Technical Physics Letters, Vol. 31, No. 5, 2005, pp. 408–410. Translated from Pis'ma v Zhurnal Tekhnicheskoĭ Fiziki, Vol. 31, No. 10, 2005, pp. 11–16.

Room-Temperature Ultrasonic Annealing of Radiation Defects in Silicon

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Received November 23, 2004

Abstract—Room-temperature ultrasonic annealing of point radiation defects in the bulk of silicon is demonstrated for the first time. The radiation defects in single crystal silicon were generated by the exposure to γ radiation from a ^{60}Co source. A qualitative model of processes in the system of radiation defects under the action of ultrasound is proposed. © *2005 Pleiades Publishing, Inc.*

In recent years, much attention has been devoted to using ultrasound as a factor that effectively influences the defect structure of crystalline semiconductors [1–4]. This direction of research is of special importance for silicon microelectronic technology, since the high degree of integration in modern devices requires the development of methods for controlled modification of the composition of defects in the base material. Previously, we demonstrated the possibility of an ultrasonically stimulated redistribution of impurities [3] and modification of the structure of defects (including interstitial silicon atoms) [4] in single crystal dislocation-free silicon.

This Letter reports for the first time on the low-temperature ultrasonic annealing of point defects generated in single crystal silicon by γ quanta from a ^{60}Co source.

The experiments were performed with Czochralski grown *n*-type silicon single crystals with a resistivity of $\rho \approx 400\ \Omega$ cm, which were cut from the central part of the ingot. The samples were mechanically polished using abrasive silicon carbide powders (M40 and M10 grades) and then chemically polished in a standard solution (CP-4). The sample crystal dimensions after preparative treatments were $25 \times 7 \times 1.44$ mm.

Radiation defects were generated by exposure to γ quanta from a ^{60}Co source (the sample temperature during irradiation was $T_{irr} < 50$°C) to a total dose of 5×10^7 rad ($\Phi \approx 8 \times 10^{16}$ cm^{-2}). The concentration of radiation-induced defects was evaluated in terms of the lifetime τ of minority charge carriers in the samples. This parameter, which is sensitive to the defect concentration, was determined using the photoconductivity decay technique [5]. It should be noted that the initial τ values measured upon preparation were approximately the same in all samples.

The ultrasonic treatment (UST) of irradiated samples was effected using ring-shaped piezoceramic transducers featuring radial oscillation modes. The transducers were glued to the samples so that ultrasonic oscillations with a frequency of 10–30 kHz were excited in the direction of the maximum crystal size. The USTs and the measurements of τ were performed at room temperature.

Figure 1 shows the typical plots of the minority carrier lifetime τ versus UST duration for γ-irradiated (curve *1*) and unirradiated (curve *2*) silicon crystals. As can be seen, UST at the selected intensity effectively influences the τ value in the irradiated samples. The observed behavior can be explained by the effect of ultrasound on the concentration of radiative recombination centers generated by the absorbed γ quanta.

Figure 2 presents the results of isochronous (15 min) annealing of a γ-irradiated silicon sample not sub-

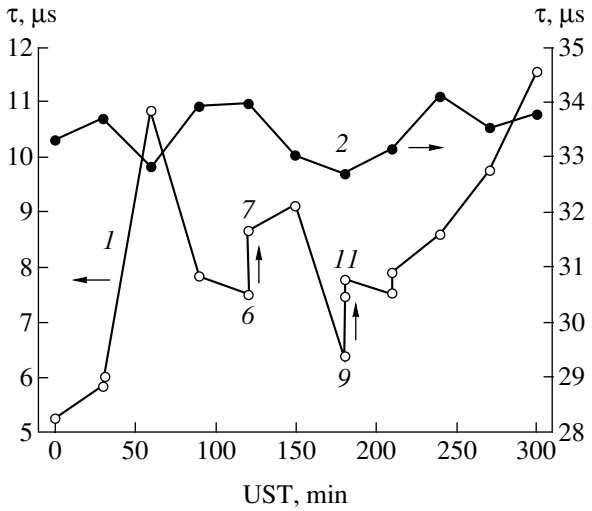

Fig. 1. Typical plots of the minority carrier lifetime τ versus UST duration for (*1*) γ-irradiated and (*2*) unirradiated silicon crystals.

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jected to any other treatment. The function $f_\tau = (\tau^{-1} - \tau_0^{-1})/(\tau_\Phi^{-1} - \tau_0^{-1})$ is the fraction (normalized to unity) of unannealed radiation defects, where τ_0, τ_Φ, and τ are the minority carrier lifetimes before and after γ-irradiation and in the course of annealing, respectively. It should be noted that the residual radiative recombination centers are annealed in the temperature interval 370–450°C. Therefore, the effect of the A-type centers ($V–O_i$ complexes between vacancies and interstitial oxygen atoms with an acceptor level at $E_c - 0.17$ eV, representing the main radiative recombination centers in Czochralski grown *n*-type silicon [6, 8]) on the minority carrier recombination in the samples studied is insignificant (the A-type centers are completely annealed at ~350°C [6, 7]).

The curve of isochronous annealing depicted in Fig. 2 is similar to the analogous curves reported previously [9, 10]. From this we infer that the main radiative recombination centers in our samples are complexes of the $C–O–V_2$ (carbon–oxygen–divacancy) type introducing an acceptor level ($E_c - 0.45$ eV) into the bandgap [9, 10]. An insignificant negative annealing observed at 260–350°C probably reflects the formation of additional $C–O–V_2$ centers [9, 10] via the interaction of vacancies (liberated as a result of decomposition of the A-type centers unstable at these temperatures) with C_iO_i (interstitial carbon–interstitial oxygen) complexes also formed in significant amounts in irradiated crystals of Czochralski grown *n*-type silicon [8].

A rather complicated variation of the minority carrier lifetime as a function of UST time (Fig. 1, curve *1*) with a general increase in τ is evidence of complex processes in the system of radiation-induced defects under UST conditions. As is known, there are several possible mechanisms favoring the annealing of radiation defects, including (i) the migration of defects to sinks, (ii) the formation of more complicated defects, and (iii) the dissociation of complexes [11].

Apparently, several mechanisms of the annealing of radiation defects are also operative under UST conditions. In the first stage (0–60 min), τ exhibits a growth that reflects a rapid decrease in the concentration of radiative recombination centers. In this stage, the defects are annealed by means of their diffusion to sinks (without dissociation), whereby they lose the recombination activity. The subsequent stage of UST (60–210 min) involves the formation of new recombination centers and their partial annealing, which is reflected by the τ variations observed in this period of time. Keeping the samples for several days at ~25°C was also accompanied by annealing of the newly formed recombination centers (see Fig. 1, jumps *6–7* and *9–11* in curve *1*, indicated by vertical arrows). This behavior can be explained by the ultrasound-stimulated dissociation of radiation defects of one type, followed by the formation of new defects. Indeed, dissociation of

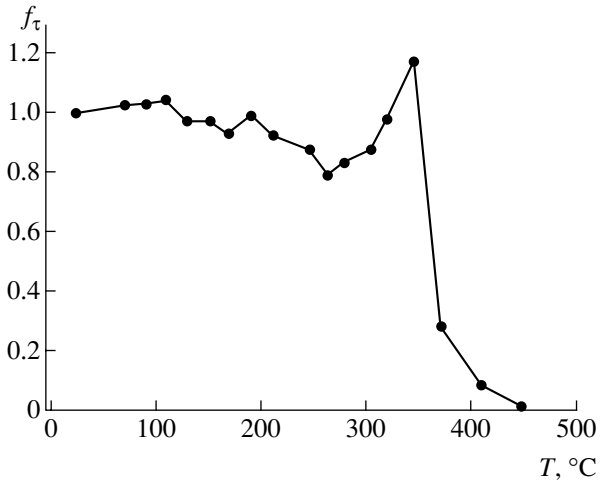

Fig. 2. Variation of the fraction f_τ of unannealed radiation defects in the course of isochronous annealing of a γ-irradiated silicon crystal.

the $C–O–V_2$ complexes may lead to the formation of new recombination-active defects, such as the A-type centers and complexes unstable at room temperature; for example, VB (vacancy–substitution boron) complexes at $E_v + 0.43$ eV [6, 7]. The appearance of such defects leads to a decrease in τ and explains the observed room-temperature annealing with jumps in τ. In the final stage (210–300 min), UST leads to a monotonic annealing of the recombination centers that is accompanied by an increase in τ. This annealing proceeds more smoothly than that in the initial stage (Fig. 1, curve *1*). The final UST stage involves dissociation of the residual recombination-active defects formed upon decomposition of the $C–O–V_2$ complexes.

It should be emphasized that the proposed model of annealing of the radiative recombination centers under the action of ultrasound is rather schematic. Further detailed investigations are necessary in order to elucidate the true picture of events in irradiated silicon under UST conditions. However, in this study, it was most important to experimentally establish the possibility of low-temperature annealing of the radiation-induced point defects of one type in silicon under the action of ultrasound.

Acknowledgments. The authors are grateful to T.I. Kibkalo and V.F. Lastovetskii (Institute for Nuclear Investigations) and A.B. Nadtochiy (Department of Physics, Kiev National University) for their help in preparation and UST of silicon samples.

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Translated by P. Pozdeev