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Dislocation-related photoluminescence in self-implanted silicon with different surface orientation

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Abstract. The regularities of the influence of initial substrate orientation and annealing conditions on the intensity and temperature dependence of the D1 luminescence line for the *p*-type silicon samples implanted with silicon ions followed by subsequent annealing are studied. It is shown that the luminescent properties of the samples depend both on surface orientation and on annealing temperature. For a silicon sample with (111) surface orientation, under certain heat treatment conditions, an anomalous temperature dependence of the D1 line intensity is demonstrated with the appearance of a second maximum in this dependence at temperatures of about 80 K.

Keywords: silicon, ion implantation, annealing, photoluminescence

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Дислокационная фотолюминесценция в самоимплантированном кремнии с различными ориентациями поверхности

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Аннотация. Исследованы закономерности влияния ориентации исходной подложки и условий постимплантационного отжига на интенсивность и температурную зависимость интенсивности линии D1 для образцов кремния *p*-типа, имплантированного ионами кремния, с последующим отжигом. Показано, что люминесцентные свойства образцов зависят как от ориентации поверхности, так и от температуры отжига. Для образца Si (111) при определенных условиях термообработки продемонстрировано аномальное поведение температурной зависимости интенсивности линии D1 с появлением второго максимума на этой зависимости при температурах порядка 80 K.

Ключевые слова: кремний, ионная имплантация, отжиг, фотолюминесценция

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Introduction

The task of creating an efficient silicon-based light emitting source remains one of the most important problems of modern optoelectronics. The indirect bandgap of this semiconductor leads to a low probability of radiative interband transitions. To date, there are several approaches to solving this problem. The most thoroughly studied among them are the formation of silicon nanocrystals in dielectric matrices, the formation of A_3B_5/Si hybrid structures, the introduction of erbium into silicon structures [1, 2] as well as synthesis of light-emitting precipitates of iron disilicide β-$FeSi_2$ [3] and implantation of rare-earth ions into silicon [4, 5]. However, using the abovementioned approaches, it was not possible to achieve the emission intensity sufficient for the use in optoelectronic integrated circuits. One of the methods for creating light-emitting structures based on silicon can be the synthesis of dislocation-related luminescence (DL) centers, the main D1 line of which is at the "communication" wavelength of ~ 1.5 μm. The promise of this method was previously demonstrated for LED structures in which the DL centers were obtained by plastic deformation [6]. However, this method is incompatible with silicon technology. There are some other methods, such as laser melting [7, 8], mechanical polishing and annealing [9], growth of heterostructures such as SiGe/Si [10].

Previously, we demonstrated the possibility of formation of DL centers by self-implantation of silicon (implantation of Si^+ ions into silicon) and possibility of controlling the light-emitting properties of such structures by additional ion-beam and thermal treatment [11–13]. In particular, it was found that, in the samples additionally doped with boron, an anomalous behavior of the temperature dependence of the D1 line photoluminescence intensity is observed, which consists in the appearance of an additional peak in the temperature region of 60–100 K, which was not previously observed [13, 14]. However, for the silicon samples in which the dislocation structure was obtained by plastic deformation, different luminescence behavior was shown for the samples with different surface orientations [6].

In this work, the features of the luminescence properties of the *p*-Si samples with different surface orientations, in which DL centers are formed by implantation of Si^+ ions followed by annealing in different atmospheres, are studied.

Materials and Methods

P-Cz-Si with the (111) and (100) surface orientations and resistivity of 10 and 12 Ω·cm, respectively, were used as the initial samples. The formation of a dislocation structure was carried out by implantation of Si^+ ions with an energy of 100 keV and a dose of $1 \cdot 10^{15}$ cm^{-2} with subsequent thermal annealing at temperatures of 900 and 1100 °C in nitrogen and oxygen atmospheres (1 h). Previously, we have found that varying the annealing conditions (annealing temperature and atmosphere) leads to a significant change in the DL parameters [12], but the features of this process were not studied and silicon wafers with different types of conductivity were used as the initial samples. The photoluminescence (PL) was measured in the temperature range of 4.2–300 K by using a standard phase-sensitive technique with a cooled germanium photoresistance 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.

Results and Discussion

Figure 1 shows the PL spectra (70 K) for the *p*-Si samples with different surface orientations irradiated with Si^+ ions followed by annealing at 900 and 1100 °C in oxygen and nitrogen atmospheres. After implantation and annealing, a PL band appears in the spectra at a wavelength of ~ 1.5 μm, corresponding to the position of the D1 line of the DL, associated with the formation of a dislocation structure.

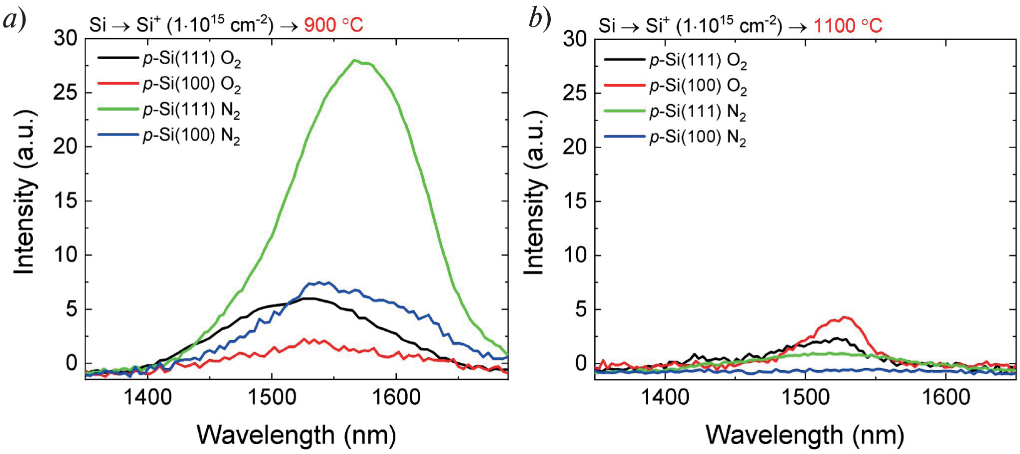

Fig. 1. PL spectra of the *p*-Si samples with different surface orientations irradiated with silicon ions after annealing at 900 (*a*) and 1100 °C (*b*) in nitrogen and oxygen atmospheres for 1 h

Annealing at a temperature of 900 °C leads to the appearance of the D1 DL line for all studied samples. Luminescence intensity of the samples after annealing in a nitrogen atmosphere is higher than that after annealing in an oxidizing atmosphere. A long-wavelength shift of the spectra is also observed for the samples after annealing in a nitrogen atmosphere. A comparison of the DL intensity for the samples annealed under the same conditions shows that, for the *p*-Si (111) samples, the intensity is much higher than that for the samples with (100) surface orientation. Increasing the annealing temperature to 1100 °C leads to a significant change in the PL spectra. Thus, for the case of annealing in an N_2 atmosphere, luminescence is practically not observed. In the case of annealing in an oxidizing atmosphere, the situation is opposite to that observed at a lower used annealing temperature: the luminescence intensity for the sample with the (100) surface orientation is higher than that for the sample with the (111) surface orientation. A noticeable shift in the position of the D1 line during annealing at a temperature of 1100 °C is not observed.

Let us consider the temperature dependence of the D1 DL line intensity. Figure 2 shows the temperature dependence of the intensity of the D1 line at the maximum for the *p*-Si samples with different surface orientations, irradiated with Si^+ ions, followed by annealing in different atmospheres. A typical shape of the temperature dependence of the D1 line is a curve with a maximum at a temperature of ~ 20 K followed by rapid temperature quenching of the intensity to temperatures of 30–40 K [15]. At low temperatures (6–30 K), the Si (100) sample exhibits the highest DL intensity after annealing in an oxidizing atmosphere at 1100 °C. In this case, all the samples annealed at a temperature of 1100 °C demonstrate rapid thermal quenching of luminescence. The situation is somewhat different for the samples after annealing at a temperature of 900 °C. Thus, for the samples after annealing in a nitrogen atmosphere, the temperature quenching is less pronounced than for the samples annealed in oxygen. The most interesting result was obtained for the *p*-Si sample with (111) surface orientation after annealing in a nitrogen atmosphere: the luminescence intensity does not only decrease at temperatures above 30 K, but also increases up to 70 K. Significant quenching of the D1 line occurs only at temperatures above 150 K.

Let us now consider what the observed effect can be associated with. It was previously shown that the presence of additionally implanted boron atoms under certain implantation regimes leads to a similar behavior of the temperature dependence of the D1 line intensity – the presence of an additional high-temperature maximum on the temperature dependence, which may be due to the

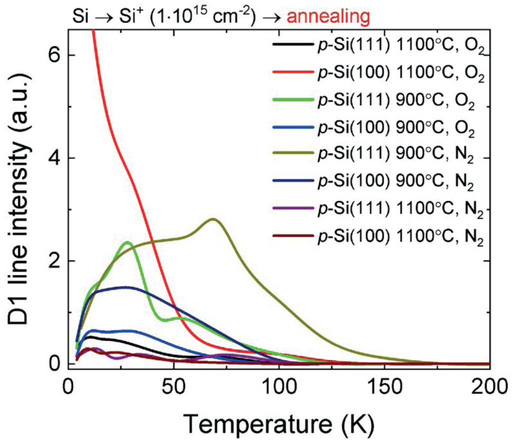

Fig. 2. Temperature dependence of the D1 line intensity for the *p*-Si samples with different surface orientations irradiated with Si^+ ions with the dose of $1{\cdot}10^{15}$ cm^{-2} after annealing in oxygen and nitrogen atmospheres at 900 and 1100 °C (1 h)

formation of boron-containing complexes that introduce additional energy levels into the band gap of silicon [15]. These levels can additionally "pump" charge carriers to light-emitting levels leading to an increase in the luminescence intensity at certain temperatures. Apparently, the formation of such complexes can also be expected in our case upon ion irradiation of the samples initially containing boron atoms. The nature of these complexes has not been fully established, however, apparently, their formation is dominated by intrinsic interstitial atoms formed during implantation process. The formation of interstitials does not significantly depend on the orientation of silicon crystal surface, but the diffusion of Frenkel pair components differs significantly for the crystals with different surface orientations [16]. Therefore, it should be expected that the formation of complexes of interstitials with boron atoms for the samples with (111) orientation occurs more efficiently than for the Si (100) samples. The presence of a high-temperature maximum in the temperature dependence for the samples after annealing at 900 °C indicates that these complexes persist at least up to this temperature. Increasing the annealing temperature to 1100 °C leads to the disappearance of this maximum probably due to the decomposition of such defect-impurity complexes.

Conclusion

The effect of surface orientation and post-implantation annealing conditions on the parameters of the D1 line of dislocation-related luminescence in self-implanted silicon has been studied. It is shown that annealing at a temperature of 900 °C leads to the appearance of more intense luminescence compared to the samples annealed at 1100 °C. The luminescence intensity in the Si (111) samples turns out to be noticeably higher than that for the Si (100) samples annealed under the same conditions. The most interesting fact is that, for the Si (111) sample, under certain heat treatment conditions, an anomalous temperature dependence of the intensity of the D1 line of dislocation-related photoluminescence is observed, and luminescence is retained up to the temperatures close to room temperature. This opens up prospects for the possible practical application of silicon light-emitting structures with dislocation-related luminescence in new-generation optoelectronic devices.

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