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The Excitation Efficiency for Dislocation-Related Luminescence Centers in Silicon with Oxygen Precipitates

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Effect of the pump power on the photoluminescence intensity for dislocation-related luminescence centers is studied in *p*-type silicon containing oxygen precipitates. Oxygen precipitates are induced as a result of three-stage annealing used for formation of a getter for fast diffusing impurities in microelectronics technology while D1 and D2 dislocation-related luminescence centers were produced during subsequent annealing in a flow of argon at 1000°C. The photoluminescence excitation efficiencies for the D1 and D2 lines were measured at a temperature of liquid helium.

Keywords: dislocation-related luminescence, silicon, oxygen precipitates, photoluminescence excitation efficiency.

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1. Introduction

Dislocation-related photoluminescence (PL) was found in silicon exposed to four-point bending at an increased temperature [1]. The spectrum consisted of four lines D1 (0.812 eV), D2 (0.875 eV), D3 (0.934 eV) and D4 (1.000 eV). The line D1 is of greatest interest since it „survives“ at room temperature. In particular, the methods of uniaxial compression [2], laser recrystallization [3], direct bonding of plates [4], as well as implantation of ions of rare-earth element Er [5] and Si [6] were used to make light-emitting diodes with electroluminescence at room temperature to the wavelength of $\sim 1.6\,\mu$m (the line D1), used in silicon-based optoelectronics [7]. Therefore, development of other process methods for the formation of structures with dislocation-related luminescence and the study of properties of the forming centers are topical. The method based on the use of oxygen precipitates, forming in the course of thermal annealing of silicon, grown by the Czochralski method, with a high oxygen concentration arouses profound interest since it is compatible with the industrial technology of integrated circuit manufacture [8–10]. Subsequent heat treatment causes a transformation of precipitates and the formation of various defects, including dislocations. Interaction of dislocations with point and other defects causes the formation of dislocation-related luminescence centers. It should be noted that the nature of the D1 and D2 centers has not been yet determined. This is to a great extent due to the peculiarities which manifest themselves in these lines of dislocation-related luminescence, for instance, depending on the technology of their formation, the position of the line maximum, its temperature dependence change, or the line becomes asymmetrical. An important parameter of light-emitting structures is the PL excitation efficiency $(\sigma \cdot \tau)$, being a product of the excitation cross-section of a light-emitting center (σ) and the center lifetime in the excited state (τ). The higher the excitation efficiency, the lower then pumping power at which the luminescence intensity is saturated. Measurement of the PL excitation efficiency for light-emitting structures at different stages of their manufacture is of interest for the development of process methods of formation of structures with dislocation-related luminescence. PL excitation efficiency for the line D1 was measured only for structures obtained by liquid-phase epitaxy and implantation of silicon and erbium ions [7] at 80 K, while data for the line D2, as far as we know, are not available. This paper is aimed at determining the PL excitation efficiency for the lines D1 and D2 in light-emitting structures formed with participation of oxygen precipitates.

2. Experimental procedure

The initial sample was a *p*-type silicon wafer grown by the Czochralski method in the direction (100), with a resistivity of 12 Ohm · cm. The oxygen concentration, according to the IR-measurement data, was $8 \cdot 10^{17}\,\text{cm}^{-3}$, while the carbon concentration was below the sensitivity limit $(2 \cdot 10^{16}\,\text{cm}^{-3})$. Multiple implantation of oxygen ions with energies of 350, 225 and 150 keV and doses of $1.5 \cdot 10^{15}$, $0.9 \cdot 10^{15}$ and $0.7 \cdot 10^{15}\,\text{cm}^{-2}$ respectively ensured a homogeneous oxygen distribution with the concentration of $5 \cdot 10^{19}\,\text{cm}^{-3}$ at a depth of 0.3 to $0.8\,\mu$m according to TRIM program calculations. The specimen was annealed in an argon flow with the temperatures and times of 1000°C/15 min + 650°C/7 h + 800°C/4 h + 1000°C/6 h. The first three annealing operations are the standard ones in the integrated-circuit technology for impurity gettering due to the formation of oxygen precipitates, in the course of which the following took place: dissolving of the oxygen growth precipitates, formation of oxygen precipitate nuclei with the given density and transformation of large-sized precipitates respectively [8,9]. Luminescence centers formed during the last annealing. PL was excited by a solid-state laser at the wavelength of 532 nm and the power of 0.45−72 mW and was recorded in the wavelength range of 1000−1650 nm at 4.2−80 K using an automated MDR-23 monochromator and InGaAs-photoreceiver operating at room temperature. The unit resolution was 5 nm.

3. Experimental results and discussion

The PL spectra for the studied sample in the wavelength range of 1350−1620 nm at 6−80 K and the pumping power of 31 mW are shown in Fig. 1. The spectrum has three lines with the wavelengths of 1532, 1418 and 1465 nm. The first two lines (D1 and D2 respectively) pertain to the centers of dislocation-related luminescence. The position of the lines in the studied temperature range is virtually unchanged.

The dominating line is the line D1, intensity of which by about an order of magnitude higher than that of D2. The third low-intensity line (OP) is observed in the temperature range of 30−70 K. This line was previously found in [10,11] and was related to the formation of free oxygen precipitates.

The dependence of the PL intensity for the line D1 on reciprocal temperature is shown in Fig. 2 (curve *1*). As seen from the figure, its intensity increases as measurement temperature rises to 80 K, while with further temperature rise it decreases.

This dependence is well described by the formula [12]

$$I(T) = I(0)\left\{1 + C/\left[1 + A \cdot \exp(-W/kT)\right]\right\}^{-1} \times \left[1 + B1 \cdot \exp(-E1/kT)\right]^{-1}, \qquad (1)$$

where W and $E1$ are, respectively, the energies of the luminescence buildup and quenching; C is a quantity including the ratio between the cross-sections of exciton capture at luminescence centers and traps; A and $B1$ are the coupling constants for a given center; k is the Boltzmann constant. At lower temperatures, excitons are captured to shallow centers. When temperature rises, they are released, diffuse, and then their capture and subsequent radiative recombination on the luminescence center D1 take place. As a result, the PL intensity increases as temperature rises; this increase is characterized by the PL intensity buildup energy $W = 1.2$ meV. As temperature continues rising, the intensity of the line D1 decreases; this decrease is characterized by the luminescence quenching energy $E1 = 12.0$ meV. PL intensity quenching is due to the formation of nonradiative recombination centers. It is interesting to compare the temperature dependences of PL intensity for the line D1 of the studied sample with the data for the sample that underwent all four annealing operations at the same temperatures, but the last 1000°C annealing of which was performed in a chlorine-containing atmosphere (curve *2* in Fig. 2 is taken from [13]). The line D1 also dominated in it, while the temperature dependence of intensity was characterized by two areas (buildup and quenching). However, the intensity of the line D1 exceeded the intensity of the studied sample in 1.3 times in the luminescence maximum at 10 K. This effect is due to the following: a significant over-saturation of silicon is with its own interstitial atoms and a significant increase in the rate of D1 center formation [11,14] takes place during annealing in the chlorine-containing atmosphere as compared to annealing in Ar. The energy of luminescence intensity buildup for the „chlorine“ sample was 6.8 meV. The observed difference in buildup energies is probably due to the different energy spectra of the exciton capture centers in the compared samples. Quenching of luminescence intensity in the both samples is characterized by virtually equal energy values (11.6 meV for the „chlorine“ sample).

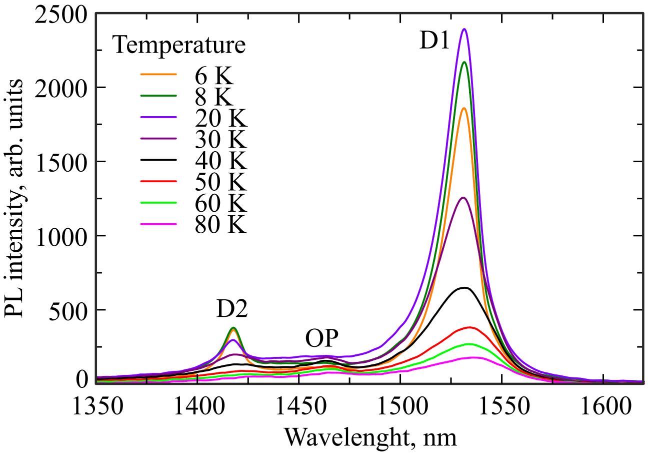

Figure 1. PL spectra for the studied sample, measured at different temperatures and the pumping power of 31 mW. (A colored version of the figure is presented in the electronic version of the article).

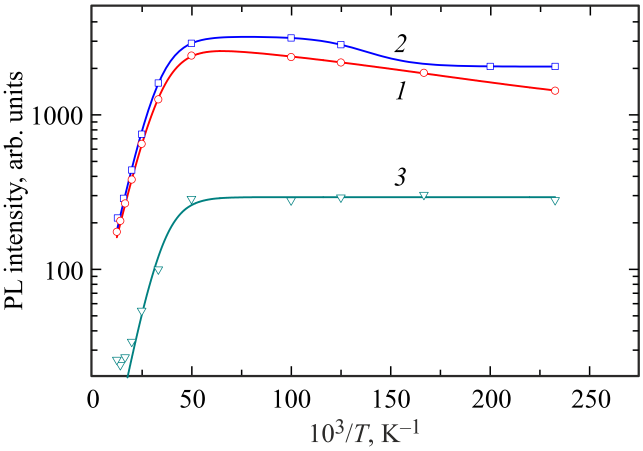

Figure 2. Temperature dependences of PL intensities for the lines D1 (*1*) and D2 (*3*) for the studied sample and the D1 (*2*) line for the sample from paper [13].

The dependence of the PL intensity for the line D2 on reciprocal temperature is shown in Fig. 2 (curve *3*). As

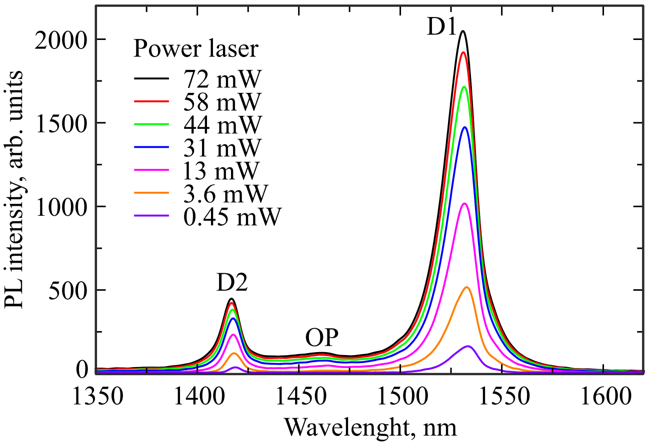

Figure 3. PL spectra measured at 4.2 K and different pumping powers.

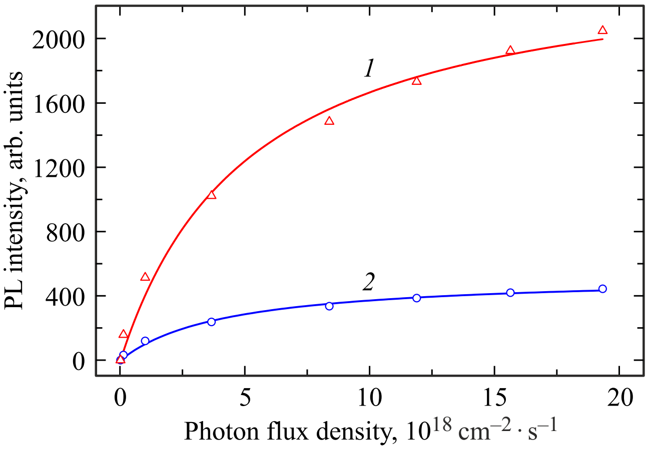

Figure 4. Dependences of PL intensities for the lines D1 (*1*) and D2 (*2*) on photon flux density.

distinct from the line D1, buildup of its intensity at low temperatures is not observed. The experimental dependence is well described by the formula

$$I(T) = I(0) \cdot [1 + B2 \cdot \exp(-E2/kT)]^{-1}, \qquad (2)$$

where $E2$ is energy of the luminescence quenching, and $B2$ is the coupling constant for the given center. The energy of luminescence intensity quenching is equal to $E2 = 5.7$ meV. The absence of buildup may be explained by the fact that the cross-section of capture of an exciton, released from a shallow center, to the center D2 is much lower than that for the D1 center. As far as we know, temperature dependence of luminescence intensity for the line D2 in the samples, formed with participation of precipitates, was studied for the first time.

Figure 3 shows the PL spectra measured at 4.2 K and different powers of exciting light. The spectra also have rather an intensive near-band-edge luminescence (this wavelength range is not shown). The positions of the dominating lines D1 and D2 do not depend on pumping power. The dependencies of the intensities for the lines D1 and D2 on the photon flux density are shown in Fig. 4. The PL excitation efficiency for these centers is described by the well-known formula [7]:

$$\mathrm{PL}(F) = \mathrm{PL}_{\max} \cdot [(\sigma\tau F)/(\sigma\tau F + 1), \qquad (3)$$

where $\mathrm{PL}_{\max}$ is the maximum PL intensity, and F is the photon flux density. Approximation of the experimental dependencies by the above-mentioned formula gives the values at 4.2 K for the line D1 (1531 nm) $\sigma\tau = 1.9 \cdot 10^{-19}$ cm$^2 \cdot$ s and for D2 (1418 nm) $\sigma\tau = 2.4 \cdot 10^{-19}$ cm$^2 \cdot$ s. It should be noted that previously the lifetime for the D1 center in the samples, made by erbium ion implantation and subsequent annealing, was by almost an order of magnitude lower than that for the D2 center (50 and 350 ms respectively at 1.8 K) [15]. It is reasonable to assume that the studied sample has a similar ratio. In this case, it follows from the approximate quality of the luminescence excitation efficiencies for both centers that the cross-section of luminescence excitation for the D2 center is much smaller than for the D1 center. This result supports the above-mentioned explanation of the absence of the PL intensity buildup effect for the D2 center at low temperatures. The measured value of $\sigma\tau$ for the D1 center in the studied sample is intermediate as compared to the samples made by implantation of Si and Er ions, as well as by liquid-phase epitaxy: $1.2 \cdot 10^{-18}$, $9.5 \cdot 10^{-21}$ and $3.3 \cdot 10^{-21}$ cm$^2 \cdot$ s respectively [7].

4. Conclusion

We have studied PL in silicon with a high oxygen concentration, where oxygen precipitates and dislocation-related luminescence centers formed during annealing. The PL intensity for the line D1 is by about an order of magnitude higher than the intensity for the line D2. The temperature dependence of the intensity for the line D1 has areas of increasing (at low temperatures) and decreasing intensities with the energies of 1.2 and 12.0 meV respectively. Intensity for the line D2 at low temperatures is virtually constant, while an intensity decrease with temperature rise is characterized by the energy of 5.7 meV. PL excitation efficiencies for the lines D1 and D2 at the liquid helium temperature are equal to $1.9 \cdot 10^{-19}$ and $2.4 \cdot 10^{-19}$ cm$^2 \cdot$ s respectively. The temperature dependence of the PL intensity and the luminescence excitation efficiency for the line D2 has not been studied earlier.

Conflict of interest

The authors declare that they have no conflict of interest.

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