Semiconductors, 2022, Vol. 56, No. 9

Silicon Light-Emitting Diodes with Dislocation-Related Luminescence Fabricated with Participation of Oxygen Precipitates

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Received June 15, 2022
Revised June 30, 2022
Accepted June 30, 2022

Silicon light-emitting diodes with dislocation-related electroluminescence have been studied at room temperature. For the fabrication of the light-emitting diode structures, a well-known method for the formation of dislocation-related luminescence centers during anneals of silicon with a high oxygen concentration in a flow of argon was modified by introducing a preliminary O^+ ion implantation and carrying out a final anneal in a chlorine-containing atmosphere. In the electroluminescence spectra, the D1 dislocation-related luminescence line dominates at currents less than $< 150\,\text{mA}$ and the near-band-edge luminescence line starts to dominate with increasing current. The electroluminescence excitation efficiency for the D1 center is $3.3 \cdot 10^{-20}\,\text{cm}^2 \cdot \text{s}$ at room temperature.

Keywords:: Light-emitting diodes, dislocation-related luminescence, silicon, oxygen precipitates.

DOI: 10.21883/SC.2022.09.54135.9917

1. Introduction

Dislocation-related luminescence (DL) in silicon was discovered in 1976 [1], and a variety of methods for its implementation have been proposed since then (see [2,3] and references therein). Light-emitting diodes (LEDs) with dislocation-related electroluminescence (EL) at room temperature have been fabricated 20 years later with the use of uniaxial compression and laser recrystallization techniques [4–6]. Room-temperature DL was achieved through the use of aluminum and phosphorus gettering and hydrogen passivation of nonradiative recombination centers. Note that the so-called D1 line with a wavelength of $\sim 1.6\,\mu\text{m}$ is the only one of several discovered DL lines that is observed at room temperature. The development of defect engineering concepts in implantation technology provided an opportunity to construct an LED with room-temperature dislocation EL via Er^+ [7] and Si^+ [8] ion implantation with subsequent annealing and via electron irradiation with subsequent annealing [9]. The search for new ways to fabricate LEDs with room-temperature dislocation-related EL is a topical issue. A method for fabrication of light-emitting structures with dislocation-related photoluminescence by multi-step annealing at $650-800^\circ\text{C}$, which induced the formation of oxygen precipitates and other structural defects (dislocations included) and was followed by final annealing at 1000°C that facilitated the formation of DL centers, is known [10–12]. All these annealing procedures were performed in a flow of argon. As far as we know, no reports on the fabrication of LEDs in this way have been published. We have proposed recently to perform preliminary implantation of O^+ ions and conduct final annealing in a chlorine-containing atmosphere in order to increase the intensity of dislocation-related photoluminescence in such structures [13,14]. The additional ion implantation raised the concentration of oxide precipitates and altered the defect structure of samples subjected to low-temperature annealing, while the use of a chlorine-containing atmosphere helped modify the defect structure and allowed for gettering of nonradiative recombination centers. The results reported in [15,16] are worth noting. In these studies, the addition of preliminary implantation of Ge^+ ions helped increase considerably the luminescence intensity in silicon structures with GeSi quantum dots, which were formed in the process of epitaxial growth. The aim of the present study is to develop a technology for fabrication and examination of LEDs with DL based on a combination of methods of ion implantation and formation of oxygen precipitates.

2. Experimental procedure

An *n*-type silicon wafer grown by the Czochralski technique with a thickness of $480\,\mu\text{m}$, a resistivity of $4.5\,\Omega \cdot \text{cm}$, and the (100) surface orientation was used as the initial sample. According to the results of IR absorption measurements, the oxygen concentration was $8 \cdot 10^{17}\,\text{cm}^{-3}$, and the carbon concentration was below $2 \cdot 10^{16}\,\text{cm}^{-3}$. O^+ ions with energies and doses of $350/1.5 \cdot 10^{15}$, $225/0.9 \cdot 10^{15}$, and $150/0.7 \cdot 10^{15}\,\text{keV/cm}^{-2}$ were implanted at room temperature. This allowed us to establish a uniform distribution of oxygen atoms at a depth of $0.3–0.8\,\mu\text{m}$ with a calculated concentration of $5 \cdot 10^{19}\,\text{cm}^{-3}$, which was determined using SRIM-2013 [17,18]. Two-stage annealing in Ar flow with the temperature and duration set to $650^\circ\text{C}/7\,\text{h} + 800^\circ\text{C}/4\,\text{h}$ was performed to anneal radiation defects and induce the formation of oxygen precipitates, dislocations, and other extended defects. Such annealing is used in the integrated circuit technology for gettering of rapidly diffusing impurities that act as nonradiative recombination centers. Subsequent annealing at 1000°C for 6 h in a chlorine-containing atmosphere (a flow of oxygen saturated with carbon tetrachloride vapor with a molar concentration of 1%) was used to create dislocation-related luminescence centers. A thermal oxide layer grew on the wafer surfaces in the process. In order to produce a p^+-n junction, windows with a diameter of 2 mm were opened in the SiO_2 layer from the side of oxygen ion implantation, and a p^+-type layer of polycrystalline silicon doped heavily with boron to a concentration of $\sim 10^{20}\,\mathrm{cm}^{-3}$ was deposited in them by chemical vapor deposition at 850°C within 6 min. On the other side of the wafer, an n^+-type layer of polycrystalline silicon doped heavily with phosphorus to a concentration of $\sim 10^{20}\,\mathrm{cm}^{-3}$ was deposited at 850°C within 6 min. Both layers has a thickness of $\sim 0.5\,\mu$m. Contacts were formed on top of polycrystalline silicon on both sides of the wafer by depositing a 0.5-μm-thick layer of aluminum. EL spectra in the 1000–1650 nm range were measured using an automated spectrometer based on an MDR-23 monochromator and an uncooled InGaAs photodiode. EL measurements were performed at room temperature in a UTRECS cryosystem with the temperature maintained constant within ±1°C. EL was excited by rectangular current pulses with a duration of 15 ms, an amplitude up to 200 mA, and a frequency of 32 Hz. The resolution of the setup was 5 nm.

3. Experimental results

The room-temperature current–voltage characteristics (CVC) of the studied diode is presented in Fig. 1. EL was examined within the linear CVC part, where the diode current is determined by the base resistance [19]. The cutoff voltage was ~ 0.6 V.

The room-temperature EL spectra for the p^+-n-n^+ LED are shown in Fig. 2. Two broad lines are seen in them: the so-called D1 line of dislocation-related luminescence with a wavelength of 1610 nm and the line of intrinsic silicon luminescence with a wavelength of 1143 nm, which is referred to as the near-band-edge (NBE) line. The positions of maxima of these lines do not change in the studied range of currents. The position of the D1 line maximum corresponds to the position of this line in samples prepared in various ways [2–9]. It is notable that the D1 line is more intense than the NBE line at the initial stage of current rise, but the latter line becomes dominant at stronger currents. Another maximum at ~ 1490 nm is also seen in the spectra in Fig. 2. It has already been observed at room temperature in LEDs fabricated by silicon ion implantation [8], but the nature of this level remains unknown.

Figure 3 presents the experimental dependence of the EL intensity for the dislocation-related (triangles) line on the diode current density at room temperature. A sublinear growth of intensity of the D1 line is seen. The efficiency of excitation of a luminescence center (product of the luminescence excitation cross section and the lifetime of a center in the excited state) is normally determined based on an experimental dependence of the EL intensity on the excitation current density in accordance with the following well-known formula, which was first derived for EL of Er^{3+} ions in silicon in [20]:

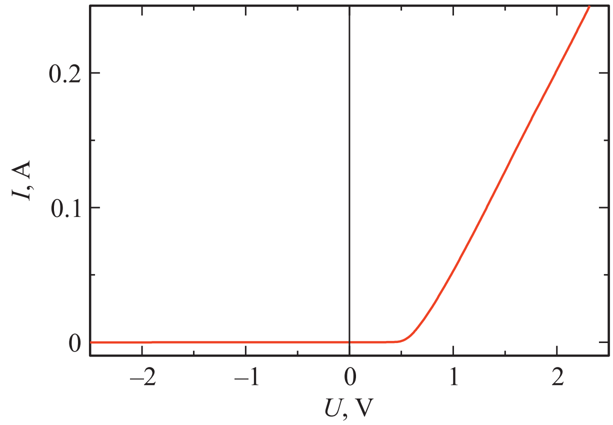

Figure 1. Room-temperature current–voltage characteristics of the diode.

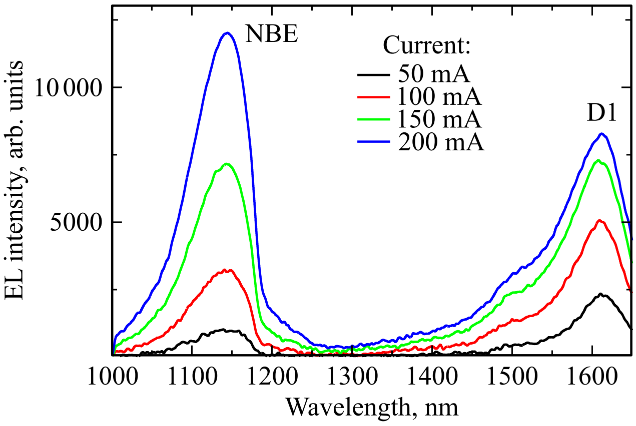

Figure 2. Room-temperature EL spectra of the light-emitting diode at different forward currents. (A color version of the figure is provided in the online version of the paper).

$$\mathrm{EL}/\mathrm{EL}_{\max} = (\sigma\tau j/q)/(\sigma\tau j/q + 1), \tag{1}$$

where $\mathrm{EL}_{\max}$ is the maximum EL intensity, σ is the EL excitation cross section, τ is the lifetime of a center in the excited state, j is the diode current density, and q is the electron charge. However, the experimental curve for dislocation-related line D1 is approximated poorly (with a large residual obtained using the least-squares method) by formula (1), but is characterized well by formula

$$\mathrm{EL}/\mathrm{EL}_{\max} = [\sigma\tau(j - j_{\mathrm{th}})/q]/[\sigma\tau(j - j_{\mathrm{th}})/q + 1], \tag{2}$$

where j_{th} is the threshold current density corresponding to the onset of intense luminescence. The approximating curve

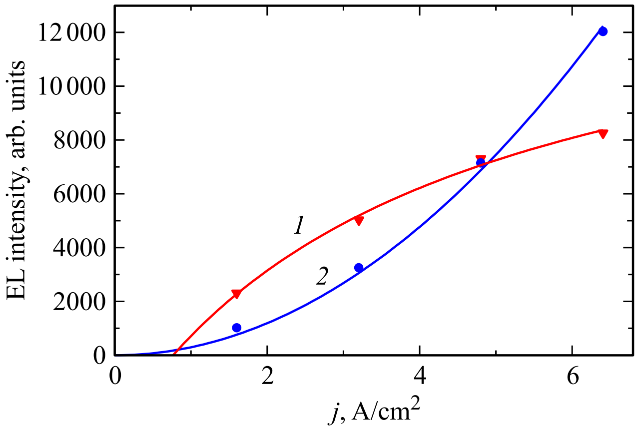

Figure 3. Room-temperature dependences of the EL intensity for dislocation-related (1) and near-band-edge (2) lines on the diode current density.

(1 in Fig. 3) is characterized by EL excitation efficiency $\sigma\tau\,(\text{D1}, 300\,\text{K}) = 3.3 \cdot 10^{-20}\,\text{cm}^2 \cdot \text{s}$ and $j_{\text{th}} = 0.76\,\text{A/cm}^2$. To date, the efficiency of excitation of EL of the D1 center has been studied only in LEDs fabricated by implantation of Si$^+$ ions, but the obtained value was ~ 3 times lower [8]. The observed discrepancy is attributable to the fact that the structure of a D1 center depends on the method of its production. The determined value of $\sigma\tau\,(\text{D1})$ in the studied diode is 2.6 ($8.7 \cdot 10^{-20}\,\text{cm}^2 \cdot \text{s}$) and 4.5 ($1.5 \cdot 10^{-19}\,\text{cm}^2 \cdot \text{s}$) times lower than the room-temperature values typical of EL centers containing rare-earth Er^{3+} and Ho^{3+} ions, respectively [21,22]. The existence of a threshold current for the D1 center is apparently attributable to the presence of nonradiative recombination centers or centers emitting outside of the studied wavelength range.

Figure 3 presents the experimental dependence of the EL intensity for the near-band-edge (circles) line on the diode current density at room temperature. The supralinear growth of intensity of the NBE line is approximated well by the following formula (curve 2):

$$\text{EL} = a \cdot j^2, \tag{3}$$

where a is a constant. A quadratic dependence implies that near-band-edge room-temperature luminescence in the studied LEDs is governed by the bimolecular recombination of carriers [23].

4. Conclusion

Thus, LED technology with dislocation-related EL based on silicon with oxygen precipitates has been developed for the first time. Dislocation-related EL was observed at room temperature in $p^+{-}n{-}n^+$ LEDs fabricated by implantation of O$^+$ ions with subsequent annealings and chemical vapor deposition. Two methods for gettering of nonradiative recombination centers are utilized in the developed technology: formation of a defect system, which involves oxygen precipitates, and annealing in a chlorine-containing atmosphere. The D1 line dominates in the EL spectra up to a current of ~ 150 mA. At higher currents, near-band-edge luminescence established by the bimolecular recombination of carriers becomes dominant. The efficiency of excitation of dislocation-related EL for the D1 center was measured in the studied diodes at room temperature; it turned out to be ~ 3 times higher than the corresponding efficiency in LEDs fabricated by Si$^+$ ion implantation.

Conflict of interest

The authors declare that they have no conflict of interest.

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