Luminescence of Er-doped amorphous silicon quantum dots

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Abstract

The role of the size of amorphous silicon quantum dots in the Er luminescence at 1.54 \( \mu \text{m} \) was investigated. As the dot size was increased, the Er luminescence intensity was decreased and the temperature quenching was also fast because of the small band gap resulting in the decrease of electron–hole pair energy. Accordingly, the critical dot size, needed to take advantage of the positive effect on Er luminescence, is considered to be about 2.0 nm, below which a small dot is very effective in the efficient luminescence of Er.

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1. Introduction

Er-doped silicon structures have attracted a great deal of interest because of its promising future in the development of light-emitting diodes and lasers operating at a wavelength of 1.54 \( \mu \text{m} \), which coincides with the absorption minimum of optical fibers. In these structures, the Er doping of Si nanocrystals holds some promise for efficiently generating light emission, since Si nanocrystals in the presence of Er act as efficient sensitizers for Er ions [1–4]. Amorphous Si quantum dots (a-Si QDs) have been fabricated and their role as an active layer in visible light-emitting diode demonstrated, which stimulated interest in the control of dot size in a small dimension compared to nanocrystals [5–7]. Theoretical calculation [8] also showed that the radiative recombination rate for a-Si QD is higher by two or three orders of magnitude than that for crystalline Si QD, indicating that better performance can be obtained when a 1.54-\( \mu \text{m} \) light source fabricated using an Er-doped a-Si QD structure is employed.

In a recent report [9], the density effect of a very small a-Si cluster on Er PL in Si-rich SiO\(_2\) was investigated, where a high density of a-Si cluster enhanced the PL efficiency compared to Si nanocrystals. In this article, we will present, for the first time, the effect of the size of a-Si QDs smaller than 2.5 nm in a mean size on Er luminescence, which is another effect to enhance the PL efficiency related to the surface area of a dot.

2. Experimental details

Fifty-nanometer-thick silicon nitride films containing a-Si QDs were grown on Si substrates by plasma-enhanced chemical vapor deposition with various dot sizes. Er\textsuperscript{3+} ions were then implanted at several energies and ion doses to produce a uniform layer with an Er atomic density of \( 1 \times 10^{21} / \text{cm}^2 \) in the silicon nitride films. The profile of implanted Er ions was monitored by Rutherford back-scattering spectroscopy (RBS) as shown in Fig. 1. Finally, the samples were annealed at a temperature of 900 \( ^\circ \text{C} \) for 0.5 h in order to reduce the residual defects left by the implantation process. The PL of the Er ions in the annealed
films was measured using an Ar laser. The samples were classified into three groups, referred to as large-dot, medium-dot, and small-dot samples in accordance with dot sizes of 2.5, 1.8, and 1.4 nm, respectively. Their visible PL spectra are shown in Fig. 2.

3. Results

Fig. 3 shows the graphs of the integrated visible and Er PL intensities as a function of annealing temperature, observed at room temperature. The annealing temperature of 0 °C means the as-grown a-Si QD film and the as-implanted film for a visible PL and a 1.54-µm IR PL, respectively. Visible PL intensity from a-Si QD increases with increasing annealing temperature up to 800 °C and decreases at higher temperature for all samples. However, the Er PL intensity at 1.54 µm increases with increasing annealing temperature up to 900 °C and saturates for small- and medium-dot samples, but shows a maximum value at 800 °C for the large-dot sample. The Er PL was observed only at an Er concentration of 10^{21} cm^{-3}, which were annealed at 900 °C for 300 min. Fig. 4 shows the Er PL intensity for three different dot-sized samples. In the large-dot sample, the annealing temperature of 800 °C was optimum for Er PL, but the PL intensity is not much higher compared to that of the sample annealed at

4. Discussion

The visible PL from the non-implanted samples shows a different behavior, compared to the implanted samples as shown in Fig. 3, where the former decreases with increasing the annealing temperature for the large-dot sample. However, the small-dot sample shows a similar trend. This means that the interaction between Er ions and dots is different as the dot size is various. Because Er PL from all samples was observed only at an Er concentration of 10^{21} cm^{-3}, the comparison of PL intensity for various dot sizes was achieved in the samples with an Er concentration of 10^{21} cm^{-3}, which were annealed at 900 °C for 300 min. Fig. 4 shows the Er PL intensity for three different dot-sized samples. In the large-dot sample, the annealing temperature of 800 °C was optimum for Er PL, but the PL intensity is not much higher compared to that of the sample annealed at

![Fig. 1. RBS depth profile of Er ions in the film. Er concentration is about 10^{21} cm^{-3}. The uniform profile of Er ions in the 50-nm film thickness was achieved by implanting Er ions at three different energies, 40, 80, and 130 keV.](image1)

![Fig. 2. PL spectra of a-Si QDs, where emission peak position was controlled by the dot size due to quantum size effect. For example, the dot sizes corresponding to 640, 540, and 470 nm peaks are 2.5, 1.8, and 1.4 nm, respectively.](image2)
900 °C, and, as a result, the trend of the PL intensity in Fig. 4 is changed when the large-dot sample annealed at 900 °C is replaced by that annealed at 800 °C. From the data in Fig. 4, we can conclude that a small dot is a very effective sensitizer in Er luminescence and enhances the luminescence efficiency.

Another important difference between different dot-sized samples can be observed in the temperature dependence of the Er PL intensity. The PL intensity from Er ions in the large-dot sample decreases rapidly over 100 °C compared to other samples as shown in Fig. 6. It is interesting to elucidate this behavior within the Auger excitation model [10], where electron–hole pairs are bound to Er-related states below the conduction band in Si QD. The excitons can then recombine and thereby excite the Er ions with an excess energy to the difference between the bound state and the conduction band in Si QD. The excess energy is related to the temperature quenching at high temperature. When a dot size increases, the band gap of the dot increases. Accordingly, this result in decreases in electron–hole pair energy and the excess energy. Therefore, a large dot counteracts the advantage of carrier confinement and enhances the Auger de-excitation. Therefore, these data...

Fig. 3. Visible and 1.54-μm IR integrated PL intensities as a function of annealing temperature for (a) large (1.4 nm), (b) medium (1.8 nm), and (c) small (2.5 nm) dot samples. The excitation wavelength is 488 nm.

Fig. 4. PL spectra of Er ions as a function of the size of a-Si QD at room temperature. Samples were implanted with an Er concentration of $10^{21}$ cm$^{-3}$ and annealed at 900 °C for 30 min.

Fig. 5. PL intensity of Er ions as a function of excitation wavelength for the various dot-sized samples annealed at 900 °C for 30 min.
suggest that the critical dot size, taking advantage of the positive effect of a-Si QDs on Er luminescence without being affected by quenching phenomena due to Er–Er interactions, is present and considered to be about 2.0 nm in this study.

5. Summary

Er PL properties as a function of the size of the a-Si QD were investigated in a silicon nitride film. The Er PL intensity is much higher in a small-dot sample than in a large-dot one, and the temperature quenching is suppressed in a small-dot sample because of its large band gap. Therefore, we conclude that the dot size is very important in the efficient luminescence of Er, which shows that a smaller size would lead to a better performance of Er luminescence, and the maximum dot size, affecting positively the enhancement of PL from Er ions, is about 2.0 nm.

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References