4769370
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v101/i23
Published by the American Institute of Physics.

APPLIED PHYSICS LETTERS **101**, 232104 (2012)

Correlated evolution of barrier capacitance charging, generation, and drift currents and of carrier lifetime in Si structures during 25 MeV neutrons irradiation

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(Received 21 September 2012; accepted 14 November 2012; published online 4 December 2012)

The *in situ* examination of barrier capacitance charging, of generation and drift currents, and of carrier lifetime in Si structures during 25 MeV neutrons irradiation has been implemented to correlate radiation induced changes in carrier recombination, thermal release, and drift characteristics and to clarify their impact on detector performance. It has been shown that microwave probed photo-conductivity technique implemented in contact-less and distant manner can be a powerful tool for examination in wide dynamic range of carrier lifetime modified by radiation defects and for rather precise prediction of detector performance. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4769370]

The main causes and evolution of radiation damage of the heavily irradiated particle detectors remain an important issue in design of the detection systems for high energy physics,[1] operational in harsh environment of high luminosity hadrons accelerators. Intensive research of specific characteristics is usually performed on post-irradiated materials and detectors, which sustain rather long term of stabilization.

In this work, the *in situ* measurements of barrier capacitance charging, carrier generation, and drift currents in Si diodes and carrier lifetime in wafer samples of the same Si material during 25 MeV neutrons irradiation have been implemented to correlate radiation induced changes in carrier recombination, thermal release, and drift characteristics and to clarify their impact on detector performance. Commonly, neutrons damage is examined by employing samples irradiated by nuclear reactor neutrons.[2,3] A spallator type source producing neutrons with energy peak at 25 MeV has been exploited in our experiments (at the Cyclotron UCL Louvain la Neuve) to perform the on-line measurements at room temperature by combining several techniques operating in distant measurement mode.

The CERN standard particle detectors made of MCz (grown by Czochralski method with applied magnetic field) Si and having a p^+nn^+ diode structure were analyzed. The wafer pieces of 20×20 mm^2 dimension samples of the same initial MCz Si material used for fabrication of p^+nn^+ pad-detectors were employed for contact-less measurements of carrier recombination characteristics by using microwave probed photo-conductivity (MW-PC) technique. The distant measurements by exploiting the MW-PC technique have been carried out employing instrumentation described in Ref. 4, although a sample holder was positioned within neutrons beam cone in air, instead of vacuum chamber necessary for on-line experiments with protons beam. Junction barrier capacitance charging and carrier generation current measurements were performed (in parallel with MW-PC experiments) on diode structures, keeping the same irradiation conditions, when employing barrier evaluation by linearly increasing voltage (BELIV) technique and instrumentation described in Ref. 5. The *in situ* control of carrier drift parameters has been implemented keeping again the same irradiation conditions and by using induced charge drift current (ICDC) pulsed technique and instrumentation for distant *in situ* measurements, mentioned in Refs. 6 and 7. The spallator type neutrons source is based[8] on cyclotron accelerated deuterons beam interacting with Be target, which generates a cone of neutrons just behind a target. A neutrons flux can be easily manipulated by varying position of sample (on holder with necessary probes) relatively to a Be target. The main advantage of such the *in situ* experiments is that the electrical noise is very low as compared to those generated in protons irradiation chamber. This enables one to use very low excitation densities in MW-PC and ICDC measurements, while getting the reliably detectable signals. This in turn purifies the experimental conditions.

The obtained variation of the mentioned characteristics as a function of neutron irradiation fluence is compared in Fig. 1.

Actually, changes of the pulsed transients (illustrated in Figs. 1(b) and 1(c)) were controlled through computer (PC) clocked irradiation exposure time, and the pulsed transients at every irradiation instant were recorded on the same PC. A single data point corresponds to about 10 averaged transients, when a single transient is registered every 10 ms. Neutrons were generated in bunches with pulse duration of about 4 ns. The exposure time of irradiation then was correlated with an actual fluence of 25 MeV neutrons. This collected fluence was additionally calibrated by using EPR spectroscopy and Bruker alanine etalon tablets. To unambiguously relate radiation damage obtained for different irradiation

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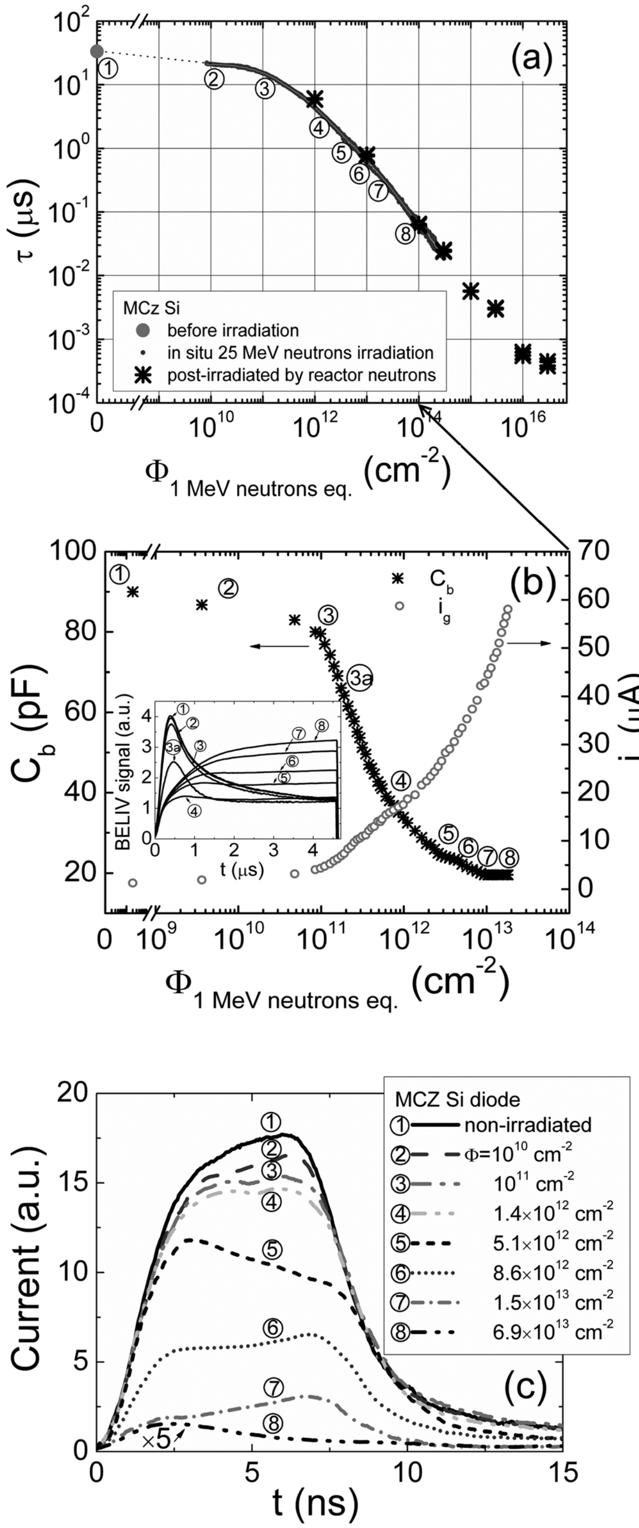

FIG. 1. Correlated variations of the carrier recombination lifetime obtained by MW-PC (a), of barrier capacitance charging and generation current, extracted from BELIV transients (b), and drift current transients, measured by ICDC technique (c) as a function of 25 MeV neutrons irradiation fluence, evaluated from exposure time of the *in situ* experiments. (a) Lifetime values measured *in situ* are denoted by circles, while star symbols represent earlier obtained (Ref. 9) lifetime dependence on fluence measured on the same material for discrete fluence values collected samples, irradiated by reactor neutrons. (b) BELIV transients at several instants of the on-line neutron irradiation exposure time are illustrated within inset. (c) Numbers denoted on the respective ICDC transients, illustrated in (c), serve for easier attribution of fluence dependent carrier lifetime, barrier capacitance charging, and generation current characteristics, shown in (a), (b), and (c) plots.

sources, the fluence of 25 MeV neutrons was re-calculated to values equivalent to 1 MeV neutrons by using the methodology of UCL.[8] The latter 1 MeV eq. fluence values are exploited in Figs. 1(a)–1(c).

In Fig. 1(a), the bulk carrier lifetime (τ_R) in n-Si wafer sample as a function of collected fluence (from non-irradiated state to $4 \times 10^{14}\,\mathrm{n/cm^2}$ 1 MeV eq.) during irradiation is illustrated (circles) for a full exposure time scale (~8 h) of the *in situ* measurements. This curve contains over 3×10^4 data points obtained from collecting of $>10^5$ MW-PC transients. The star symbols represent lifetime dependence on fluence obtained earlier on the same material, irradiated with discrete fluence values by reactor neutrons.[9] Within the initial range of small fluence, carrier lifetime decreases slowly with enhancement of fluence, as lifetime values are determined by simultaneous action of grown-in and, the radiation-induced defects. Starting from fluence $\Phi \geq 10^{11}\,\mathrm{cm}^{-2}$, the radiation defects become dominating. Further carrier lifetime decrease is nearly linear (in log-log scale, while it is hyperbolic in the linear scale). This linear lifetime reduction proceeds further for the larger fluence of reactor neutrons (points marked by stars), and it can be implied for 25 MeV neutrons, since in the range of $\Phi > 10^{11}$–$10^{14}\,\mathrm{cm}^{-2}$ an excellent agreement between values for the on-line and post-irradiation measurements was obtained.

An evolution of BELIV transients (in the inset, a few of them are shown for several instants of the on-line exposure time) is illustrated within inset of Fig. 1(b). Two main components in these transients represent barrier capacitance charging current (i_C), the initial one, and generation current (i_g), when observable increase in the rearward range of the BELIV pulses. These components[6] can be expressed as

$$i(t) = i_C(t) + i_g(t) = \frac{\partial U}{\partial t}\left(C_b + U\frac{\partial C_b}{\partial w}\frac{\partial w(t)}{\partial U(t)}\right) + \sum_M \frac{e m_{0,M} S w(U(t))}{\tau_{g,M}}, \quad (1)$$

where the barrier capacitance is $C_b = \varepsilon\varepsilon_0/w(t)$ (of a unite surface area (S)). The barrier capacitance charging current decreases with time for a reverse bias LIV voltage $U(t) = At$ pulse of a ramp A, due to an increase of the depletion width $w(U(t))$. The generation current (i_g) is a sum over all types of traps M, distributed over $w(t)$, which represents thermally released carriers of density m_0, with a specific generation lifetime, commonly assumed as $\tau_g = N_C s_T v_T \exp(\Delta E_A/kT)$, and it ($i_g$) increases with $w(t)$. The symbols represent: N_C is an effective density of band states, s_T is an effective cross-section, v_T is thermal velocity, ΔE_A is trap activation energy, and kT is thermal energy. These current components compete and determine the observed changes of the shape of a BELIV pulse. The extracted values of barrier capacitance and of generation current as a function of fluence are shown in Fig. 1(b). The clearly noticeable decrease of C_b and the enhancement of i_g correlate well mutually and with that of recombination lifetime decrease observed in the same range of neutron irradiation fluence (Fig. 1(a)). The obtained reduction of $C_b \sim N_{def}^{1/2}$ ($N_{def} = N_D$-N_{AM} is an effective density of doping for donors N_D doped material containing N_{AM} acceptor-type trap density) and the prevailing increase of

$i_g \sim m_{0,M} \sim$ M (with M, as a density of specific type traps) indicate that radiation induced traps are the efficient recombination/generation centers that compensate N_{def} dopants leading to the degradation and further destruction of a junction.

A set of ICDC transients are shown at several instants of the on-line exposure time in Fig. 1(c), when green light laser pulse injects surface charge domain $q_0 = eK/S$ of K electrons within area of laser beam spot, nearby the metallurgic junction boundary. Here, more complicated changes of the pulse shape are obtained. These changes can be again understood by the competition of several current components in the overall current pulse shape. In the non-irradiated diode, a drift current of density $j_{dr} = q(dy/dt)$ prevails leading to an invariable value $j = q_0/\tau_{dr}$, as a drift time $t_{dr} \approx \tau_{dr} = d^2/\mu U \ll \tau_R$ is the shortest one among characteristic times. Here, $y(t) = (X_0(t)/d)$ is a dimensionless position of drifting surface charge domain within inter-electrode space, d is a width of active layer or inter-electrode gap, and μ is carrier mobility. For non-irradiated detector, a rising with time current shape of the ICDC pulse might appear due to RC of the measurement circuit, which can be included by a convolution integral $j(t) = (1/RC)\int_0^t (q_0/\tau_{dr})\exp(-\zeta/RC)\mathrm{d}\zeta$ resulting in $j(t) = (q_0/\tau_{dr})[1 - \exp(-t/RC)]$ for $0 \le t \le t_{dr}$. In the irradiated detector, drift current is modified by specific times of dielectric relaxation of the space charge $\tau_{Ndef} = \varepsilon\varepsilon_0/e\mu N_{def}$ and $\tau_m(t) = 2\varepsilon\varepsilon_0/e\mu m_0 (1 - \exp(-t/\tau_g))$ (due to change of $N_{def}(t)$ by thermal emission of $m(t) = m_0\,(1 - \exp(-t/\tau_g)$ trapped carriers with initial density $m(t = 0) = m_0$). As usually, e and ε, ε_0 represent elementary charge and permittivities, respectively. The drifting charge domain of surface density $q(t) = q_0\ \exp(-t/\tau_R)$ is also varied in time due to carrier capture (τ_R) and dielectric relaxation with $\tau_q(t) = \varepsilon\varepsilon_0/\mu[q_0\ \exp(-t/\tau_R)/d]$, respectively, when density of traps and carrier lifetime is modified by neutron irradiation. Carrier capture (recombination) current $i_{tr} \approx q/\tau_R$ prevails when trapping lifetime, $\sim\tau_R$, becomes shorter than drift time t_{dr}. Then, the generalized ICDC current density $j(t)$ is represented as

$$j(t) = q(t)\frac{dy}{dt} + \frac{q(t)}{\tau_R}[1 - y(t)] + \frac{ed}{2}\frac{dm}{dt}. \qquad (2)$$

Time dependent position $y(t)$ changes are evaluated by solution of a drift velocity ($v(y) = [dy/dt]d$) field equation $dy/dt - [\tau_m{}^{-1}(t) + \tau_q{}^{-1}(t) - \tau_{Ndef}{}^{-1}]\quad y(t) - [\tau_{dr}{}^{-1} - \tau_m{}^{-1}(t)] = 0$, being the first order ordinary differential equation with time dependent coefficients and boundary conditions $y(t = 0) = y_0$ and $y(t = t_{dr}) = 1$. Assuming that τ_{dr}, τ_{Ndef} and τ_R are rather short, in comparison with other characteristic times, Eq. (2) for $0 \le y(t) < 1$ can be approximated as $j(t) = [q_0\ \exp(-t/\tau_R)/\tau_{dr}] + [q_0\ \exp(-t/\tau_R)/\tau_R] + [em_0 d\ \exp(-t/\tau_g)/2\tau_g]$. Increase of fluence leads to a decrease of ICDC pulse amplitude, due to carrier trapping and reduction of q_0 with enhancement of fluence (as a fixed excitation density was kept). Pulse duration, measured between kink points on pulse vertex, indicating start of domain drift and its arrival to the rear electrode, is in good agreement with τ_{dr} value estimated using parameters of the experiment. The current density exponentially decreases $j(t) \sim \exp(-t/\tau_R)$ within pulse vertex when τ_R approaches to τ_{dr} and t_{dr}. The generation current component can be ignored within ICDC pulse when $\tau_g > \tau_R > t_{dr}$. Finally, the recombination current becomes dominating (the 8-th transient, in Fig. 1(c)), when $\tau_R \le \tau_{dr}$, and the relaxing ($j_{tr}(t) = q_0\ \exp(-t/\tau_R)/\tau_R$) current decay hides a charge drift current.

In summary, the observed changes of MW-PC, BELIV, and ICDC transients well correlate mutually when considered relatively to an increasing fluence value. Thus, MW-PC correlated lifetime changes, measured in contact-less and distant manner, calibrated with other parameters is a powerful tool for examination in a wide dynamic range of carrier lifetimes, modified by radiation defects. Approach of carrier lifetime values to those of charge drift specific time scale leads to the non-operational junction. The observed increase of generation current within BELIV transients will cause a considerable increase of detector noise level. Thus, carrier recombination lifetime values, measured by MW-PC technique, can be employed in prediction of detector performance. The detectors studied in this work are nearly destructed (non-operational junction) after irradiation with 4×10^{14} n/cm^2 1 MeV eq. fluence.

Development of the employed measurement techniques and instrumentation has been supported by the Research Council of Lithuania, grant MIP-054/2011, and neutron irradiations were performed within frame of FP-7 "AIDA" project. E. Tuominen, J. Harkonen, and J. Raisanen are appreciated for samples.

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