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Journal of Nuclear Materials 283–287 (2000) 907–911
journal of nuclear materials
www.elsevier.nl/locate/jnucmat

Radiation-induced conductivity of doped silicon in response to photon, proton and neutron irradiation

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Abstract

The opto-electronic performance of semiconductors during reactor operation is restricted by radiation-induced conductivity (RIC) and the synergistic effects of neutrons/ions and photons. The RICs of Si due to photons, protons and pulsed neutrons have been evaluated, aiming at radiation correlation. Protons of 17 MeV with an ionizing dose rate of 10^3 Gy/s and/or photons ($h\nu = 1.3$ eV) were used to irradiate impurity-doped Si (2×10^{16} B atoms/cm^3) at 300 and 200 K. Proton-induced RIC (p-RIC) and photoconductivity (PC) were intermittently detected in an accelerator device. Neutron-induced RIC (n-RIC) was measured for the same Si in a pulsed fast-fission reactor, BARS-6, with a 70-μs pulse of 2×10^{12} n/cm^2 ($E > 0.01$ MeV) and a dose rate of up to 6×10^5 Gy/s. The neutron irradiation showed a saturation tendency in the flux dependence at 300 K due to the strong electronic excitation. Normalization of the electronic excitation, including the pulsed regime, gave a fair agreement among the different radiation environments. Detailed comparison among PC, p-RIC and n-RIC is discussed in terms of radiation correlation including the in-pile condition. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Radiation damage of opto-electric semiconductors is one of the key issues in fusion plasma diagnostics. The opto-electronic performance of semiconductors is affected by the phenomenon of radiation-induced conductivity (RIC) prior to deterioration by cumulative defects. The RIC process is caused by excited electrons and holes during the minority-carrier lifetime. It was established decades ago that the minority-carrier lifetime of crystalline Si decreases with increasing defects as deep recombination centers. Extensive data on the post-irradiation decrease of carrier lifetime have been accumulated for electron [1–3], proton [3–8] and neutron irradiation [2,3,7,8]. An important factor is the radiation correlation of RIC between photons, ions and neutrons. In evaluating the in-pile n-RIC, it is essential to apply a pulsed reactor and extract the net RIC under the gamma-ray background. Quantitative comparison of the different time regimes requires an understanding of the time-dependent behavior of RIC.

Up to the present, we have studied the fluence dependence of photoconductivity (PC) and RIC of Si [4,5] under 17-MeV proton irradiation, mainly at 200 K. Shallow-impurity doping at a moderate level (10^{15}–10^{16}/cm^3) showed good radiation resistance, not only for the dark conductivity but also for the PC, i.e., for the carrier lifetime [4]. By virtue of radiation resistance, it may be possible to define RIC as a material property, specific to each radiation condition. The purpose of the present research is to explore the radiation correlation of RIC between 17-MeV protons and fast neutrons, as well as photons.

2. Experimental procedures

Specimens of $3 \times 4 \times 0.2$ mm^3 were cut from a Cz-Si wafer of p-type with 2×10^{16} B atoms/cm^3. Ohmic electrodes (two areas of 3×1.5 mm^2 each) of planar type (distance: 1.0 mm) were formed and the surface for irradiation (3×1.0 mm^2) was chemically etched. The

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protons and photons were irradiated at 0° and 45° to the normal of the specimen surface. The proton dose rate and photon flux were typically 40 nA/cm^2 and 5×10^{14} photons/cm^2 s at $hv = 1.3$ eV, respectively. To measure the pulsed-proton induced RIC (p-RIC), a pulsed proton beam was generated by chopping the RF acceleration power, whose pulse-width was 0.27–1.1 ms. The blunting time of the square pulse was approximately 70 μs. A digital storage oscilloscope of 2G-samplings/s processed the transient current signal. Damage conditions for proton irradiation were evaluated with the TRIM-code [9], using a displacement energy, $E_d = 15.8$ eV [10]. The conversion ratio used for Si was 40 nA/cm^2 (2.5×10^{11} ions/s) $= 1.2 \times 10^{-9}$ dpa/s, which corresponds to an energy dose rate of 1×10^3 Gy/s.

The neutron-induced conductivity (n-RIC) of Si was measured in a pulsed reactor designated BARS-6. By virtue of the pulsed operation, the net RIC was extracted from the synergistic effects in the reactor. The neutron pulse, of a half-height width down to 70 μs, gave a neutron dose per pulse of up to 2×10^{12} n/cm^2 ($E > 0.01$ MeV). The radiation conditions were evaluated with the MCNP neutron-dosimetry code, and the electronic dose rate of 70-μs pulses varied up to 6×10^4 Gy/s. For the remote experiments, we used a computerized data-acquisition system based on the multi-channel ADC. Owing to the high dark conductivity of the specimen, possible leakage currents have negligible effect on RIC measurement. Low input-resistance of the ADC ensures the elimination of the effects of radiation-induced electromotive force in the measuring circuit.

3. Results and discussion

In the fluence dependence for moderately-doped (10^{15}–10^{16}/cm^3) Si [4,5,11], the PC and RIC varied in parallel and did not decrease significantly up to a certain fluence which was called critical fluence ϕ_C [4]. Above the ϕ_C, both PC and RIC steeply decrease corresponding to a drop in the minority-carrier lifetime. Therefore, the good radiation resistance (below ϕ_C) justifies quantitative comparison of RIC as a fluence-independent property. Fig. 1 shows the dc conductivity of *p*-Si with 2×10^{16} B atoms/cm^3 during beam-on and -off, at 300 (upper) and 200 K (lower), where the dose rates are 33 and 40 nA/cm^2, respectively. The RIC is measured as a step height of dc conductivity on irradiation, since the dc conductivity continuously decreases, especially around 300 K. The measured ratio of p-RIC to PC was $\Delta\sigma_p/\Delta\sigma_L = 10$ for a proton dose rate of 40 nA/cm^2 and 5×10^{14} photons/cm^2 s [5]. Since the charge mobility is identical for p-RIC and PC, the correlation factor η can be discussed by normalizing the dose rate in electronic excitation:

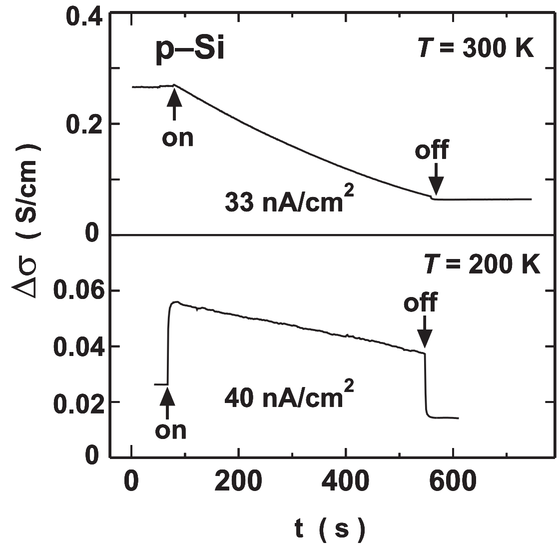

Fig. 1. Electrical conductivity of *p*-Si with 2×10^{16} B atoms/cm^3 during beam-on and -off, at 300 (upper: 33 nA/cm^2) and 200 K (lower: 40 nA/cm^2). The RIC corresponds to a step height on or off the irradiation.

$$\eta = \left(\frac{\Delta\sigma_p}{\Delta\sigma_L}\right) \Big/ \left(v\frac{Q_p}{Q_L}\right), \tag{1}$$

where Q_i ($i =$ p or L) and v denote density of excitation energy and relative efficiency in creating excess-carrier density, respectively. Bulk photon excitation energy is obtained from the photon flux by multiplying it by the absorption coefficient. Using an absorption constant of Si ($\alpha = 300/\text{cm}^{-1}$ at 1.3 eV), the photon excitation is obtained as $Q_L = [5 \times 10^{14}$ photons/cm^2 s $\times$ 1.3 eV$\times$ 300/cm$^{-1}] \sim 13$ Gy/s. The volumetric ionization energy of protons is $Q_p = 1 \times 10^3$ Gy/s and the energy ratio is estimated as $Q_p/Q_L \sim 80$. If electron-hole generation energies of 3.88 eV [12] for protons and 1.1 eV for photons are assumed, the carrier-production efficiency is $v \sim 1/4$. Finally, the correlation factor of proton to photon is given to be $\eta \sim 1/2$.

To compare with the pulsed n-RIC, the pulsed proton beam was also applied to measure the p-RIC. Using a simple Laplace transformation, the pulsed response $\Delta\sigma_{max}$ to a square pulse of width w is expressed by

$$\Delta\sigma_{max} = \Delta\sigma_0\{1 - \exp(-w/\tau)\}, \tag{2}$$

where $\Delta\sigma_0$ and τ denote the saturated value and the lifetime of RIC, respectively. In the two extreme cases of the shorter and longer τ-limits, $\Delta\sigma_{max}$ approaches the simple relations:

$$\Delta\sigma_{max} = \Delta\sigma_0 \quad \text{for } \tau \ll w, \tag{2a}$$

$$\Delta\sigma_{max} = \Delta\sigma_0 w/\tau \quad \text{for } \tau \geqslant w. \tag{2b}$$

While the shorter τ case (2a) is equivalent to continuous irradiation, the longer τ case (2b) $\Delta\sigma_{max}$ is proportional to the pulse width.

Fig. 2 shows time-dependent changes of proton-induced RIC of Si at 300 K in response to different pulse widths of 0.27 (lower) and 1.1 ms (upper), where the flat top of the beam corresponds to the dose rate of 170 nA/cm^2. The doses per pulse, 3×10^8 (lower) and 1.2×10^9 ions/cm^2 (upper), are negligible compared to the total fluences 4×10^{13} and 5×10^{13} ions/cm^2, respectively. Slopes of the rise and decay correspond to the generation and recombination rates of excited carriers, respectively. The time constants can be obtained from the slope fitting with a single exponential curve. The generation time and lifetime of carriers are similar to each other, i.e., $\tau \sim 0.4 \pm 0.1$ ms in this case. The $\Delta\sigma_{max}$ gives 0.01 and 0.002 S/cm for the 1.1- and the 0.27-ms pulses, respectively, where the flat-top dose rate is 4.3×10^3 Gy/s. In comparing the two pulse-widths, the intensity of $\Delta\sigma_{max}$ is roughly proportional to the pulse width. The experimental condition is rather close to the longer-τ case of Eq. (2b). Here, it should be noted that the peak intensity of the RIC depends not only on the peak excitation intensity but also on the ratio w/τ. Accordingly, information of the lifetime is requisite in considering radiation correlation.

Although PC and p-RIC around 200 K are found to be insensitive to proton fluence ($\phi < \phi_C$), those at 300 K are dependent on the fluence. Fig. 3 shows the fluence dependence of the minority-carrier lifetime, dark conductivity and the maximum height of p-RIC for the 0.27-ms proton beam. The dark conductivity at 300 K begins to gradually drop from about 10^{13}–10^{14} ions/cm^2, earlier than at 200 K (from $\sim 5 \times 10^{14}$ ions/cm^2). The carrier lifetime, taken from the RIC decay curve, also drops at around 10^{14} ions/cm^2. This drop of τ indicates a decrease in continuous p-RIC above the critical fluence ϕ_C, though the ϕ_C is not so clear-cut at 300 K. Thus, the RIC-process around RT is stable only below $\sim 5 \times 10^{13}$ ions/cm^2 ($\sim 2.5 \times 10^{-7}$ dpa) for the *p*-Si used, and keeps decreasing towards the higher fluences. As seen in Fig. 3, the maximum height of p-RIC, $\Delta\sigma_{max}$, shows a peak at 2×10^{14} ions/cm^2. The variation of $\Delta\sigma_{max}$ results from comparison of the τ and the pulsed width w, being expressed by Eqs. (2), (2a) and (2b). In the fluence range of $\tau \geqslant w$, the $\Delta\sigma_{max}$ cannot reach the steady-state value $\Delta\sigma_0$; it approaches $\Delta\sigma_0$ with decreasing τ. In the range $\tau < w$, the $\Delta\sigma_{max} \sim \Delta\sigma_0$ decreases with decreasing carrier lifetime. It can be explained that, around the critical fluence ϕ_C, the carriers trapped by defects, being accumulated, require a carrier-generation energy much less than 3.88 eV [12] and excess carriers could increase. In the higher fluence range ($\phi > \phi_C$), the increase in excess carriers is smeared by rapidly decreasing τ. Around the ϕ_C, the critical balance between an intermediate τ and abundant excess carriers is able to give the peak.

On the basis of the understandings of photon and proton effects, key points to assess radiation correlation are (1) normalization of electronic excitation, i.e., dose

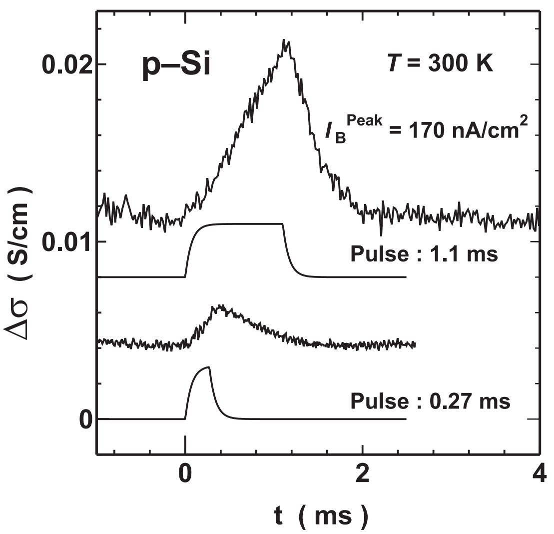

Fig. 2. Time-dependent variations of proton-induced RIC of *p*-Si at 300 K in response to different pulse widths of 0.27 (lower) and 1.1 ms (upper). The flat top of the beam corresponds to the dose rate of 170 nA/cm^2.

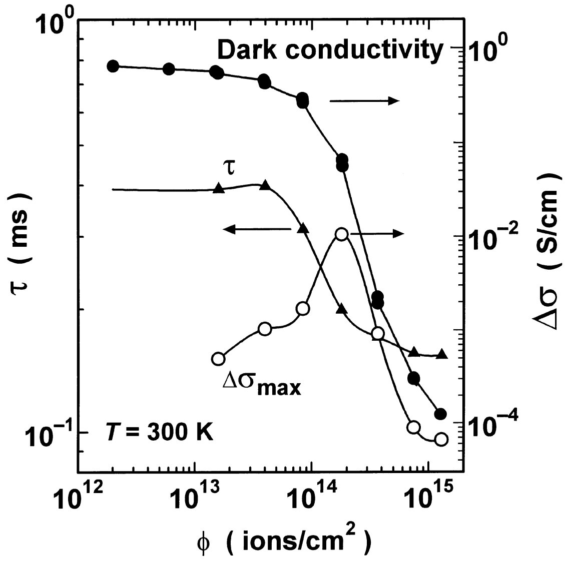

Fig. 3. Fluence dependence of the minority-carrier lifetime, dark conductivity and the maximum height of p-RIC for *p*-Si. The maximum p-RIC, $\Delta\sigma_{max}$, is the peak value for the 0.27-ms proton beam.

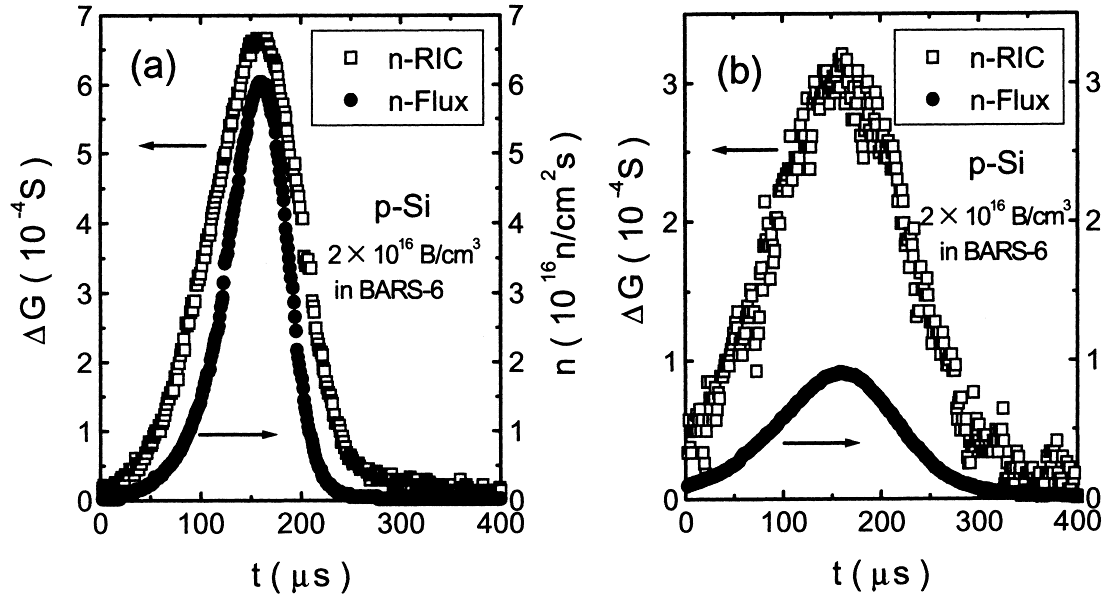

Fig. 4. Neutron-induced RIC in response to neutron pulses with half-height widths of (a) 70 μs and (b) 150 μs. The RIC in this case is given by a conductance change ΔG (S). The total fluence before these measurements is about 5×10^{12} n/cm^2.

rate in electronic energy, (2) pulsed response, dependent on carrier lifetime and (3) total fluence effects unless $\phi < \phi_C$. Results of n-RIC (conductance ΔG in Siemens) for two neutron pulses with half-height widths of 70 and 150 μs are shown in Figs. 4(a) and (b), respectively. Here, the fluence accumulated before these measurements is about 5×10^{12} n/cm^2 and is much less than ϕ_C. The conductance ΔG is converted to the conductivity $\Delta\sigma$ by multiplying by the specimen form-factor 40. The peak values of n-RIC correspond to $\Delta\sigma_{max} = 2.7 \times 10^{-2}$ S/cm (6×10^4 Gy/s) for the 70-μs pulse and 1.3×10^{-2} S/cm (1×10^4 Gy/s) for the 150-μs pulse. As for the time dependence of n-RIC, the Lorentzian-like response basically follows the signal of neutron flux, but is broader. The peak position of n-RIC roughly coincides with that of neutron flux. No irreversible change of conductivity is detected. The proton data (Fig. 3) as well as the photon data imply that the carrier lifetime should be longer than the neutron pulse-widths, i.e., the peak values of n-RIC here are not saturated values $\Delta\sigma_0$ but $\Delta\sigma_{max}$, in the pulsed irradiation regime (Eq. (2)). This tendency is analogous to the case of Eq. (2b).

Fig. 5 shows dose rate dependence of n-RIC in *p*-Si for the neutron pulse with half-height width of 70 μs. The peak RIC response is proportional to the square root of the dose rate. The n-RIC process is dominated by bimolecular recombination of high-density electrons and holes. In the proton irradiation experiment, the square-root dependence was observed for the longer lifetime at 200 K [13]. The present observation for neutron irradiation around RT implies that the electronic excitation is strong enough to neglect other recombination paths [13]. Here, the important factor is the energy partitioning of neutrons dissipated in the solid. According to the calculation of the MCNP code, neutrons deposit the energy via neutron elastic collisions (62%), neutron absorption (7%) and incident/produced

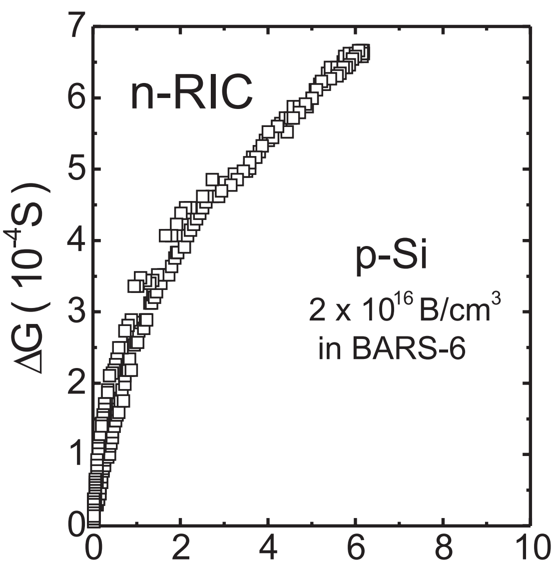

Fig. 5. Dose rate dependence of neutron-induced RIC, ΔG, in *p*-Si in response to pulses with half-height width of 70 μs.

gamma photons (31%). The portion of elastic collisions is obviously large for fast neutrons, but the component of electronic excitation still yields 1/3 of the incident energy.

The correlation factor between n-RIC and p-RIC, normalized by the electronic excitation energy and pulse width, is given by

$$\eta = \frac{\Delta\sigma_{\mathrm{n,max}}/(Q_{\mathrm{n}}w_{\mathrm{n}})}{\Delta\sigma_{\mathrm{p,max}}/(Q_{\mathrm{p}}w_{\mathrm{p}})} \approx 3 \tag{3}$$

where $\Delta\sigma_{\mathrm{n,max}}$ and $\Delta\sigma_{\mathrm{p,max}}$ are used for experimental values for 70-μs neutron pulse and 270-μs proton pulse (or 1.1-ms proton pulse), respectively. The Q_i and w_{n} $(i = \mathrm{n, p})$ are the electronic dose rate (Gy/s) and the pulse-widths, respectively. The correlation factor of ~3 implies that the RIC process is approximately equivalent between neutron and proton irradiation, if one properly normalizes the electronic excitation energy (Gy/s) and the time regime. If the ambiguity of the parameters was small enough, it might be speculated that the efficiency of n-RIC may be higher than that of p-RIC, suggesting significant contribution by gamma rays.

4. Conclusion

Radiation-induced conductivity of *p*-type Si in response to photons, protons and pulsed fast neutrons has been evaluated using in-situ pulsed techniques. The peak p-RIC and the minority-carrier lifetime were obtained as a response of proton pulses. The p-RIC showed a peak variation around the critical fluence. The pulsed neutron-induced RIC was successfully measured in BARS-6 in response to 70-μs and 150-μs pulses. The peak n-RIC at RT was proportional to the square root of the dose rate, indicating bimolecular recombination due to the strong excitation. The correlation factor between n-RIC and p-RIC was evaluated to be about 3, being normalized by the electronic excitation energy and the pulse width. The correlation factor of RIC among photon, proton and neutron irradiation was found to be of the order of unity after the energy dose rates were normalized.

Acknowledgements

The authors are indebted to Dr V.M. Chernov (IPPE) for encouraging effective collaboration between NRIM and IPPE.

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