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## INFRARED LUMINESCENCE IN Er AND Er+O IMPLANTED 6H SiC

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Photoluminescence in the neighbourhood of  $1.54 \mu\text{m}$  due to the  ${}^4I_{13/2} - {}^4I_{15/2}$  intra- $4f$ -shell transitions of  $\text{Er}^{3+}$  ions in 6H SiC is studied. Effects of oxygen coimplantation is also investigated. No difference in the photoluminescence spectra of Er only and Er+O implanted SiC was found. It is concluded that the emission around  $1.54 \mu\text{m}$  in SiC:Er originates from erbium-oxygen complexes, which are formed as a result of thermal annealing.

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The research interest in erbium doped semiconductors is growing rapidly [1], because  $\text{Er}^{3+}$  ions exhibit luminescence around  $1.54 \mu\text{m}$  originating in the  ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$  electronic transitions within the  $4f$  shell. This wavelength corresponds to the minimum absorption of silica-based fibers, making Er-doped light sources and amplifiers promising for applications in optical telecommunications.

While many Er-doped semiconductors have been studied to date, only a few reveal  $1.54 \mu\text{m}$  emission at 300 K. Favennec et al. [2] have observed that the quenching processes of the  $4f-4f$  photoluminescence (PL) of  $\text{Er}^{3+}$  ions become less effective with the increase of the semiconductor band gap. Attempts to increase the emission efficiency of erbium in Si and GaAs with oxygen codoping were quite successful [3-5], however, the intensity of light from Er+O doped Si and GaAs electroluminescent diodes has been still too low for any practical applications. Once again the relatively narrow band gaps of semiconductors, particularly in case of Si, appeared to be the dominant parameter affecting excitation and relaxation of the  $4f$ -shell. All these observations point to the necessity to use wide band gap semiconductors, like SiC, GaN, AlN, etc., as hosts, to receive the efficient  $4f-4f$

emission of  $\text{Er}^{3+}$  ions at 300 K [1]. This conclusion was confirmed, i.e., by Choyke et al. [6] who showed that the integrated  $4f-4f$  PL intensity of  $\text{Er}^{3+}$  from 1.49  $\mu\text{m}$  to 1.64  $\mu\text{m}$  in different SiC polytypes is almost constant up to about 400 K.

In this paper the results of a study of the  $4f-4f$  PL due to  ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$  electronic transitions of  $\text{Er}^{3+}$  ions around 1.54  $\mu\text{m}$  in 6H SiC are presented. First experimental data on SiC:Er intentionally codoped with oxygen are also shown.

Samples of 6H SiC crystal doped with nitrogen to a concentration of  $10^{18} \text{ cm}^{-3}$  were implanted at 300 K with 800 keV  $\text{Er}^+$  ions. Some samples were implanted with 1 MeV  $\text{Er}^+$  ions at 350°C to avoid amorphization of the surface layer. The Er ion doses were  $10^{13}$ ,  $10^{14}$ , and  $2 \times 10^{15} \text{ cm}^{-2}$ . Oxygen ions were implanted into SiC:Er to doses of  $1-5 \times 10^{15} \text{ cm}^{-2}$  and at an energy of 125 keV to produce the O-impurity profiles overlapping those of erbium.

The implanted samples were annealed in a nitrogen gas flow at temperatures 1000–1500°C for half an hour. PL was excited with a 50 mW power of a 355 nm line of an  $\text{Ar}^+$  laser and measured within the 1.48–1.6  $\mu\text{m}$  spectral range. SiC samples were also analysed using Rutherford backscattering (RBS) to follow the redistribution of the Er impurity profile as a result of high temperature annealing.

The  $4f-4f$  emission of  $\text{Er}^{3+}$  near 1.54  $\mu\text{m}$  could be observed only in samples annealed at 1500°C. Figure 1 shows the  ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ , 1.54  $\mu\text{m}$  PL spectra of 6H SiC at temperatures ranging from 1.4 K to 293 K. At 1.4 K, the dominant line at 1.534  $\mu\text{m}$  is accompanied with a variety of much weaker lines located on the low as well as on the high energy side of the spectra. At elevated temperatures the intensity of the high energy lines increases on the expense of the dominant line at 1.534  $\mu\text{m}$ . It suggests that they are due to the radiative transitions from the excited levels of the  ${}^4I_{13/2}$  multiplet. The integrated PL intensity from 1.5 to 1.6  $\mu\text{m}$  remains constant up to 200 K. At temperatures above 200 K the intensity decreases and at room temperature it is by a factor of 2 lower than at 1.4 K, in some disagreement with the results of Choyke et al. [6] and Yoganathan et al. [7].

As SiC crystals are grown at very high temperature and also annealing temperatures exceed 1500°C, the contamination of SiC samples with oxygen either during the growth or annealing is highly probable. The presence of oxygen would affect the structure of Er emitting centres, like in Si:Er [4], because of the very high chemical affinity of erbium element to oxygen. To check a possible role of oxygen in forming the emitting centres, some SiC samples implanted at 350°C with 1 MeV  $\text{Er}^+$  ions were coimplanted with  $\text{O}^+$  ions and annealed in the same way as samples doped solely with Er. Once again the  $4f-4f$  emission of  $\text{Er}^{3+}$  was observed only after annealing at 1500°C.

The PL spectra at 120 K of Er and Er+O implanted samples are compared in Fig. 2. It is seen that there is no difference in the overall shape of the spectra. This very close similarity has been noticed for all temperatures between 1.4 K and 300 K. It gives strong support to the conclusion that in 6H SiC the dominant Er emitting centres are complexes involving oxygen. Some broadening of the PL lines in the spectrum of SiC:Er:O is most probably due to the higher concentration of residual defects than in SiC:Er.

We have found, using RBS, that the implanted Er atoms segregate at the surface of SiC samples after annealing at temperatures exceeding 1300°C (Fig. 3).

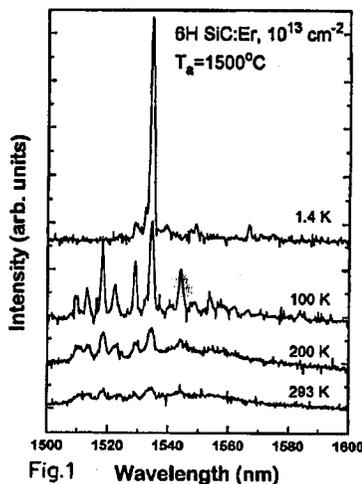


Fig. 1

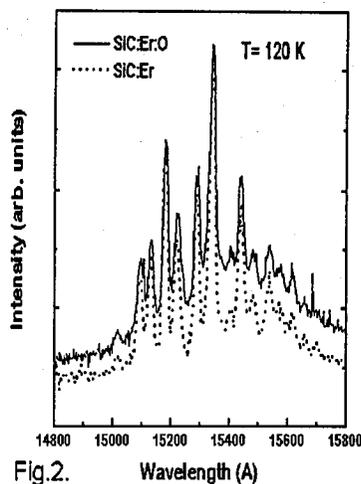
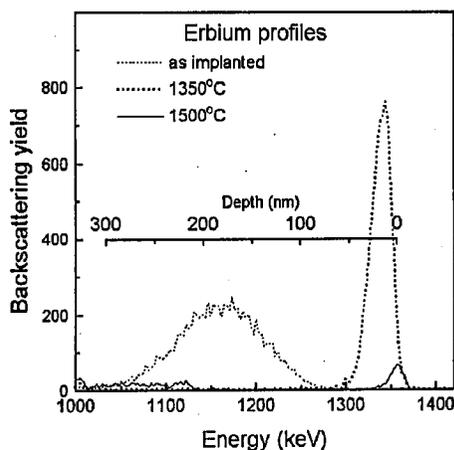


Fig. 2.

Fig. 1. PL spectra of 6H SiC:Er<sup>3+</sup>.

Fig. 2. Comparison of the PL spectra at 120 K of SiC:Er and SiC:Er:O.

Fig. 3. Er impurity profiles in as-implemented and annealed SiC. Er dose —  $2 \times 10^{15} \text{ cm}^{-2}$ .

An analysis shows that approximately 17% of the total number of Er atoms is lost as a result of annealing at 1350°C, most probably due to the formation of some volatile compounds of Er, Si, C and O. Annealing at 1500°C causes more than 95% loss of the number of Er atoms (Fig. 3). As a result, the most intense  $4f-4f$  emission of Er<sup>3+</sup> was observed in samples implanted with a dose of  $10^{13} \text{ cm}^{-2}$ , too low to amorphize the surface layer.

Our data suggest that temperature quenching of the  $4f-4f$  PL of Er<sup>3+</sup> in SiC is more efficient than in previously published results.

There are two major differences in the experimental conditions in this work and in experiments of Choyke et al. [6], and Yoganathan et al. [7]: in our work the maximum annealing temperature was 1500°C, in comparison with 1700°C used by them. Therefore the concentration of residual defects which may act as nonradiative recombination centres is probably much higher in our samples. The second difference is nitrogen donor concentration, being in our crystal higher by a factor of two. According to the observation of Yoganathan et al. [7] more efficient quenching may be expected, i.e., due to Auger processes. This issue has not been studied yet. The spectra presented in Fig. 1 are the same like those presented in papers [6] and [7], in spite of the different implant and annealing conditions, suggesting the same structure of the emitting centres. With respect to our observation they are most probably complexes involving erbium and oxygen atoms.

The experimental data presented here suggest that some Er+O complexes are responsible for the emission at 1.54  $\mu\text{m}$  in SiC:Er. These complexes are formed as a result of annealing at temperatures exceeding 1500°C. RBS analysis shows that most of Er atoms diffuse out of SiC and are lost due to the formation of volatile compounds. It clearly shows that implantation and annealing conditions have to be elaborated to maximize the emission at 1.54  $\mu\text{m}$  from SiC:Er.

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