Light Generation by Er in Si Related Materials

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Er-doped Si is utilized for Si-based light generation in the 1.54 µm region, which is of particular interest for optical data communication. The main problem of Si: Er was so far the huge temperature quenching of the luminescence yield of forward biased diodes. It turned out that properly designed diodes driven in reverse bias avoid this temperature quenching due to different excitation and deexcitation mechanisms. The fabrication and annealing conditions for maximum luminescence yield at room temperature are presented.

1. Introduction

One of the last unsolved problems and challenges in Si technology is the integration of compatible light sources as needed for optical communication within or between chips. Although there are different approaches followed worldwide, there is no obvious solution so far [1]. One of the most promising principles proposed is the light generation by intra-4f transitions in Er, which can be integrated in very different hosts giving always the same characteristic sharp spectra. Additionally, as a consequence of the well shielded 4f-shell, the emission wavelength at 1.54 µm is temperature independent. Since the first diodes fabricated by Ennen [2] *et. al*, the temperature quenching of the luminescence yield in forward bias is still the main problem, although several groups [3], [4] were focused on Si:Er. The intensity of the room temperature emission in forward bias, however, is rather weak and comparable to the dislocation related luminescence.

For reverse bias, a completely different situation occurs. Almost no temperature quenching of the electroluminescence (EL) signal is observed indicating different excitation and deexcitation mechanisms of the Er-ions compared to forward biased diodes [5]. High resolution spectra show, that no additional emission centers are excited in reverse bias. The excitation efficiency of some specific center is very different in the two excitation modes. The efficiency for exciting isolated Er centers with a sharp emission is higher in forward bias, whereas in reverse bias mainly centers are excited with an emission similar to Er-doped silica. At elevated temperatures only the SiO_2 centers are excited, in both forward and reverse biased diodes. Therefore we investigated the preparation conditions for optimum formation of Er-doped SiO_2 centers within the Si host, which lie in a narrow region of Er and O concentrations and specific annealing treatments after ion implantation.

2. Experimental

Erbium was implanted in n-type (100)-CZ-Si with a resistivity of 10 Ωcm at room temperature. The Er-dose at an implantation energy of 300 keV was varied between 10^{12}

and 10^{15} cm^{-2} producing a maximum Er concentration in a depth of 100 nm ranging from 10^{17} to 10^{20} cm^{-3}. The dose and energy of oxygen was adjusted to reach a ten times higher O concentration than Er concentration, which was found to give maximum photoluminescence (PL) yield. In order to remove the implantation damage and to optically activate the dopants, the samples were annealed for 30 min at temperatures between 400 and 1000 °C. Si: Er diodes were implanted through a SiO_2-mask for improved diode characteristics in reverse bias. The p/n-junction in a depth of 100 nm was formed by implantation of Er with a dose of 3×10^{14} cm^{-2} at an energy of 600 keV and with B at 40 keV and a dose of 6×10^{13} cm^{-2}. Ohmic contacts were formed by implantation of B with a dose of 2×10^{14} cm^{-2} at 30 keV at an implantation angle of 80° and with P at 30 keV and a dose of 10^{15} cm^{-2} at the back side. After annealing at 1000 °C Al contacts were evaporated, the light output was enabled through an open area of the front contact.

3. Results and Discussion

At low Er concentrations an increase of the PL intensity with increasing Er concentration is observed for samples annealed at 900 °C. These samples emit atom-like spectra with linewidths of 0.5 nm. Although O co-doping increases the number of optically active Er ions, above an Er concentration of 10^{18} cm^{-3} a decrease of the PL intensity at 77 K for samples annealed at 900 °C is observed.

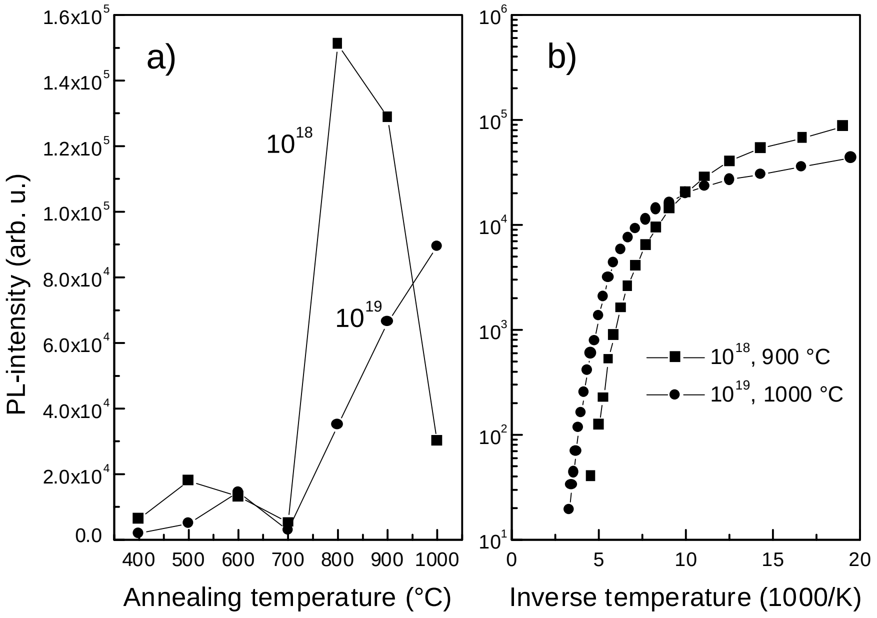

Fig. 1: a) Dependence of the PL-yield on the annealing temperature for Er concentrations of 10^{18} and 10^{19} cm^{-3} at 77 K. b) Temperature quenching of the PL intensity from samples with Er concentrations of 10^{18} and 10^{19} cm^{-3} annealed at 900 °C and 1000 °C.

An annealing treatment at 1000 °C increases the maximum emission yield to an Er concentration of 10^{19} cm^{-3}, accompanied by a change of the emission spectra. Samples annealed at 1000 °C show spectra similar to Er-doped SiO_2, independent of the particular

Er concentration. The conditions for the formation of the SiO_2 center are optimized at an Er concentration of 10^{19} cm^{-3}.

The luminescence intensity of the dominating center is shown in Fig. 1a for an Er-concentration of 10^{18} and 10^{19} cm^{-3}. Between 400 and 600 °C, the emission is rather weak due to implantation induced defects depending on the Er dose. Although the PL intensity of the 1000 °C annealed sample is lower at 77 K than from the 900 °C annealed sample, the onset of the temperature quenching is shifted to higher temperatures, as shown in Fig. 1b, allowing weak room temperature emission of the 1000 °C annealed sample. Different deexcitation energies of 150 meV (Er: 10^{19} cm^{-3}, 1000 °C) and 100 meV (Er: 10^{18} cm^{-3}, 900 °C) indicate different levels in the Si bandgap participating in the energy backtransfer from Er to the host. Such a backtransfer mechanism is responsible for the temperature quenching of 3 orders of magnitude of the luminescence intensity and this amount is nearly independent of the applied sample treatment under PL conditions.

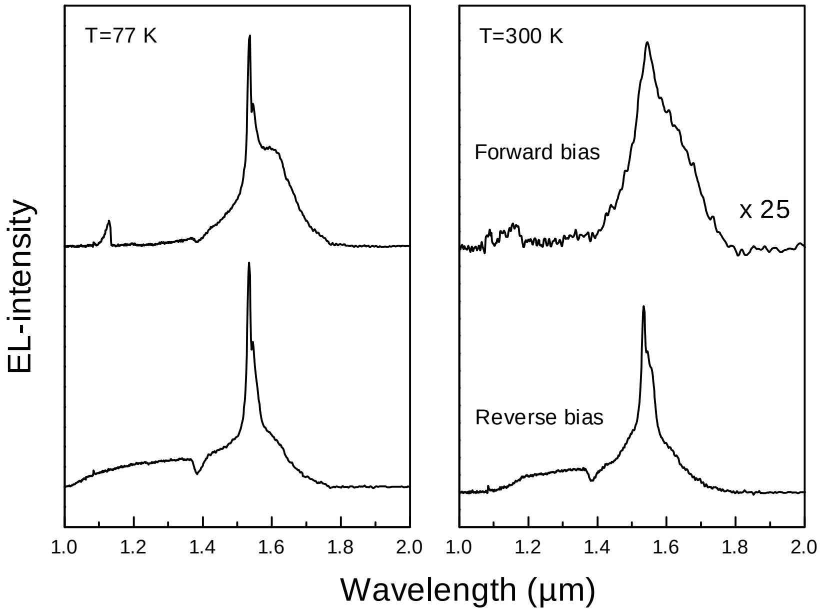

Fig. 2: EL spectra of forward and reverse biased Si:Er LEDs at 77 K and at room temperature. In forward bias, the Er emission is nearly quenched, whereas the EL yield under reverse bias conditions is practically temperature independent.

The electroluminescence (EL) yield of forward biased diodes suffers, similar to PL conditions, from backtransfer induced quenching at higher temperatures. The EL spectra at 77 K indicate that the efficiency in exciting dislocations is higher in forward bias compared to the reverse biased diode, as shown in Fig. 2. The room temperature spectrum of the forward biased diode is dominated by dislocation related luminescence, the Er-related EL is hardly visible.

In reverse bias, however, almost no difference of the EL yield is observed by increasing the temperature up to 300 K. In addition to the Er-4f-emission, a broad background extending up to the visible range is emitted from the reverse biased diode. This background is proposed to originate from scattered hot carriers, which were accelerated within the high electric field in the reverse biased p/n-junction. In contrast to the exciton mediated excitation of forward biased diodes, the Er-ions are impact-excited by hot carriers under reverse bias [6]. The absence of the strong temperature quenching of the EL yield in reverse bias indicates a different deexcitation as compared to forward bias. Either the backtransfer path is passivated in the high electric field or only those Er ions are impact-excited which lie within silica precipitates without efficient energy transfer back to the Si host. The spectra of highly O codoped diodes are similar to Er doped silica, indicating the possibility of Er doped SiO_2 precipitates responsible for room temperature emission.

4. Conclusion

The standard annealing treatment at 900 °C after Er implantation induces the formation of isolated Er centers giving rise for sharp emission at low temperatures. The emission of those centers, however, is quenched already at temperatures below 200 K. Increasing the annealing temperature to 1000 °C removes all sharp lines, the obtained spectra are similar to those of Er doped silica. The EL spectra of Si: Er diodes indicate that mainly those Er doped silica precipitates are excited in reverse bias. Therefore, the conditions for the formation of this particular center were optimized. Strong room temperature EL was obtained from diodes in reverse bias with an Er concentration of 10^{19} cm^{-3} and an annealing treatment at 1000 °C.

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