Sensitization effect of 1.53 \textmu m Er\textsuperscript{3+}-related emission in Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} crystalline thin film fabricated by directed self-assembly using layer-by-layer deposition

Fangli Jing\textsuperscript{1}, Tatsunori Shinagawa\textsuperscript{1}, Takayuki Nakajima\textsuperscript{1}, Takuya Sugawara\textsuperscript{2}, Yousong Jiang\textsuperscript{2}, Tadamasa Kimura\textsuperscript{1} and Hideo Ishihiki\textsuperscript{1}

\textsuperscript{1}Department of Engineering Science, The University of Electro-Communications, Tokyo, JAPAN
\textsuperscript{2}R&D Center, Shincron Co. Ltd., Yokohama, JAPAN
e-mail: hishishi@ee.ucc.ac.jp

1. Introduction

The incorporation of optically active Er\textsuperscript{3+} into the silicon has attracted great interests since it improve the development of silicon based light sources that will interface with both CMOS technology and optical fiber communications\cite{1}[2]. Crystalline Er\textsubscript{2}SiO\textsubscript{5} contains a few ten percent of Er\textsuperscript{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\textsuperscript{22}cm\textsuperscript{-3}). The superlattice structure of Er\textsubscript{2}SiO\textsubscript{5} with the period of 0.84 nm have been prepared by pulsed laser deposition (PLD) method\cite{3}. Photoluminescence (PL) emission at 1.53 \textmu m with fine structure with line width of less than 4 meV has been generated at room temperature. By doping Y\textsuperscript{3+} into the thin film to dilute the concentration of Er\textsuperscript{3+}, upconversion process could be suppressed. In the present work, besides doping Y\textsuperscript{3+}, Yb\textsuperscript{3+} ions have also co-doped into the thin films. Because Yb\textsuperscript{3+} have a large absorption cross section of one order of magnitude higher than that of Er\textsuperscript{3+} at 980 nm optical pumping. We expect that Yb\textsuperscript{3+} act as a sensitizer of Er\textsuperscript{3+} pumping at 980 nm.

2. Experiment

Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} (x=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)\cite{4} for the layer-layer deposition. In order to promote the directed self-assembly of Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} crystals, rapid thermal anneal in argon atmosphere was performed. Its structure and spectroscopic properties have been studied comparing with Er\textsubscript{x}Y\textsubscript{2-x}SiO\textsubscript{5} film.

3. Results and discussion

Figure 1 shows X-ray diffraction patterns of Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} and Er\textsubscript{x}Y\textsubscript{2-x}SiO\textsubscript{5} films. X-ray diffraction pattern of both films exhibits (n00) diffraction peaks of Er\textsubscript{2}SiO\textsubscript{5} crystal, indicating a highly orientated structure with (100) direction perpendicular to silicon (100) face. The strong peaks at 33\textdegree are (100) diffraction peak of silicon substrate. Both thin films exhibit the intense diffraction peaks at 10.32\textdegree, 20.35\textdegree and 31.23\textdegree, corresponding to the (100), (200) and (300) diffraction of Er\textsubscript{2}SiO\textsubscript{5}. It is indicated that doping of Yb\textsuperscript{3+} almost has no effect on the crystalline structure.

![Fig. 1 XRD patterns of Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} and Er\textsubscript{x}Y\textsubscript{2-x}SiO\textsubscript{5} films.](image)

The Stark levels of \textsuperscript{1}I\textsubscript{15/2} (Er\textsuperscript{3+}) main fold of the films shown in PL spectra at 20K agrees well with each other, as well as those of Er\textsubscript{2}SiO\textsubscript{5}, suggesting the same luminescence center. The energy transfer processes have been studied by PL spectroscopic analysis. By exciting Er\textsubscript{x}Y\textsubscript{2-x}SiO\textsubscript{5} and Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} films at 654.5 nm, energy transfer from \textsuperscript{3}I\textsubscript{11/2} (Er\textsuperscript{3+}) and \textsuperscript{2}F\textsubscript{5/2} (Yb\textsuperscript{3+}) was observed in Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} film.

Figure 2 presents the PL intensity of Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} and Er\textsubscript{x}Y\textsubscript{2-x}SiO\textsubscript{5} at 1.53 \textmu m as a function of pumping power. With increasing of the pumping power, the PL intensity of Er\textsubscript{x}Y\textsubscript{2-x}SiO\textsubscript{5} increased and reaches saturation at high pumping power. While, for Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} thin film, the PL intensity is similar with those of Er\textsubscript{x}Y\textsubscript{2-x}SiO\textsubscript{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 \textsuperscript{1}I\textsubscript{13/2} \rightarrow \textsuperscript{1}I\textsubscript{15/2} transitions of Er\textsuperscript{3+} of the thin films excited at this condition. The ratio between the PL intensity of Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} to that of Er\textsubscript{x}Y\textsubscript{2-x}SiO\textsubscript{5} is 3.4. It should note that the increase of PL intensity of Er\textsubscript{x}Yb\textsubscript{y}Y\textsubscript{2-x-y}SiO\textsubscript{5} thin film come from two contributions, one is the sensitization effect of Yb\textsuperscript{3+} ions, the
other is the increase of fluorescent efficiency. The PL intensity is proportional to fluorescent efficiency due to increase of lifetime. The measured lifetime for Er3Y2.5SiO5 and Er3Yb2.5SiO5 thin films are 260 and 410 μs, respectively. The contribution from increase of the fluorescent efficiency is 1.6 times. From the above considerations, the increase of luminescence of Er3Yb2.5SiO5 thin film based on the sensitization effect of Yb3+ is 2.1 times. The realization of Yb3+ sensitized Er3+ based Er3Yb2.5SiO5 thin film, taking advantage of high absorption cross section of Yb3+, and in combination with efficient Yb3+−Er3+ 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 Er3Y2.5SiO5 and Er3Yb2.5SiO5 thin films at 1.53 μm as a function of pumping power. The insert is the PL emission of Er3+: 4I13/2 →4I15/2 transition of the films excited at 975 nm and 158 mW at room temperature.](image)

4. Conclusions
Er3Y2.5SiO5 and Er3Yb2.5SiO5 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 Er3Yb2.5SiO5 thin films, excited by 654.5 nm laser, the energy transfer between Yb3+ and Er3+ is confirmed by PL spectra. For 975 nm excitation, 1.53 μm emission of Er3Yb2.5SiO5 is much intense than that of Er3Y2.5SiO5 at higher excitation power due to the sensitization of Er3+ by Yb3+. This may allow to design a compact planar-optical-waveguide amplifier on silicon.

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References