Sensitization of Er^{3+} Emission in Er- and Yb-doped Si Thin Films by Laser Ablation

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Abstract

Erbium (Er)- and ytterbium (Yb)-doped Si (Si:Er,Yb) thin films have been controllably synthesized over the Er and Yb concentrations ranging from 10^{18} to 10^{20} cm^{-3} by laser ablation technique. From the PL spectra and the concentration dependence of the intensity of Er3+ emission at 1.54 μm, Yb^{3+} acts as an efficient sensitizer of the Er^{3+}-related PL. Enhancement by a factor of 1.5 due to Yb codoping is observed from the Si:Er,Yb films.

1. Introduction

Rare-earth (RE) doping of Si and Si-related materials [1-5] has attracted much attention for the development of Si-based optoelectronic devices initiated by the report on the photoluminescence (PL) centered at around 1.54 μm of Er^{3+} ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) in Si [1]. Ytterbium (Yb) is known as a sensitizer for Er^{3+} emission at 1.54 μm in Er-doped materials [2]. Since the energy level of the Yb^{3+}-$^2F_{5/2}$ state is close to that of the Er^{3+}-$^4I_{11/2}$ state, optical transitions between them are expected to raise the excitation efficiency of the Er^{3+}. Therefore, much attention has been given to Er, Yb-codoped Si and Si-related materials for Si-based optoelectronic device application. Kozanecki et al. presented that the codoping of Yb leads to the enhancement of Er^{3+}-related PL at 1.54 μm in the Er-doped SiO_2 films [2]. However, there are few studies on Er and Yb codoping of Si matrix.

In this study, we investigate the synthesis of Er- and Yb-doped Si (Si:Er,Yb) thin films by laser ablation. Laser ablation technique is simple and useful for doping the RE elements into the host materials [3]. The relationship between the Er^{3+}-related PL and the Yb doping level is discussed.

2. Experimental

The ceramic target prepared by a hot press technique from a mixture of Si, prescribed amount

1 wt % Er_2O_3, and Yb_2O_3 was used in our experiments. The Er atomic density included in the target is calculated to be 5.5×10^{19} cm^{-3}. Komuro et al. have showed that the Er atomic densities in the Er-doped Si (Si:Er) films linearly depend on those in the targets by x-ray fluorescence spectroscopy (XFS) and secondary ion mass spectroscopy (SIMS) [4, 5]. A schematic of our laser ablation chamber is shown in Fig. 1. A Q-switched YAG (QW-YAG) laser with fourth harmonics (wavelength of 266 nm; pulse duration of 5 ns; energy density per pulse of approximately 1 J/cm^2) was used to ablate the target. The background pressure of the vacuum chamber before ablation was lower than 1×10^{-7} Torr. The bulk target and Si(100) substrate were separated by the distance of approximately 40 mm in the chamber. Six targets samples with different amounts of Yb_2O_3 (0.03, 0.1, 0.3, 1, 3, and 10 wt %) were used to synthesize the Si:Er,Nd films with various Yb concentrations (1.1×10^{18}, 4.0×10^{18}, 1.1×10^{19}, 4.0×10^{19}, 1.1×10^{20}, and 4.0×10^{20} cm^{-3}). The Si:Er,Yb films with approximately 200 nm thick were synthesized on Si(100) substrates at room temperature (RT). After deposition, the Si:Er,Yb films were annealed at 800 ^{o}C for 5 min in an N_2 atmosphere to activate RE incorporation in the films. PL measurements were performed by using Ar^+ laser irradiation at 488 nm. The visible and near infrared (IR) emissions were detected by a photomultiplier tube and a liquid-N_2 cooled Ge p-i-n photodiode, respectively.

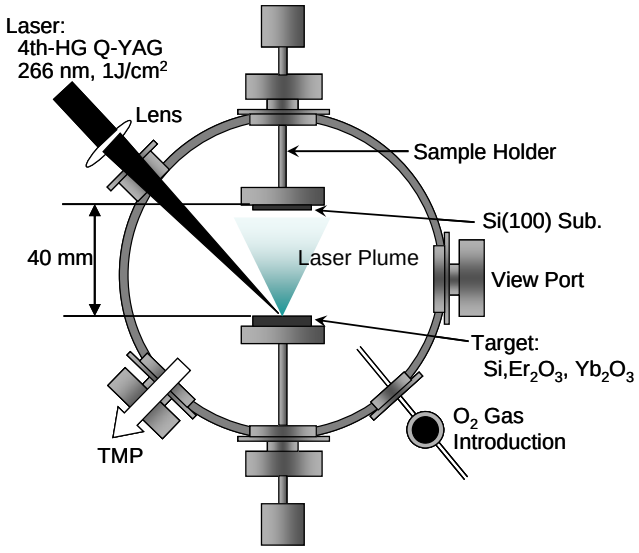


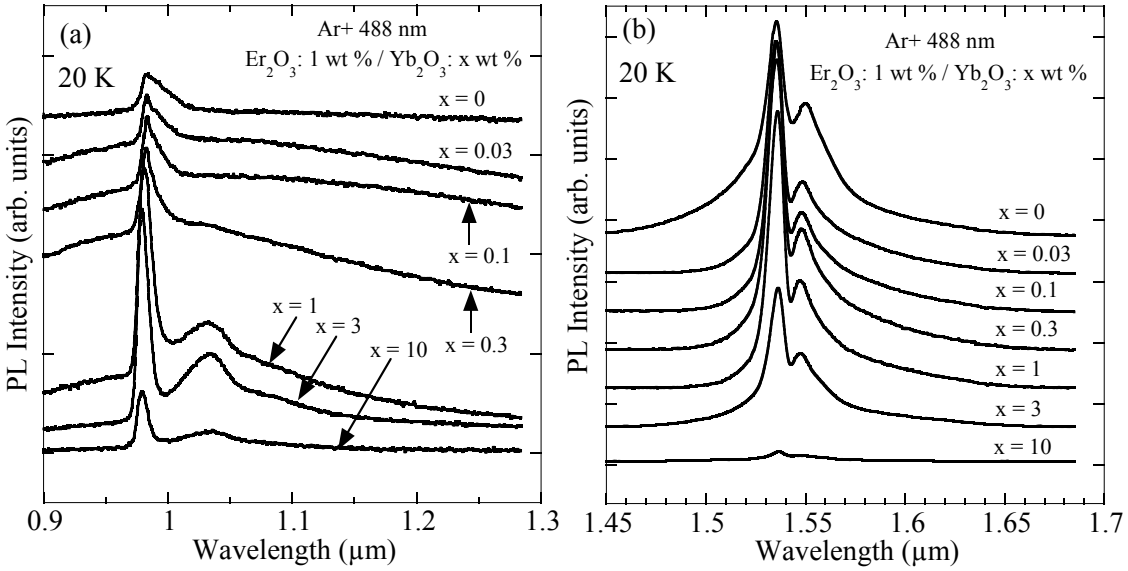
Figure 1 A schematic of our laser ablation chamber.

3. Results and discussion

In order to characterize the structure of the films, x-ray diffraction (XRD) measurements were performed. No appreciable diffraction peaks (not shown) were observed from the samples. This

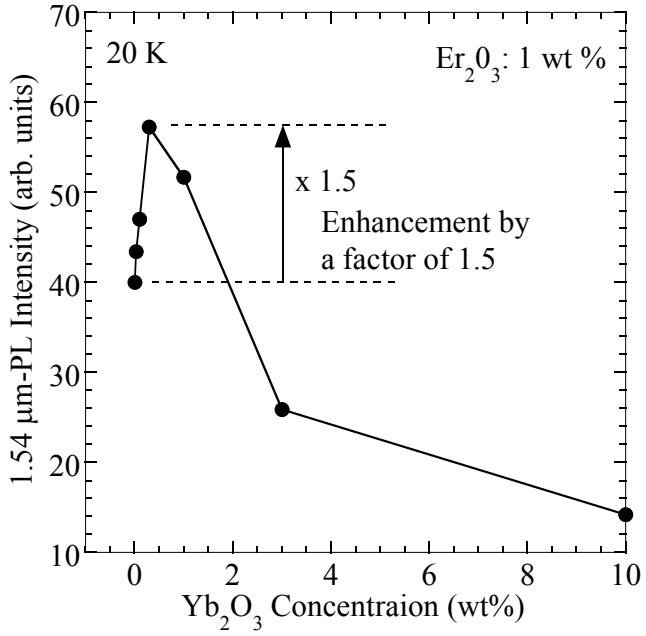
indicates that the Si:Er,Yb films consist of amorphous phase. Previously, we showed that SiOx phase is formed in the Si:Nd films synthesized by laser ablation because the broad PL peaks due to SiOx is observed at around 658 nm [5], which is consistent with the result of the present XRD measurements.

Figures 2 (a) and (b) show the PL spectra from the annealed Si:Er,Yb films at 20 K in the two near IR regions. As shown in Fig. 2 (a), the PL peak at 0.983 μm is attributed to the $^4I_{11/2} \rightarrow {}^4I_{15/2}$ transition in Er^{3+}, which is observed from the samples with 1 wt % Er_2O_3 and 0.03 – 1 wt % Yb_2O_3. In the samples with 3 and 10 wt % Yb_2O_3, the PL peak at 0.979 μm due to the $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition in Yb^{3+} is observed while the peak at 0.983 μm disappears. From Fig. 2 (b), intense and sharp PL originating from intra-4f transitions in Er^{3+} is observed from the 1 wt % Er_2O_3 and 0.3 wt % Yb_2O_3 samples.



Figures 2 (a) and (b) PL spectra at 20 K from the films with different Yb concentrations.

Figure 3 shows the Yb concentration dependence of the intensity of the 1.54 μm-PL due to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition in Er^{3+} at 20 K. The PL intensity increases the Yb concentration in the range from 0.03 to 0.3 wt % Yb_2O_3 while it decreases with that in the range from 1 to 10 wt % Yb_2O_3. Noted that the 1.54 μm-PL intensity for the Si:Er,Yb films with 1 wt % Er_2O_3 and 0.3 wt % Yb_2O_3 is enhanced by a factor of 1.5 higher than that for the Si:Er films with 1 wt % Er_2O_3. Therefore, it is found that for the excitation wavelength at 488 nm Yb^{3+} act as the efficient sensitizers of the Er^{3+} emission at 1.54 μm due to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition.



Figures 3 Yb concentration dependence of the Er3+ emission intensity at 1.54 μm.

4. Conclusions

We showed a simple and useful technique to synthesize Si:Er thin films codoped with Yb. The control of Yb codoping level ranging from 10^{18} to 10^{20} cm^{-3} in films was achieved. The sensitization of the intra-4f-shell emission of Er^{3+} due to Yb codoping was observed in the Si:Er,Yb films. Our results suggest a possibility of fabricating Si-based optoelectronic devices such as light-emitting diodes and lasers by using the Si:Er,Yb films.

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Reference

[1] H. Ennen et al., Appl. Phys. Lett. **43**, 943 (1983).

[2] A. Kozaneki at al., Appl. Phys. Lett. **73**, 2929 (1998).

[3] S. Komuro et al., Appl. Phys. Lett. **69**, 3896 (1996).

[4] S. Komuro et al., Appl. Phys. Lett. **74**, 377 (1999).

[5] S. Kawai et al., Phys. Status Solidi C **7**, 579 (2010).