ANNALES
UNIVERSITATIS MARIAE CURIE-SKŁODOWSKA
LUBLIN – POLONIA
VOL. LVII, 8 SECTIO AAA 2002

Recombination of non-equilibrium charge carriers in silicon irradiated with high energy ions

V.Yu. Yavid, S.N. Jakubenja and A.R. Chelyadinskii

Byelorussian State University, Department of Semiconductors Physics,
pr. F. Skarina 4, 220050 Minsk, Belarus

ABSTRACT

Temperature dependencies of nonequilibrium charge carriers lifetime in n-type silicon layers implanted with 92 MeV boron ions have been investigated. It was established that τ is determined by recombination centres localized in strongly compensated defect clusters produced during the implantation process and subsequent annealing. It was shown that dominant recombination centres are concerned with multivacancy complexes and produce in silicon band gap energy levels E_c – (0.12 – 0.18) eV.

1. INTRODUCTION

Ion implantation is followed by generation of a vast number of structural defects, which determines to a great extent electrophysical properties of the material. Ensemble of the recombination-active defects can be singled out in the introduced damages. Due to their high values of the capture cross section for holes and electrons (or their asymmetry) these defects condition the processes of recombination and trapping of non-equilibrium charge carriers. Recombination of carriers pairs is described by the value of lifetime of non-equilibrium charge carriers. It is one of the most sensitive parameters to impact of high energy particles on semiconductors [1, 2].

The study of the recombination-active defects in ion implanted semiconductors allows one to make a contribution to solving of at least two problems existing in physics of interaction of high energy ions with solids: firstly, to specify the processes of generation of radiation damage and the laws of its annealing and, secondly, to determine the nature and parameters of the introduced defects. A certain success has been achieved in solving these problems by studying the recombination centres in silicon limited to the implanted impurity region or to the proximate surroundings [3–6].

It should be noticed that high density of damage and its stretched spatial distribution are typical features of high energy ion implantation which are likely to have a direct connection to the space energy distribution generated by the stopping particles [7]. The defect formation peculiarities can be naturally expected to affect the formation of the recombination-active defects too.

2. EXPERIMENT

Phosphorus doped silicon with specific resistivity of 20 and 70 Ohm cm grown both by the Czochralski method and by floating zone method has been studied. The lifetime value at a room temperature in silicon grown by the Czochralski method was $(6.0 \pm 0.8)\times10^{-5}$ s and by floating zone method was $(1.8 \pm 0.3)\times10^{-4}$ s. The implantation was carried out with boron ions of 92 MeV energy at doses of 2×10^{13} and 1×10^{15} cm^{-2}.

The lifetime value of non-equilibrium charge carriers has been determined by the phase detection method of the microwave photoconductivity [8, 9]. Photoconductivity excitation in the samples under analysis has been carried out under sinusoidally modulated irradiation of a He-Ne laser with at a wave length of 632.8 nm. The light flow modulation frequency was determined taking into consideration the minimal error in estimation the lifetime value τ [10] and was limited to the range of 1–10 kHz. The photoconductivity signal is detected by means of microwave technique at 3 cm wave length. The samples with the measuring microwave cavity have been put into a cryostat with liquid nitrogen to study temperature dependencies of the lifetime. Isochronal annealing of the ion irradiated samples has been carried out in the temperature range of 300–625°C in a nitrogen atmosphere. The value of electrical conductivity and thermal e.m.f. have been also measured.

3. RESULTS AND DISCUSSION

The high degree of damage in the regions subjected to the boron ion irradiation has been shown by electrical conductivity, thermo-e.m.f., photoconductivity investigations. The average projected ion range predicted by TRIM-94 code is R_p = 239 μm. The fact of conductivity compensation during the process of implantation has been established. In some cases even the conversion of the conductivity type occurs. The concentration of the recombination-active centers is so high that it is not possible to measure the lifetime value by the employed technique (τ ~1.5×10^{-7} s). A high value of the degradation coefficient of the lifetime (K_τ > 10^{-6} cm^2 s^{-1}) is typical for silicon crystals, irradiated by heavy particles: neutrons, protons, α-particles and ions of different energies [1–4].

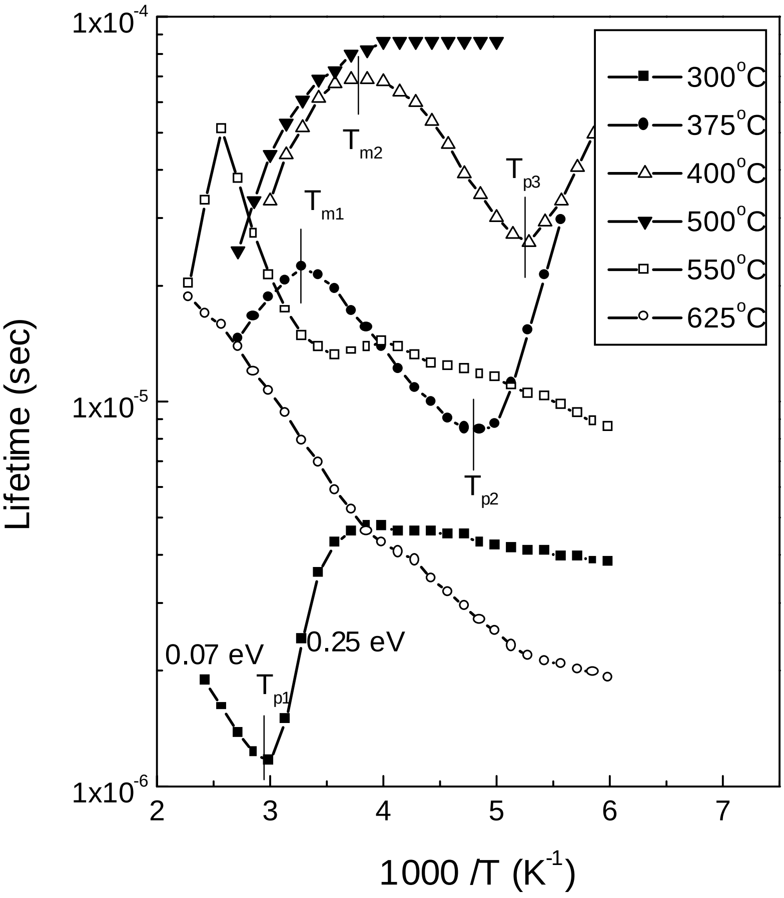

Fig. 1. Temperature dependencies of non-equilibrium charge carrier lifetime τ on different stages of isochronal annealing of n-Si implanted with boron ions of an energy of 92 MeV. Ion dose is 2×10^{13} cm^{-2}

The majority of lattice defects formed during ion implantation in silicon is annealed in several stages at temperatures up to about 600°C

[7, 11, 12]. The first stage of annealing (< 270°C) shows mainly a dissociation of isolated defects such as impurity-defect complexes and divacancies. The lifetime temperature dependencies of non-equilibrium charge carriers are shown in Figure 1 at different stages of isochronal annealing. As it is shown a 20 min annealing at the temperature of 300°C leads to a partial recovery of the lifetime value. The dependence $\ln\tau = f(10^3/T)$ acquires the typical for these cases form when the recombination processes are determined by two types of recombination-active defects, one of them is the recombination centre and the other one is the trapping centre for minority carriers [13]. The evaluation of the energy level position in the energy band gap from the decline of a straight-line part of the dependency $\ln\tau = f(10^3/T)$ according to the Streetman model [13] shows the following values: the recombination centre has the energy level at E_c - 0.07 ± 0.01 eV, the trapping centre has the level at E_v + 0.25 ± 0.02 eV.

The annealing in a range of 300–400°C (curves 2, 3) is accompanied by essential lifetime increase, transition point changes from the recombination region to the trapping region of minority carriers (T_{p1}, T_{p2} and T_{p3}) to the lower temperatures and by showing of a peculiar maximum on the dependencies $\tau = f(10^3/T)\,(T_{m1}, T_{m2})$. Attempts to analyse the changes of temperature dependencies of lifetime in the limits of the main recombination models [13–15] in the annealing process encounter certain difficulties. It is true when the n-type semiconductor is used with recombination level in the upper half of the band gap:

$$\tau \cong \frac{1}{\gamma_p N}\left(\frac{n_0 - n_1}{n_0}\right), \tag{1}$$

where n_0 is equilibrium electron concentration in crystal matrix, n_1 is electron concentration in conduction band if the Fermi level coincides with the defect level, N is the recombination centre concentration, γ_p is the capture coefficient for holes. The decrease of N leads to the increase of the lifetime at temperatures where the recombination level is dominant ($T > T_{p_i}$). But the T_{p_i} temperature shift and τ growth in the trapping region cannot be explained by the N decreasing during the annealing process. The lifetime cannot depend on N at temperatures lower than T_{p_i} value and in the limit it reaches a value [13]:

$$\tau \cong \frac{1}{n_0\, \gamma_{nt}}, \tag{2}$$

where γ_{nt} is capture coefficient for electrons on the trapping level. In its turn according to the relations (1) and (2) mentioned above and conductivity compensation, i.e. n_0 decreasing under annealing process leads to τ increase both in the temperature region of ionisation of the recombination centres and in the temperature region of trapping. At the same time there is a shift of the curve $\tau = f(10^3/T)$ to the lower temperatures as it is observed experimentally.

Such an explanation contradicts the results obtained by the electrical conductivity measurements: the conductivity of the damaged crystal grows with the annealing temperature. The given contradiction can be solved assuming that the recombination and trapping of non-equilibrium charge carriers occur mainly on the centres which are localised in defect clusters with compensate the conductivity during the annealing. Then a relation can be written in the following form [16]:

$$\tau \cong \frac{1}{b\gamma_p N^r}\left(\frac{n_0^r + n_1}{n_0^r}\right), \tag{3}$$

where

$$n_0^r = n_0 \exp\left(-\frac{\psi_0}{kT}\right) \tag{4}$$

is an equilibrium concentration of electrons inside the defect cluster, ψ_0 is an equilibrium height of the potential barrier around the defect cluster, N^r is the concentration of the recombination centres inside the defect cluster, b is a relative volume occupied by the defect clusters.

The precise identification of recombination and trapping centres which are localised in the defect clusters is not possible. Nevertheless the dependency type $\tau = f(10^3/T)$ and numerical values of the lifetime should be noted to be the same both for silicon grown by the Czochralski method and by the floating zone method. This indicated that the centre formation and their nature are not connected with the main technological impurities, which appear to be mainly oxygen in silicon. Since divacancies in the defect clusters and disordered regions in particular are annealed at $T \approx 550$ K [7] one can suppose that the recombination centres are stable multivacancy complexes. The value of the potential barrier ψ_0 should be taken into consideration at position of levels of the recombination-active centres in the band gap depending on the activation energy found from straight-line part of the dependencies $\ln\tau = f(10^3/T)$. Usually ψ_0 value is in the energy range of 0.05 to 0.11 eV in silicon and germanium [16–19]. Consequently according the present model the recombination centre level is located at E_c – (0.12 – 0.18) eV.

Equilibrium electron concentration n_0^r in the defect clusters can be estimated according to the temperature peaks at T_{m1} and T_{m2} on the dependencies $\ln\tau = f(10^3/T)$ (curves 2 and 3) which correspond to the transition to the intrinsic conduction regime [14, 15]. They are 1.9×10^{10} cm^{-3} and 7.2×10^8 cm^{-3} for the crystals annealed accordingly at 300 and 450°C. This means that defect clusters formed during high energy ion implantation process and sequential annealing are highly compensated inclusions.

The sequential annealing of the lifetime at higher temperatures (curves 5 and 6) points to the change of the recombination mechanism of non-equilibrium charge carriers and is connected to the defect cluster decay. Annealing up to 625°C does not lead to the complete restoration of the lifetime value. This is likely to be connected with the presence of more stable defects formed at edge dislocations and dislocation loops in the crystal [7, 11].

4. CONCLUSION

It can be concluded that the implantation of boron ions with energy of 92 MeV and subsequent annealing cause formation in silicon highly compensated defect clusters which include the centres determining processes of recombination and trapping of non-equilibrium charge carriers. One can suppose that dominant recombination centres are connected to multivacancy complexes having energy levels at E_c – (0.12 – 0.18) eV in the silicon band gap.

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