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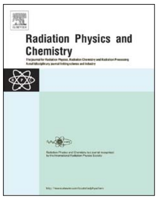

Surface profile of minority carrier lifetime in 65 and 100 MeV fluorine ion irradiated n-Si (111)

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HIGHLIGHTS

- Heavy fluorine ion irradiation was used to modify the minority carrier lifetime in c-Si.
- Lifetime profiling of irradiated n-Si were compared using LED based lifetime measurement system.
- Spatial and Depth distribution of defects over a volume are important for device performance.

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ABSTRACT

Irradiation-induced modifications of excess minority carrier recombination time (lifetime) τ in CZ-grown crystalline n-Si (111) with resistivity 60 Ω cm are reported. Samples were irradiated with 65 and 100 MeV fluorine ions in the fluence range of 2×10^{10}–10^{14} ions/cm^2. The surface and depth profile of lifetime was measured using photoconductive decay (PCD) technique. In the entire set of ion-irradiated samples, lifetime was found to decrease monotonously with increasing ion fluence. This decrease in lifetime is attributed to the electronic energy loss S_e induced generation of carrier traps and vacancies. Moreover, the higher S_e in 65 MeV energy fluorine ions is responsible for the rapid decrease in lifetime as compared to the 100 MeV ions. The excess S_e in 65 MeV fluorine ions is consumed in defect production over the ion track as well as surface and sub-surface recrystallization, thus exhibiting S_e dependence. The variation in the surface lifetime is associated to the competition between surface defects and S_e dependent recrystallization. Almost complete recovery in the lifetime towards the pre-irradiation level after annealing at 750 °C for a period of 1 h, confirms that the lifetime modification is due to irradiation-induced carrier trapping centers.

1. Introduction

Minority carrier lifetime, τ, is an important parameter for a large variety of silicon devices. With the increasing need of fast switching devices, tailoring of lifetime is carried out to reduce lifetime values. The recent trends in the tailoring of lifetime in silicon show that energetic ion implantation/irradiation is quite popular. This is due to the different tuning parameters of the ion beams such as energy, fluence, charge-state and ion species. A literature survey indicates that considerable amount of work has been carried on various irradiation-induced modification of lifetime (Carles et al., 1997; Brotherton and Bradley, 1982; Mogro Campero et al., 1986; Hallen and Bakowski, 1989; Bhoraskar et al., 1991; Khanh et al., 1997; Keskitalo et al., 1997; Ziegler et al., 1985). The present understanding of these irradiation-induced processes is that, upon entering the medium, the energetic heavy ions deposit a large amount of its energy through ionization/excitation energy loss i.e. electronic energy loss S_e. When the ion is about a few keV, the effective charge on the ion is zero, the energy is transferred to the medium by dislodging the atoms from their lattice positions and creating defects. This latter process dominates at the stopping range of the ion in the medium and is termed as nuclear energy loss S_n (Ziegler et al., 1985). These irradiation-induced defects act as recombination centers, which reduce the minority carrier lifetime (Shroder, 1997). In most of the lifetime measurement method used for characterization of irradiation-induced defects, the sample was generally etched to various thicknesses to measure the actual defect density, or else the bulk carrier lifetime τ_b has been assigned to these excess defects (Bhoraskar et al., 1991; Khanh et al., 1997; Chavan et al., 1997).

Understanding these drawbacks from earlier works, we have

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tried to measure the lifetime profile spatially along the X-Y plane of the surface as well as at a certain depth in silicon samples irradiated with 65 MeV and 100 MeV fluorine ions. The need of spatial lifetime measurement arises from the fact that, there are millions of micro-transistors on a single silicon IC of area 1 square centimeter. Even if one is successful in reducing the lifetime by using irradiation techniques, the spatial lifetime may not be uniform, which can seriously limit the device efficiency. For this purpose, a computer controlled PCD excess minority carrier lifetime measurement system is used. In the PCD method, a square pulse of light ($h\nu = E > E_g$) generates electron-hole pairs in the semiconductor during the ON-time. Due to the transient generation of excess carrier the conductivity of the sample increases, which in turn results in a drop in resistivity, generating a potential difference across the sample. When the pulse is OFF, the excess minority carriers annihilate through various processes, such as radiative recombination, Auger recombination, recombination through traps, excitons and dislocations, generating a decay pulse. Then the time required for the decay voltage to reach 1/e corresponds to the lifetime τ. Hence, the measured lifetime corresponds to an average of sum of the lifetimes from the various recombination processes (Schwab et al., 1997). Moreover, the principle of mass absorption can be applied to obtain the lifetime depth profile. It means that, photons of the particular wavelength λ will generate excess carrier only up to a depth δ and not in the bulk of the medium. Hence, measured lifetime τ actually corresponds to the average carrier lifetime till that depth. The penetration depth δ (Flohr and Helbig, 1989), absorption coefficient α of a wavelength λ (far IR ~925 nm to blue ~462 nm) (Aspnes and Studna, 1990) used in the present case is given in the Table 1 and details of which are discussed elsewhere (Grove, 1967).

The ability of the energetic heavy ions to generate defects in the sample is termed as radiation damage coefficient, K that is related to the measured value of the pre-irradiation lifetime τ_0 and post irradiation lifetime τ at fluence Φ by the following expression (Chavan et al., 1995a).

$$\frac{1}{\tau} - \frac{1}{\tau_0} = K\phi \tag{1}$$

The damage coefficient K, for a given type of radiation can then be determined from the slope of the plot $1/\tau - 1/\tau_0$ versus Φ. Thus, one can achieve the purpose to understand the irradiation-induced defect production in silicon. Furthermore, these irradiation-induced defects are known to anneal out at high temperatures. Hence, annealing at a temperature in the range of 250–750 °C was carried out to obtain more information about the defect annealing.

2. Experimental

A few 3″ CZ-grown crystalline Si (111) n-doped wafers of resistivity 60 Ω cm and thickness 350 μm were cut into samples of size 15 mm × 15 mm. Ohmic contacts were prepared by depositing Al and sintering at 400 °C. These sets of samples were irradiated with 65 MeV and 100 MeV energy fluorine ions in the fluence Φ range of 2×10^{10}–10^{14} ions/cm^2. The samples were irradiated in vacuum of the order of 10^{-7} Torr. The irradiations were carried out at the 14UD Pelletron of T.I.F.R., Mumbai. The lifetime measurements were carried out on the pre and post irradiated samples in the air. As the measurements are done in air, it should be noted that natural surface oxidation cannot be avoided even if oxide layer is removed prior to measurement. An automated PCD system was used to measure the excess minority carrier recombination time in at surface, bulk and various depths of the silicon samples. Light source of wavelength λ of 925, 866.5, 638, 581, 525 and 462 nm were incident at surface normal and raster scanned at 1 mm per measurements (Grove, 1967). Another set of irradiated samples was annealed for period of 1 h each in the temperature range of 250–750 °C and then lifetime measurements were performed for all wavelengths λ.

Table 1
Penetration depth δ and absorption coefficient α for various incident wavelengths λ also shown is photon energy.

Spectral color	Wavelength λ (nm)	Photon energy, hν (eV)	Absorption coefficient $\alpha \times 10^3$ (cm^{-1})	Penetration depth δ (μm)
Far IR	925	1.34	0.31	31.5
IR	866.5	1.43	0.52	19.2
Red	638	1.94	3.65	2.7
Yellow	581	2.13	6.45	1.5
Green	525	2.36	13.86	0.7
Blue	462	2.68	32.59	0.3

3. Results and discussion

The Figs. 1 and 2 show that, lifetime decreases with increasing ion fluence for all the samples irradiated with 65 and 100 MeV fluorine ions, respectively. It can also be seen that within a given sample, lifetime decreases with the measured depth for any given fluence, except for 462 and 525 nm measurements. This decrease in lifetime is due to generation of carrier traps and vacancies by the energetic ions throughout their trajectory (Belykh et al., 1990). Moreover, it is important to note that the stopping range of the ions is more than the photon penetration depth (see Table 1). This means that the observed damage generated at the end of ion trajectory has marginal effect on the lifetime modifications. However, at any particular fluence the decrease in lifetime in the 100 MeV fluorine ion irradiated n-Si (111) is greater than that of the 65 MeV fluorine ion irradiated n-Si (111) except for 525 and 462 nm wavelengths. From Fig. 1, it is seen that the bulk lifetime τ_b (since for $\lambda = 925$ nm penetrate upto 31.5 μm in Si (111) and the measured τ is thus assumed to be τ_b [Table 1]), decreases from 15.8 μs to 8.3 μs in the sample irradiated with 65 MeV fluorine ions at a fluence of 10^{14} ions/cm^2. This change in the lifetime is about 47.46%. If we compare the percentage change for 100 MeV

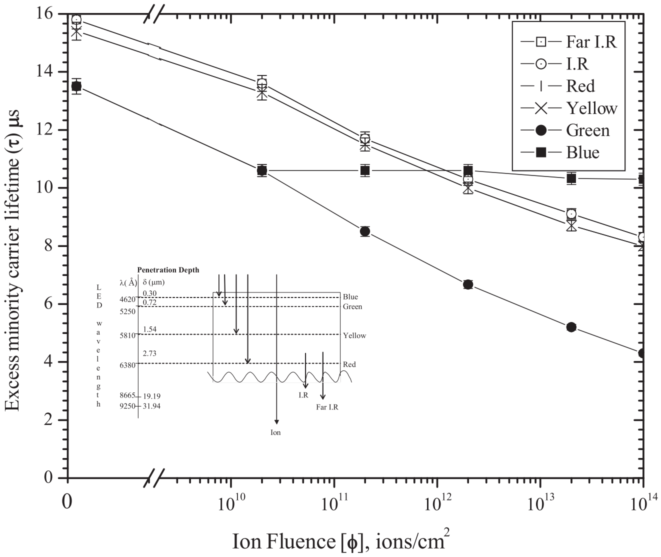

Fig. 1. Variation in carrier lifetime with ion fluence in 65 MeV energy fluorine ion irradiated n-type silicon for all wavelengths.