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2009 J. Phys.: Condens. Matter 21 012204

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## FAST TRACK COMMUNICATION

# 1.53 $\mu\text{m}$ photo- and electroluminescence from $\text{Er}^{3+}$ in erbium silicate

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Received 16 October 2008, in final form 8 November 2008

Published 1 December 2008

Online at [stacks.iop.org/JPhysCM/21/012204](http://stacks.iop.org/JPhysCM/21/012204)

## Abstract

Si-rich silicon oxide (SRO)/Er–Si–O/SRO multilayers were prepared on p-Si substrates using magnetron sputtering. X-ray diffraction measurements indicate that a mixture of silicates  $\text{Er}_2\text{Si}_2\text{O}_7$  and  $\text{Er}_2\text{SiO}_5$  was formed after the multilayers were annealed at 1000 and 1150 °C. Strong  $\text{Er}^{3+}$  1.53  $\mu\text{m}$  photoluminescence (PL) at room temperature has been observed from these multilayers and the full width at half-maximum of the 1.53  $\mu\text{m}$  peak is less than 1.8 nm for the multilayers annealed at 1150 °C.  $\text{Er}^{3+}$  1.53  $\mu\text{m}$  electroluminescence has been observed from erbium silicate films for the first time.

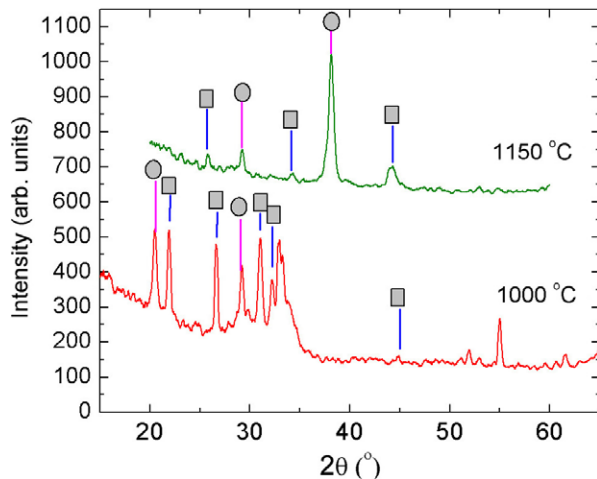
(Some figures in this article are in colour only in the electronic version)

$\text{Er}^{3+}$ -related luminescence at 1.53  $\mu\text{m}$  from Er-doped materials has been under intense investigation [1–5] for its wide applications in optical telecommunications and Si photonics, where Si-compatible high-gain waveguide amplifiers [6] and high efficiency Si-based light-emitting diodes [7, 8] are key devices. However, in these Er-doped materials, the optical gains and luminescence efficiencies are limited by the low doping concentration of Er due to its low solid solubility in most host materials. In recent years, erbium compounds such as erbium oxide or erbium silicates, in which erbium ions are present as a major component rather than a dopant, are investigated [9–18]. Efficient room temperature photoluminescence (PL) at 1.53  $\mu\text{m}$  from erbium silicates (Er–Si–O) has been reported [11, 15]. Furthermore, the  $\text{Er}^{3+}$ -related PL spectra of Er–Si–O crystalline films prepared by the wet-chemical method and metal–organic molecular beam epitaxy show very sharp peaks with a linewidth of less than 7 nm (4 meV) at room temperature [13, 16]. The high Er content, relatively small thermal quenching of Er emission intensity and narrow emission linewidth suggest that

erbium silicate represents a very interesting material for future application in Si-based amplifiers, light-emitting diodes and lasers [12]. However, as far as we know, there is no report about  $\text{Er}^{3+}$  electroluminescence (EL) from erbium silicates or erbium oxide.

In this paper, we have studied the structure and luminescence properties of Si-rich silicon oxide (SRO)/Er–Si–O/SRO/p-Si multilayers deposited by reactive magnetron sputtering with  $\text{Er}_2\text{O}_3$  and Si targets. Efficient 1.53  $\mu\text{m}$  EL from  $\text{Er}^{3+}$  in erbium silicate films has been measured at room temperature for the first time.

In our experiments, SRO/Er–Si–O/SRO sandwich structures were prepared on p-type Si substrates (8–12  $\Omega$  cm) using reactive magnetron sputtering. The SRO deposition was performed by sputtering with a pure Si target in Ar and  $\text{O}_2$  mixed gas. The Si content of SRO layers is controlled to the optimum value for the highest  $\text{Er}^{3+}$  EL efficiency in [8]. The deposition of Er–Si–O layer was carried out by co-sputtering with  $\text{Er}_2\text{O}_3$  and Si targets in Ar and  $\text{O}_2$  mixed gas. The thicknesses of the as-deposited Er–Si–O layer and both the

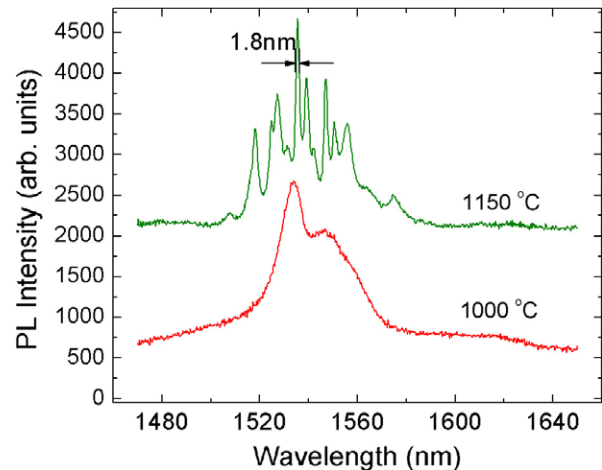


**Figure 1.** XRD spectra of the SRO/Er-Si-O/SRO/p-Si multilayers annealed at 1000 and 1150 °C. The spectra are offset for clarity. The circles and squares indicate the diffraction peaks associated with the stoichiometric silicates  $\text{Er}_2\text{Si}_2\text{O}_7$  and  $\text{Er}_2\text{SiO}_5$ , respectively.

SRO layers were 60 nm and 35 nm, respectively. After deposition, the samples were annealed in  $\text{N}_2$  atmosphere at temperatures of 1000 or 1150 °C for 1 h. The samples were characterized by x-ray diffraction (XRD) measurements in a Philips X'Pert MRD diffraction system with  $\text{Cu K}\alpha_1$  radiation as an x-ray source. The fraction of Er in the Er-Si-O layer was measured by an energy-dispersive x-ray (EDX) spectroscope. The EDX measurement revealed that the fraction of Er in the as-deposited Er-Si-O layers is as high as about 24%. The PL spectra were taken with a microzone confocal Raman spectrometer (LabRam HR 800). The PL excitation spectra were measured at room temperature using eight visible lines from an  $\text{Ar}^+$  laser as the excitation sources. Semitransparent Au films (20 nm) were evaporated onto the SRO/Er-Si-O/SRO/p-Si multilayers to fabricate Au/SRO/Er-Si-O/SRO/p-Si structures. The EL signals were detected by a liquid- $\text{N}_2$ -cooled Ge detector and recorded with a lock-in amplifier.

Figure 1 shows the XRD spectra of the SRO/Er-Si-O/SRO/p-Si multilayers. The XRD spectra of the multilayers annealed at 1000 and 1150 °C show quite a few peaks, indicating that the anneals at these two temperatures have induced crystallization of the films. From analysis of these XRD spectra, the patterns<sup>4,5</sup> of  $\text{Er}_2\text{Si}_2\text{O}_7$  and  $\text{Er}_2\text{SiO}_5$  marked in figure 1 appear together in both the XRD spectra of the multilayers annealed at 1000 and 1150 °C. It indicates that the multilayers annealed at 1000 and 1150 °C consist of a mixture of the silicates  $\text{Er}_2\text{Si}_2\text{O}_7$  and  $\text{Er}_2\text{SiO}_5$ .

PL studies of the SRO/Er-Si-O/SRO/p-Si multilayers were carried out at room temperature. Figure 2 shows room temperature PL spectra excited with the 488 nm line of an  $\text{Ar}^+$  laser for the multilayers annealed at 1000 and 1150 °C in a  $\text{N}_2$  ambient for 1 h. The PL spectrum of the multilayer annealed at 1000 °C shows a peak of 1534 nm, corresponding to the transition between the first excited level  $^4\text{I}_{13/2}$  and the ground state  $^4\text{I}_{15/2}$  of  $\text{Er}^{3+}$  ions. However, the PL spectrum of



**Figure 2.** Room temperature photoluminescence spectra of the SRO/Er-Si-O/SRO/p-Si multilayers annealed at 1000 and 1150 °C. The spectra are offset for clarity.

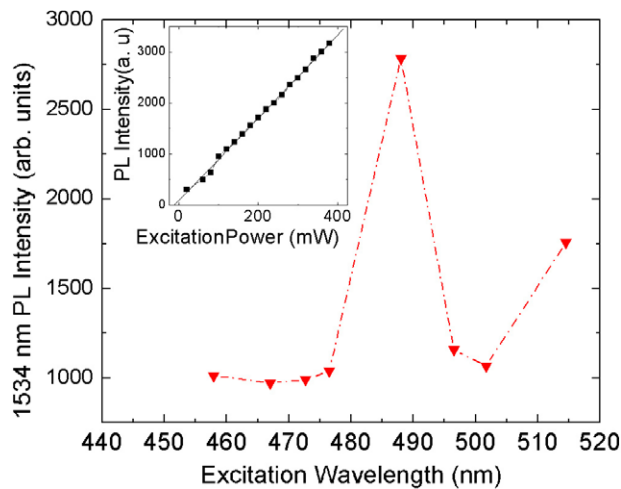
the multilayer annealed at 1150 °C has a fine structure with many very sharp peaks around the main peak at 1534 nm. It is interesting to note that the linewidth of the main peak is about 1.8 nm at room temperature, much less than that of about 7 nm (4 meV) from the erbium silicate prepared by the wet-chemical method and metal-organic molecular beam epitaxy reported in [13] and [16], respectively. In figure 1, the peaks of  $\text{Er}_2\text{Si}_2\text{O}_7$  are much higher than those of  $\text{Er}_2\text{SiO}_5$  in the XRD spectra of the multilayer annealed at 1150 °C, but in contrast the XRD spectra of the multilayer annealed at 1000 °C show mainly the peaks of  $\text{Er}_2\text{SiO}_5$ . We infer that the fine structure in the PL spectrum of the multilayer annealed at 1150 °C may originate from the Stark splitting of  $\text{Er}^{3+}$  transitions in the crystalline  $\text{Er}_2\text{Si}_2\text{O}_7$  rather than from that in the crystalline  $\text{Er}_2\text{SiO}_5$ . Moreover, we have observed the typical red photoluminescence with a wide peak around 750 nm which is related to Si nanocrystals in the SRO layers by measuring the visible PL spectrum of the multilayer annealed at 1000 °C in our experiments. But we have not observed it in the visible PL spectrum of the multilayer annealed at 1150 °C.

Figure 3 shows the PL excitation spectra of the multilayer annealed at 1000 °C. For each pump wavelength, the laser power was adjusted to 20 mW. From this figure, evident enhancement of PL intensity detected at 1534 nm is observed when the wavelengths of pumping are 488 and 514.5 nm, which correspond to direct optical excitation of the  $\text{Er}^{3+}$  ions from the ground state ( $^4\text{I}_{15/2}$ ) to the excited states of  $^4\text{F}_{7/2}$  and  $^2\text{H}_{11/2}$  levels, respectively. The inset shows PL intensity detected at 1534 nm as a function of excitation power of the 488 nm line from an  $\text{Ar}^+$  laser. The PL intensity exhibits a linear trend without saturation when the excitation power increases from 3 to about 400 mW. This behavior indicates that a huge amount of  $\text{Er}^{3+}$  ions can be excited in the erbium silicates layer.

Figure 4(a) depicts the room temperature EL spectra from the Au/SRO/Er-Si-O/SRO/p-Si structures with the SRO/Er-Si-O/SRO/p-Si multilayers annealed at 1000 and 1150 °C. The EL spectrum of the structure with the multilayer annealed

<sup>4</sup> Joint Committee for Powder Diffraction Standards, file no. 25-1416.

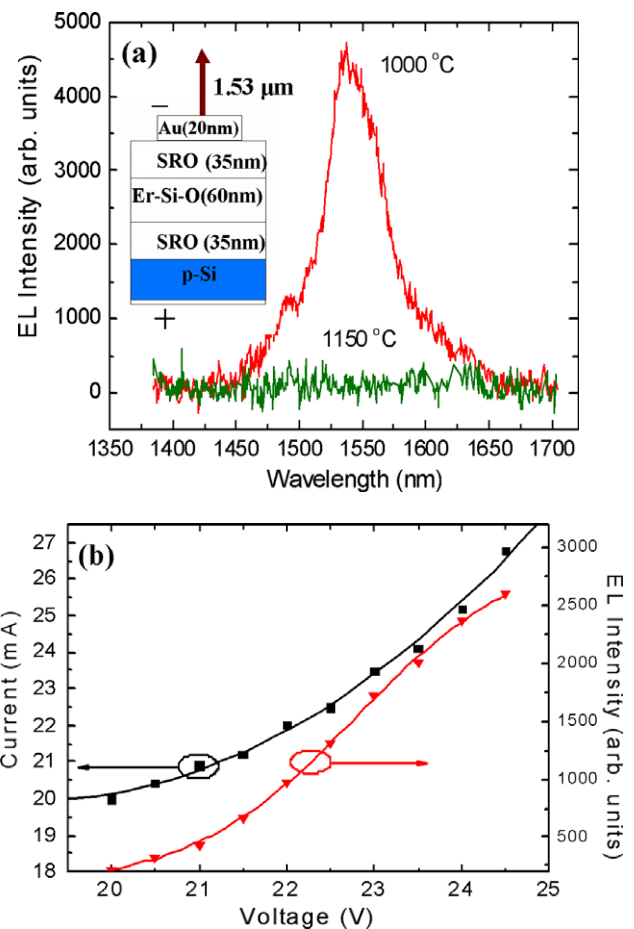
<sup>5</sup> Joint Committee for Powder Diffraction Standards, file no. 40-0384.



**Figure 3.** Photoluminescence excitation spectra at 1534 nm of the SRO/Er–Si–O/SRO/p–Si multilayer annealed at 1000 °C. For each pump wavelength, laser power at the sample = 20 mW. Dashed–dotted lines are guides for the eye. The inset shows photoluminescence intensity at 1534 nm as a function of excitation power of the 488 nm line from an Ar<sup>+</sup> laser.

at 1000 °C shows a peak of 1535 nm. In contrast, the EL spectrum of the structure with the multilayer annealed at 1150 °C shows no EL. For comparison, Er–Si–O single layers (130 nm) deposited on p–Si substrates were also prepared. We have not observed any 1.53  $\mu\text{m}$  EL from the Au/Er–Si–O/p–Si structures with the Er–Si–O/p–Si annealed at 1000 or 1150 °C in a N<sub>2</sub> ambient for 1 h. Therefore we can infer that the SRO layers play a key role in the EL from the SRO/Er–Si–O/SRO multilayer. In the SRO layers, the holes from the p–Si substrate can be injected into the valence bands of Si nanocrystals and the electrons from the Au cathode can be transported by hopping between two adjacent Si nanocrystals [8]. Thus the presence of Si nanocrystals in the SRO layers improves the carrier injection greatly to form a large amount of electron–hole (e–h) pairs and the e–h pairs recombining excites the Er<sup>3+</sup> ions in the Er–Si–O layer. Figure 4(b) shows the current and the EL intensity at 1534 nm from the Au/SRO/Er–Si–O/SRO/p–Si structure with the SRO/Er–Si–O/SRO/p–Si multilayer annealed at 1000 °C as a function of forward bias. Both current and EL intensity increase with increasing forward bias, but the EL intensity saturates at about 24.5 V. The turn-on voltage is about 19.5 V.

In summary, SRO/Er–Si–O/SRO multilayers on p–Si substrates have been prepared by the reactive magnetron sputtering technique fully compatible with Si technology. Strong room temperature 1.53  $\mu\text{m}$  PL from Er<sup>3+</sup> has been measured in these multilayers annealed at 1000 and 1150 °C. The PL spectrum of the multilayer annealed at 1150 °C shows a lot of very sharp peaks originated from the Stark splitting of Er<sup>3+</sup> transitions in the crystalline Er<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>. Room temperature 1.53  $\mu\text{m}$  EL from Er<sup>3+</sup> has been observed from the Au/SRO/Er–Si–O/SRO/p–Si structure with the SRO/Er–Si–O/SRO/p–Si multilayer annealed at 1000 °C. The above findings may open a route towards possible application of erbium silicate in Si-based optoelectronics.



**Figure 4.** (a) Room temperature electroluminescence spectra from Au/SRO/Er–Si–O/SRO/p–Si structures with the SRO/Er–Si–O/SRO/p–Si multilayers annealed at 1000 and 1150 °C measured at 23 V. The inset is the schematic configuration of the Au/SRO/Er–Si–O/SRO/p–Si structures. (b) The current (squares) and the EL intensity at 1534 nm (triangles) versus voltage characteristics of the structure with the SRO/Er–Si–O/SRO/p–Si multilayer annealed at 1000 °C.

This work was supported by the National Natural Science Foundation of China (nos. 50732001, 10574008 and 10674012) and the National Basic Research Program of China (973 Program, no. 2007CB613401).

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