Towards an efficient light-emitting source based on self-implanted silicon with dislocation-related luminescence

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Abstract. The regularities of ion synthesis of dislocation-related luminescence centers in silicon have been investigated. By varying the conditions of additional irradiation with boron ions, as well as the conditions of subsequent annealing, we obtain an increase in the luminescence intensity, as well as a shift of maximum of the temperature dependence towards higher temperatures. It was found for the first time that, for the highest used dose of boron ions \(3 \times 10^{17} \text{cm}^{-2}\) and additional heat treatment at 830 °C, it is possible to get the measurable luminescence at room temperature.

1. Introduction
Creating an efficient silicon-based light-emitting source is an important, but still not fully resolved problem. Due to the indirect band gap structure, the band-to-band luminescence intensity of silicon is extremely low. One of the ways to solve this problem can be the use of dislocation-related luminescence (DL), one of the spectral lines of which \(D1\) (1.5 μm) is in the region of maximum transparency of silicon optical fibers and has the highest temperature stability with respect to other DL lines. However, the traditional method of producing silicon structures with DL by the method of plastic deformation [1,2] is not suitable for practical use. An important result of recent years has been the discovery of possibility of synthesis of silicon layers with an intense DL by high-temperature annealing of silicon implanted with Si\(^+\) ions (self-implanted silicon) [3]. This approach has such advantages as full compatibility with silicon technology, high reproducibility and the ability to control the properties of the formed structures by varying the parameters of ion irradiation and subsequent annealing. However, such structures are characterized by a significant temperature quenching of the DL intensity, and, as a result, very low intensity at room temperature.

One of the appropriate models of the \(D1\) line emission is based on the fact that centers responsible for luminescence are the centers that contain intrinsic interstitial atoms, as well as impurities and defects located in dislocation atmospheres [2]. By varying the composition of these atmospheres, for example, by using additional ion irradiation, it is possible to modify the light-emitting properties of the \(D1\) centers. We have previously found that, in the samples subjected to additional implantation of boron ions, the intensity of the \(D1\) line is higher than that in the samples not subjected to additional implantation but annealed in the same conditions [4,5]. In this paper, we present the results of additional studies aimed at the control of temperature dependence of the DL intensity by additional ion-beam and heat treatment.
2. Experimental
The initial samples were $n$-Si (100) substrates with a resistance of $4.5 \, \Omega \cdot \text{cm}$. The formation of a dislocation structure was carried out by implantation of Si$^+$ ions with an energy of 100 keV and a dose of $1 \cdot 10^{15} \, \text{cm}^{-2}$ with annealing in an oxidizing atmosphere for 1 hour. Additional irradiation with boron ions was carried out with an energy of 50 keV and doses of $1 \cdot 10^{16}$ and $3 \cdot 10^{17} \, \text{cm}^{-2}$. Subsequent annealing was carried out sequentially at temperatures of 600, 700 and 800 °C in a dried nitrogen atmosphere (30 min each).

The synthesized samples were subjected to additional heat treatment in a mixed atmosphere (Ar + H$_2$) at 830 °C (60 min), followed by uniform cooling to 300 °C for 3 h. The temperature dependencies of the photoluminescence (PL) were measured in the temperature range of 4.2–300 K by using the standard phase-sensitive technique with a cooled germanium photodiode as a detector. PL was excited by photons with a wavelength of 920 nm at an optical excitation level of 10 mW/mm$^2$, corresponding to the linear part of the dependence of the PL intensity on the pump power.

3. Results and discussion
We start our consideration with the results of studying the effect of additional boron implantation with subsequent annealing into the samples, in which dislocations were formed by Si$^+$ ion implantation into silicon substrates with subsequent annealing in an oxidizing atmosphere. The study of temperature dependence of the $D1$ line intensity reveals a change in the nature of temperature quenching in the samples implanted with boron with respect to the sample that was not subjected to additional boron irradiation (Figure 1). In particular, along with the presence of a maximum in the temperature dependence of the intensity of the $D1$ line located at a temperature of ~ 40 K, characteristic of all samples studied, the implantation of boron ions leads to the appearance of an additional maximum at temperatures of ~ 60-70 K.

![Figure 1](image_url)

**Figure 1.** Dependence of the $D1$ line intensity on temperature for the Si-DL samples irradiated with B$^+$ ions before additional annealing at 830 °C (reference samples). Enlarged image of the low-intensity region is shown in the inset.

The most pronounced effect is observed at a boron dose of $1 \cdot 10^{16} \, \text{cm}^{-2}$; with increase in the dose of boron to $3 \cdot 10^{17} \, \text{cm}^{-2}$, a significant weakening of the second maximum is observed. We also note the decrease in the absolute intensity of the low-temperature DL in samples irradiated with boron, which
is associated with the formation of radiation defects, which are the centers of nonradiative recombination. The temperature dependence of the intensity of $D1$ DL line in the samples irradiated with boron ions is discussed in detail in [6].

Further, the samples were subjected to additional heat treatment at 830 °C under the conditions of slow cooling of the samples, in contrast to preliminary annealing, in which the cooling of the samples occurred more quickly – when the container with samples was unloaded from the furnace immediately after the annealing was completed. Temperature dependences of the PL intensity of the samples before and after additional heat treatment are shown in Figure 2.

As can be seen from the figures, additional heat treatment at 830 °C leads to quenching the DL intensity at low temperatures in both boron-implanted samples and samples without boron implantation (reference). This may be due to the contamination during annealing with random impurities that form nonradiative recombination centers [4]. However, in the high-temperature region, the effect of additional annealing at 830 °C for the boron-implanted samples differs significantly from the samples without implanted boron. In the sample without boron implantation, as a result of annealing, there is a slight improvement in the temperature dependence of the DL intensity in the temperature range of 80–200 K. In a sample irradiated with boron to a dose of $1 \cdot 10^{16}$ cm$^{-2}$, additional annealing leads to a significant shift of the high-temperature maximum from 60 to 140 K. It is important that the temperature quenching of DL is less pronounced as compared with the sample that was not subjected to additional heat treatment. The most interesting result was obtained by annealing the sample irradiated with B$^+$ to a dose of $3 \cdot 10^{17}$ cm$^{-2}$. As a result of additional heat treatment, a high-

Figure 2. Dependence of the D1 line intensity on temperature for the Si-DL samples without B$^+$ irradiation (a), irradiated with B$^+$ ions with the dose of $1 \cdot 10^{16}$ cm$^{-2}$ (b) and $3 \cdot 10^{17}$ cm$^{-2}$ (c), before (reference samples) and after additional annealing at 830 °C (1 h).
temperature peak with a maximum at ~ 160 K is observed in the temperature dependence of the $D1$ line intensity; however, unlike the sample irradiated with boron to a dose of $1 \cdot 10^{16}$ cm$^{-2}$, the measurable PL is maintained up to room temperature. Next, this sample was subjected to additional annealing at 830 °C (annealing 2) under conditions completely identical to the first annealing. As a result, the luminescence intensity increased in both the low and high temperatures and the second annealing shifts the high-temperature maximum to the lower temperatures.

The observed behavior of the temperature dependence of $D1$ line intensity can be explained as follows. During the heat treatment, the interaction of implanted boron atoms with DL centers occurs, which, as shown earlier [6], contributes to the appearance of an additional maximum on the temperature dependence at 70 K. At the same time, the effect at the maximum used dose of B$^+$ ions ($3 \cdot 10^{17}$ cm$^{-2}$) was much weaker than at lower doses, which was explained by the formation of a significant amount of boron precipitates, leading to the PL quenching. Additional heat treatment at higher temperatures (830 °C) and longer annealing time (1 h) can lead to a decomposition of such precipitates. This leads to a sharp increase in the concentration of free boron atoms and intrinsic interstitial atoms, and causes the formation of additional emission centers, as well as defects, from which, according to the model outlined in [6], thermal “pumping” of electrons to these centers occurs. We also note the fact that, at the used annealing temperature, silicon becomes plastic, which can be accompanied by a transformation of the system of dislocations responsible for DL. The role of boron atoms is confirmed by the data demonstrating the best result for a boron dose of $3 \cdot 10^{17}$ cm$^{-2}$. The behavior of the temperature dependence of DL intensity after the second annealing can be related to a competition between the formation of nonradiative centers introduced by uncontrolled impurities in the annealing process and an increase in the concentration of boron-containing centers, which increase the luminescence intensity.

An important feature of these experiments is that the cooling after additional annealing was carried out slowly, and this helps to eliminate the effect of introducing additional (thermal) defects associated with rapid cooling.

4. Conclusions
The effect of additional heat treatment on the temperature dependence of the photoluminescence intensity of the $D1$ line of dislocation-related luminescence in self-ion-implanted silicon has been studied. The effectiveness of such heat treatment for the samples subjected to additional irradiation with boron ions is shown. A detailed study of the observed patterns requires a separate careful investigation. The discovered effect opens up new possibilities for obtaining an acceptable external quantum efficiency of dislocation-related emission for the use in silicon optoelectronics.

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