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Luminescence from erbium oxide grown on silicon

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ABSTRACT

The luminescence properties of erbium oxide grown on crystalline and amorphous silicon substrates were studied by means of photo- and cathodoluminescence techniques. Differences in the luminescence spectra for samples grown on the two types of substrates used are explained in terms of the different types of erbium centers formed by taking into account the substrate properties and the thermal treatments during growth. For comparison, erbium implanted and oxygen coimplanted crystalline and amorphous silicon have been also investigated by luminescence techniques. In the implanted samples, the sharp transitions from erbium ions in the visible range were quenched and the main emission corresponds to the intraionic transitions in Er^{3+} ions in the infrared range peaked at 1,54 μm .

INTRODUCTION

The efficiency of luminescence emission associated to the intraionic Er^{3+} radiative transitions in different matrix is related to the mechanism of energy transfer from the hosts to the complexes formed by erbium and the surrounding atoms [1, 2]. The presence of other codopant elements in the Er neighborhood as well as the structure of the host matrix was found essential in determining the Er complexes formation [3, 4]. The presence of oxygen in the neighborhood of the erbium ions causes a strong enhancement of the efficiency of Er emission at 1.5 μm wavelength [5]. Other luminescence bands of the Er related transitions from visible to infrared range could be observed by a selective excitation.

In this work, the influence of the host matrix and of the excitation energies on the luminescence emission of erbium oxide grown on amorphous and crystalline substrates was investigated. The techniques used were photoluminescence (PL) and cathodoluminescence (CL) in the scanning electron microscope. The different emission bands detected are suggested to be originated at different types of Er centers formed in the erbium oxide overlayer.

EXPERIMENTAL DETAILS

Two sets of erbium doped silicon samples were investigated: erbium deposited and erbium implanted silicon films. In the former case, erbium vapor was deposited on amorphous and crystalline silicon substrates and the samples were then submitted to a thermal treatment at 950 °C during 1 hour in oxygen or nitrogen atmosphere. On the other hand, crystalline and amorphous silicon substrates were implanted with 200 keV ^{166}Er ions at doses of 5×10^{15} ions/cm². Some of the amorphous silicon substrates were coimplanted with 200 keV Er ions and 40 keV ^{16}O ions at doses of 5×10^{15} and 10^{16} ions/cm² respectively. All the implanted samples

Table I. Summary of the samples investigated.

(a) Er deposited samples			(b) Er implanted samples		
Er deposited samples	substrate	annealing atmosphere	Er implanted samples	substrate	ion implantation
c-Si/Er/O	crystalline	oxygen	c-Si:Er	crystalline	Er
a-Si/Er/O	amorphous	oxygen	a-Si:Er	amorphous	Er
a-Si/Er/N	amorphous	nitrogen	a-Si:Er,O	amorphous	Er, O

were submitted to a rapid thermal annealing (RTA) process at 1000°C for 15 s. A summary of the samples investigated in this work and their corresponding labels is displayed in table I.

All the samples were observed in the CL mode of operation in a Hitachi S2500 SEM in the temperature range of 80 - 300 K and at accelerating voltage of 20 kV. For the detection of visible light a Hamamatsu R-928 photomultiplier was used while for the near infrared light a cooled ADC germanium detector was employed. The PL measurements were performed with a CD-900 spectrometer system from Edinburgh Instruments. Samples were cooled at 10 K in a closed cryostat. The excitation sources were a He-Cd laser of 325 nm and 422 nm wavelengths with an excitation power of 50 mW and an Ar-ion laser (lines 457.9 nm, 488 nm and 514.5 nm) with an excitation power of 20 mW.

RESULTS AND DISCUSSION

Due to the low diffusivity of erbium in silicon the applied treatment leads to the formation of a thin film of erbium oxide overlayer on the sample. In order to get a better understanding of the luminescence results, we have first studied the light emission from erbium oxide pure powders. Figure 1 shows the PL spectra obtained at 10 K from Er_2O_3 in the visible range (figure 1a) and in the infrared range (figure 1b). All the peaks are attributed to intraionic transitions from different excited levels in the Er^{3+} ions to the fundamental state [6]. The set of

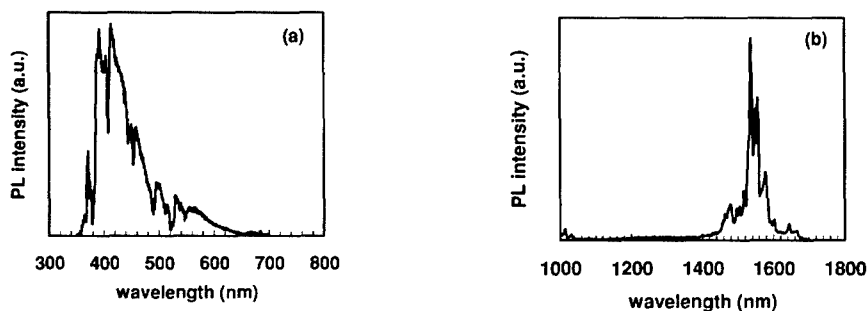


Figure 1. (a) PL spectrum from erbium oxide powder in the visible range. The excitation wavelength was 325 nm. (b) PL spectrum from erbium oxide powder in the infrared range. The excitation wavelength was 488 nm.

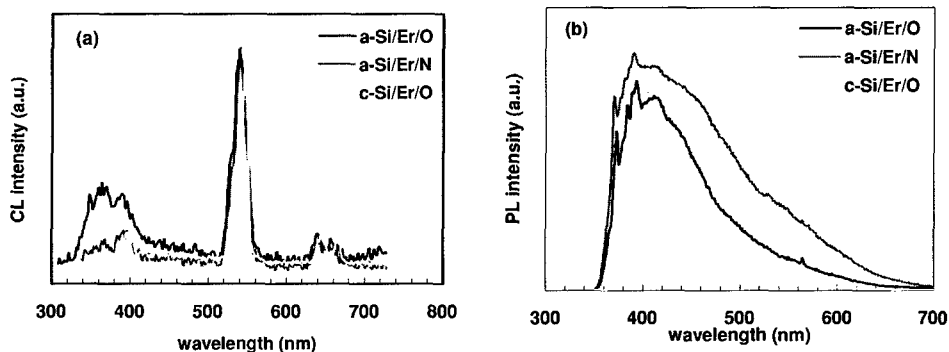


Figure 2. (a) CL spectra from Er deposited samples at 90 K. The acceleration voltage was 20 keV. (b) PL spectra from Er deposited samples obtained at 10 K.

sharp peaks around $1.54 \mu\text{m}$ has received more attention in the literature in view of further applications in optoelectronic devices and it has also been obtained when Er ions are embedded in other semiconductor matrix [7,8].

Figure 2 shows the CL and PL spectra in the visible range from the erbium deposited silicon samples. CL spectra show blue, green and red bands. The green band dominates the CL spectra at 90 K in all samples, with crystalline or amorphous substrates, (figure 2a), but at room temperature the main CL emission from the c-Si/Er/O sample corresponds to the red band, as we have reported in a previous work [9]. These green and red bands are due to intraionic Er transitions and the observed trend has been previously reported by Jaba *et al.* in other host matrix [10]. The fact that similar spectra are obtained for amorphous substrates treated in O and in N atmospheres while differences are found between amorphous and crystalline substrates, suggests that the formation of erbium oxide is determined by the oxygen content of the substrate rather

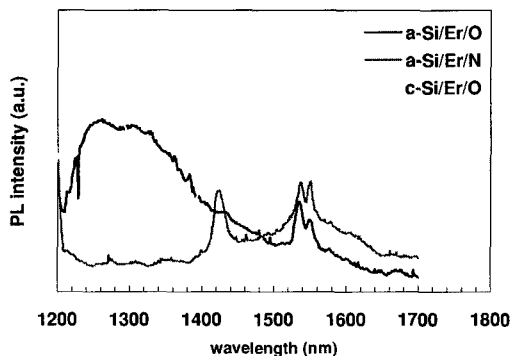


Figure 3. PL spectra from Er implanted silicon substrates, at 10 K in the infrared range. The excitation wavelength was 488 nm.

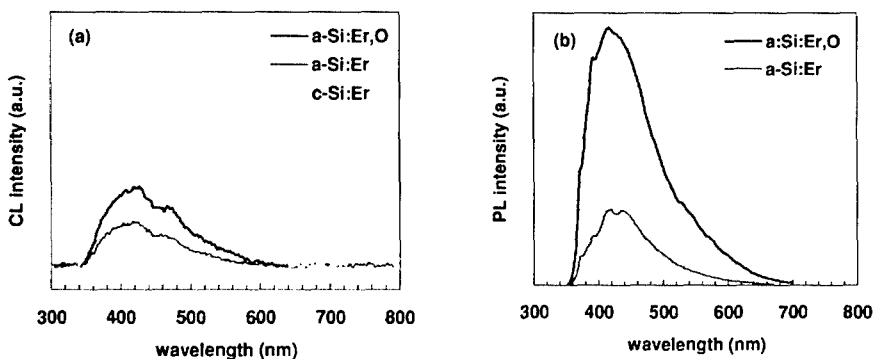


Figure 4. (a) CL spectra from Er implanted on amorphous silicon and crystalline silicon, and coimplanted with Er and O. (b) PL spectra from amorphous implanted substrates.

than the atmosphere during the treatment. The amount of oxygen provided by the substrate during growth could influence the defect structure of the layer and hence its emission properties. The difference among the samples grown on amorphous and crystalline substrates is also clearly observed in Figure 2b. Under a 325 nm laser excitation, all deposited samples show a dominant broad blue band at about 400 nm with a shoulder peaked around 540 nm (figure 2b). When we excited with the line 488 nm of the Ar laser, no significant PL signal is detected from erbium deposited on crystalline substrates, while for the amorphous substrates a sharp peak at 540 nm is clearly revealed in accordance with the CL spectra. The differences between PL and CL spectra were attributed to the different excitation energies used in both kinds of experiments and to the more selective character of the PL excitation.

In the infrared range, the CL signal was too low to record spectra with our experimental system. PL emission from deposited samples changes markedly depending on the specific substrate used. Figure 3 displays the PL spectra from the three erbium deposited samples. We observe a broad band around 1.25 – 1.30 μm in samples which were submitted to a thermal treatment in oxygen atmosphere. This band seems to be rather independent on the substrate and its maximum shifts towards lower energies when the temperature increases, similar as a near band edge emission. The origin of this band, which is not present in erbium oxide powder, could be related to defects involving oxygen introduced in the overlayers during the thermal treatment. The emission from erbium ions, peaked at 1.54 μm is well defined, but with low intensity, in the case of amorphous substrates. For crystalline substrates, however, a strong emission at 1.54 μm in form of a complex band is observed. This result suggests that in these films the erbium oxide could present a different stoichiometry, Er_2O_x , than the oxide Er_2O_3 .

The luminescence results from Er implanted and Er and O coimplanted silicon substrates are shown in figure 4. In Fig 4(a) the CL spectra is presented, whereas in Fig. 4(b) PL spectra are shown. In all implanted samples we observe contributions from the matrix to the luminescence spectra both in crystalline and amorphous substrates. From PL measurements corresponding to excitation with the line 488 nm of the Ar laser, no significant emission has been detected which shows that the green and red bands observed in erbium deposited samples have been quenched during implantation. The CL spectra are also similar to PL spectra, with broad blue band and

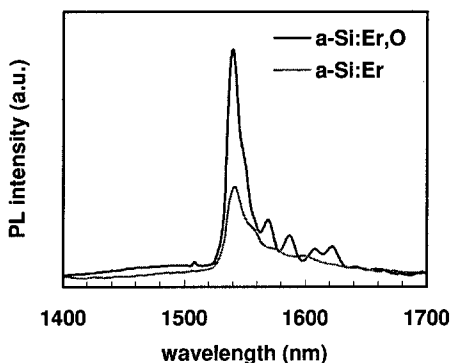


Figure 5. PL spectra at 10 K in the infrared range of implanted and coimplanted samples on amorphous substrates.

only in the case of crystalline substrates a green shoulder is appreciated in the CL spectra. In the infrared range, the strongest emission corresponds to Er and O coimplanted amorphous silicon and subsidiary peaks near 1.54 μm were clearly resolved.

CONCLUSIONS

In summary, luminescence properties of erbium deposited and erbium implanted in different silicon substrates have been studied. In erbium deposited samples the main contribution to the luminescence comes from the erbium oxide overlayer formed at the surface. In the visible range, depending on the excitation source different peaks related to intraionic transitions in erbium ions appear in the luminescence spectra. In the infrared range, the 1.54 μm peak interesting for optoelectronic applications, only dominates in the case of crystalline substrates and as a broad band. A defect related band in 1.2 – 1.3 μm range is also observed in oxygen treated samples. On the other hand, Er and O coimplanted silicon leads to the most efficiently emission of the 1.54 μm peak.

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