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Sensitization effect of 1.53 μm Er^{3+}-related emission in $Er_xYb_yY_{2-x-y}SiO_5$ crystalline thin film fabricated by directed self-assembly using layer-by-layer deposition

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1. Introduction

The incorporation of optically active Er^{3+} into the silicon have attracted great interests since it improve the development of silicon based light sources that will interface with both CMOS technology and optical fiber communications[1][2]. Crystalline Er_2SiO_5 contains a few ten percent of Er^{3+} as a constitutional element. The single crystalline nature gives suppression of the Er clustering and defects, resulting in realization of huge active erbium density (~10^{22}cm^{-3}). The supperlattice structure of Er_2SiO_5 with the period of 0.84 nm have been prepared by pulsed laser deposition (PLD) method[3]. Photoluminescence (PL) emission at 1.53 μm with fine structure with line width of less than 4 meV has been generated at room temperature. By doping Y^{3+} into the thin film to dilute the concentration of Er^{3+}, upconversion process could be suppressed. In the present work, besides doping Y^{3+}, Yb^{3+} ions have also co-doped into the thin films. Because Yb^{3+} have a large absorption cross section of one order of magnitude higher than that of Er^{3+} at 980 nm optical pumping. We expect that Yb^{3+} act as a sensitizer of Er^{3+} pumping at 980 nm.

2. Experiment

$Er_xYb_yY_{2-x-y}SiO_5$ (x,y=0.33) thin films with period structure have been prepared by the layer-by-layer deposition methods. We chose PLD as the deposition method using rotatable targets, and also attempted to use radical assisted sputtering (RAS)[4] for the layer-layer deposition. In order to promote the directed self-assembly of $Er_xYb_yY_{2-x-y}SiO_5$ crystals, rapid thermal anneal in argon atmosphere was performed. Its structure and spectroscopic properties have been studied comparing with $Er_xY_{2-x}SiO_5$ film.

3. Results and discussion

Figure 1 shows X-ray diffraction patterns of $Er_xYb_yY_{2-x-y}SiO_5$ and $Er_xY_{2-x}SiO_5$ films. X-ray diffraction pattern of both films exhibits (n00) diffraction peaks of Er_2SiO_5 crystal, indicating a highly orientated structure with (100) direction perpendicular to silicon (100) face. The strong peaks at 33° are (100) diffraction peak of silicon substrate. Both thin films exhibit the intense diffraction peaks at 10.32°, 20.35° and 31.23°, corresponding to the (100), (200) and (300) diffraction of Er_2SiO_5. It is indicated that doping of Yb^{3+} almost has no effect on the crystalline structure.

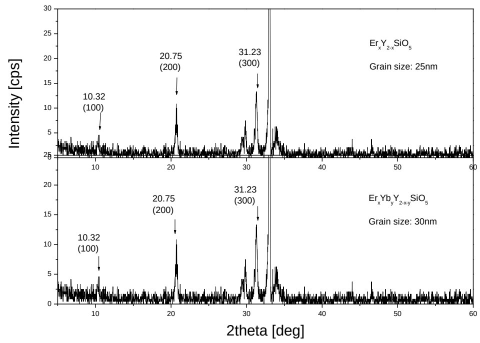

Fig. 1 XRD patterns of $Er_xYb_yY_{2-x-y}SiO_5$ and $Er_xY_{2-x}SiO_5$ films.

The Stark levels of $^4I_{15/2}$ (Er^{3+}) main fold of the films shown in PL spectra at 20K agrees well with each other, as well as those of Er_2SiO_5, suggesting the same luminescence center. The energy transfer processes have been studied by PL spectroscopic analysis. By exciting $Er_xY_{2-x}SiO_5$ and $Er_xYb_yY_{2-x-y}SiO_5$ films at 654.5 nm, energy transfer from $^4I_{11/2}$ (Er^{3+}) and $^5F_{7/2}$ (Yb^{3+}) was observed in $Er_xYb_yY_{2-x-y}SiO_5$ film.

Figure 2 presents the PL intensity of $Er_xYb_yY_{2-x-y}SiO_5$ and $Er_xY_{2-x}SiO_5$ at 1.53 μm as a function of pumping power. With increasing of the pumping power, the PL intensity of $Er_xY_{2-x}SiO_5$ increased and reaches saturation at high pumping power. While, for $Er_xYb_yY_{2-x-y}SiO_5$ thin film, the PL intensity is similar with those of $Er_xY_{2-x}SiO_5$ thin film in the range from 10 to 130 mW; over 140 mW, the PL intensity increases sharply and reaches its maximum at the excitation power of 158 mW. This is because the operation wavelength of LD becomes long with increasing the injection current. The excitation wavelength is about 975nm at the optimum sensitization, corresponding to the absorption peak of Yb ion..

The insert of Fig. 2 is the spectra of $^4I_{13/2} \rightarrow ^4I_{15/2}$ transitions of Er^{3+} of the thin films excited at this condition. The ratio between the PL intensity of $Er_xYb_yY_{2-x-y}SiO_5$ to that of $Er_xY_{2-x}SiO_5$ is 3.4. It should note that the increase of PL intensity of $Er_xYb_yY_{2-x-y}SiO_5$ thin film come from two contributions, one is the sensitization effect of Yb^{3+} ions, the other is the increase of fluoresce efficiency. The PL intensity is proportional to fluorescence efficiency due to increase of lifetime. The measured lifetime for $Er_xY_{2-x}SiO_5$ and $Er_xYb_yY_{2-x-y}SiO_5$ thin films are 260 and 410 μs, respectively. The contribution from increase of the fluorescence efficiency is 1.6 times. From the above considerations, the increase of luminescence of $Er_xYb_yY_{2-x-y}SiO_5$ thin film based on the sensitization effect of Yb^{3+} is 2.1 times. The realization of Yb^{3+} sensitized Er^{3+} based $Er_xYb_yY_{2-x-y}SiO_5$ thin film, taking advantage of high absorption cross section of Yb^{3+}, and in combination with efficient $Yb^{3+}\rightarrow Er^{3+}$ energy transfer, offers a potential material for a small size planar-optical-waveguide amplifier on silicon substrate with lower threshold and increased gain.

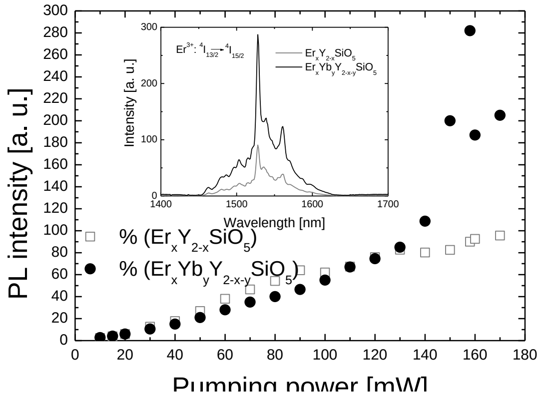

Fig. 1 PL intensity of $Er_xYb_yY_{2-x-y}SiO_5$ and $Er_xY_{2-x}SiO_5$ thin films at 1.53 μm as a function of pumping power. The insert is the PL emission of Er^{3+}: $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of the films excited at 975 nm and 158 mW at room temperature.

4. Conclusions

$Er_xY_{2-x}SiO_5$ and $Er_xYb_yY_{2-x-y}SiO_5$ thin films have been prepared by directed self-assembly using layer-by-layer deposition. The annealed thin films exhibit highly orientation structure with (100) direction perpendicular to silicon substrate, and both thin films contain the same type of luminescence center. For $Er_xYb_yY_{2-x-y}SiO_5$ thin films, excited by 654.5 nm laser, the energy transfer between Yb^{3+} and Er^{3+} is conformed by PL spectra. For 975 nm excitation, 1.53 μm emission of $Er_xYb_yY_{2-x-y}SiO_5$ is much intense than that of $Er_xY_{2-x}SiO_5$ at higher excitation power due to the sensitization of Er^{3+} by Yb^{3+}. This may allow to design a compact planar-optical-waveguide amplifier on silicon.

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