Light Emission from Er-Doped Si Diodes

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Depending on the incorporation and annealing conditions and the oxygen content, erbium produces a big variety of different centers in silicon and silicon related materials. Isolated centers can be excited by electron-hole pair recombination produced by forward bias in a diode with surprisingly high quantum efficiency below 100 K, but they are strongly quenched at higher temperatures. Another type of spectrum – with a much higher line width (~20 nm) and weak thermal quenching up to 370 K – is obtained after annealing at temperatures above 950 °C. This type of spectrum is identified as being due to Er in $SiO_{2-\delta}$ precipitates. Such centers have much smaller quantum efficiencies for forward bias excitation than for reverse bias. We present a study on the optimization of LED structures based on this type of centers for room temperature operation.

1. Introduction

Silicon is the by far most widely used material in microelectronics: More than 95% of the electronic devices are fabricated from it. There is only one area in which Si cannot be used so far, namely that of light generation, because of fundamental physical reasons [1]. On the other hand there is large interest in the integration of Si-based optoelectronics into Si technology for a substantial number of different applications like inexpensive displays, data communication on very different scales ranging from optical interconnects within a chip, *e.g.*, within a microprocessor as a replacement of one of the metallic interconnect planes or within a smart power electronics chip where galvanic separation of the intelligent and the high power parts are necessary. Optical communication is the main component of high performance long distance communication lines already and will be even more so in the foreseeable future where every household will be connected by an optical fiber for TV programs, internet, etc. Also for the control of complex systems, like cars or factories, the conventional wiring of sensors and actuators will be reduced to a power supply line and an optical bus, the latter steering each device via an intelligent optoelectonic device.

In recent years several concepts have been developed and investigated in order to obtain room temperature light emission from Si [1], [2]. Many of the concepts are based on the destruction of translation invariance by structurization on nm scale, like in porous Si, or a-Si, or quantum dot formation. These concepts, some of which appear very promising, suffer still from one drawback: In order to achieve emission at a particular wavelength, the dimensions must be kept very precisely which up to now is not possible. An alternative that has been proposed for the optical communication at 1.5 µm is based on optical transitions within the 4f shell of Er in various hosts including Si [3], [4]. Recently, the achievement of light emitting diodes working at 1.54 µm has been reported [4]. In this report, we describe our progress in improving the output of such devices.

2. Luminescence excitation and quenching

We introduce Er into Si by ion implantation at energies of 300 keV and above. Because of the resulting lattice damage the samples are annealed after implantation at temperatures above 900 °C. If the implanted dose exceeds the amorphization limit, a two stage annealing procedure is chosen were the amorphous layer is recrystallized by annealing at 600 °C prior to the 900 °C step. Additional oxygen doping has been proven to have several beneficial effects and as an optimum ratio, we found a factor of 10 times higher O than Er dose where the O implantation is done at an energy that provides overlap with the Er profile. Figure 1 shows typical photoluminescence spectra taken at 77 K for two identically prepared samples, one annealed at 900 °C, the other at 950 °C. The 900 °C sample shows the typical spectra of isolated Er-O complexes which are well defined in their geometrical arrangement and thus they show sharp lines originating from a well defined crystal field [5]. The 950 °C sample, in contrast, shows a rather wide spectrum, indicative of inhomogeneous broadening. This type of spectrum has been identified by us as that of Er in $SiO_{2-\delta}$ precipitates [6]. Such precipitates are formed in oxygen rich material at annealing temperatures above 950 °C.

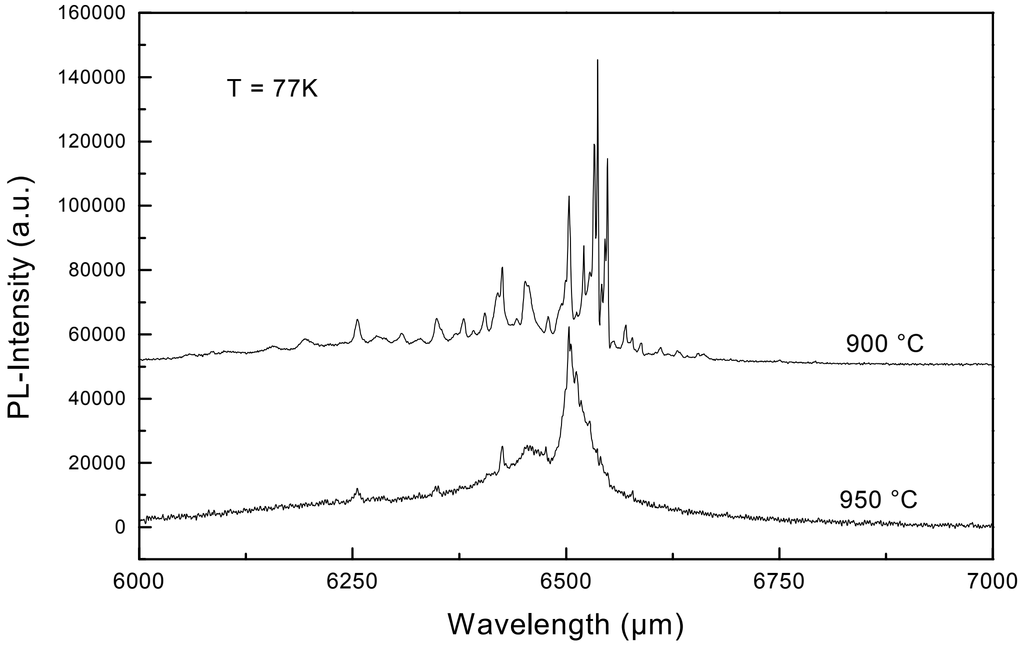

Fig. 1: Photoluminescence spectra of two Er and O implanted samples, one annealed at 900 °C, and one at 950 °C.

The two types of spectra show quite different quenching behavior: the isolated centers exhibit strong quenching already at 150 K whereas the precipitates can be observed up to 300 K. In photo-excitation, electron-hole pairs are excited and these are bound at some oxygen related defect level that acts as a "co-activator". Finally the energy is transferred from the excited co-activator to the Er 4f shell where it causes the Er excitation. Finally, the Er relaxes to its ground state emitting a photon in the 1.5 µm band. The same type of mechanism is envisioned also for the forward bias excitation in a light emitting diode built from Si:Er. In Fig. 2, the quenching behavior is shown for photo- and electro-luminescence, the latter of diodes described below.

In Fig. 2 the temperature dependent luminescence intensity is given The quenching of the photoluminescence is ascribed to two processes: (i) back-transfer of the Er excitation to the coactivator and (ii) Auger transfer to free carriers [4]. Both processes are effective in forward biased diodes but they can be suppressed under reverse bias excitation as can be seen in Fig. 2. There the excitation is achieved by hot electrons transferring their kinetic energy to the Er 4f shell. Under reverse bias, the free carriers concentration is much lower in the junction and therefore the Auger process is ineffective. The back-transfer process is also suppressed, most likely because of smaller coupling of the 4f shell to coactivators (which are not needed here anyway) [6].

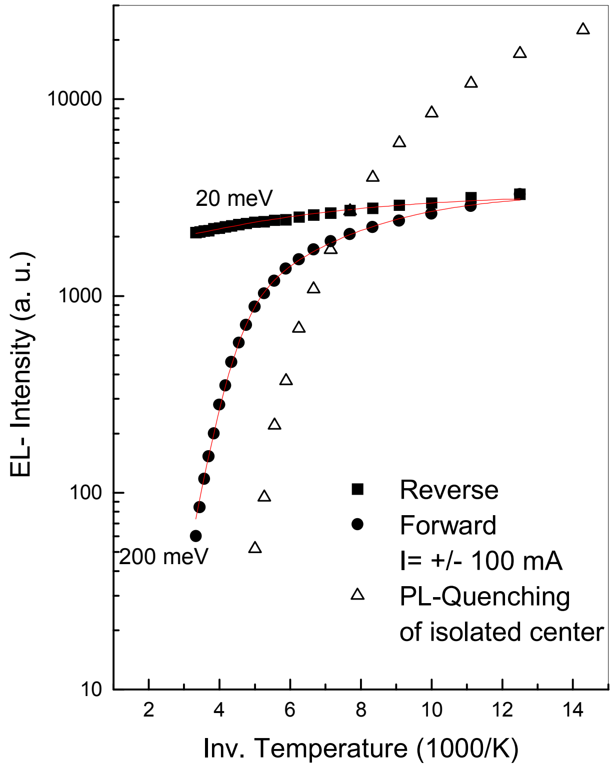

Fig. 2: Luminescence intensities of Si:Er for the isolated centers (triangles, photo- and forward bias give the same results) and for precipitates with forward bias (dots) and reverse bias (squares) excitation.

The quenching behavior shown in Fig. 2 clearly shows that room temperature emission can be achieved only on diodes containing precipitates under reverse bias excitation. Therefore we have concentrated in the following on the optimization of the precipitate luminescence excited by hot electrons.

3. LED design

There are two quantities to be optimized: (i) the size distribution of the precipitates and (ii) the volume in the diode in which precipitates are met by hot electrons. The first aim can be achieved by variation of the implantation doses and energies, the annealing procedures. Figure 3 shows typical results demonstrating that pre-annealing is of minor importance.

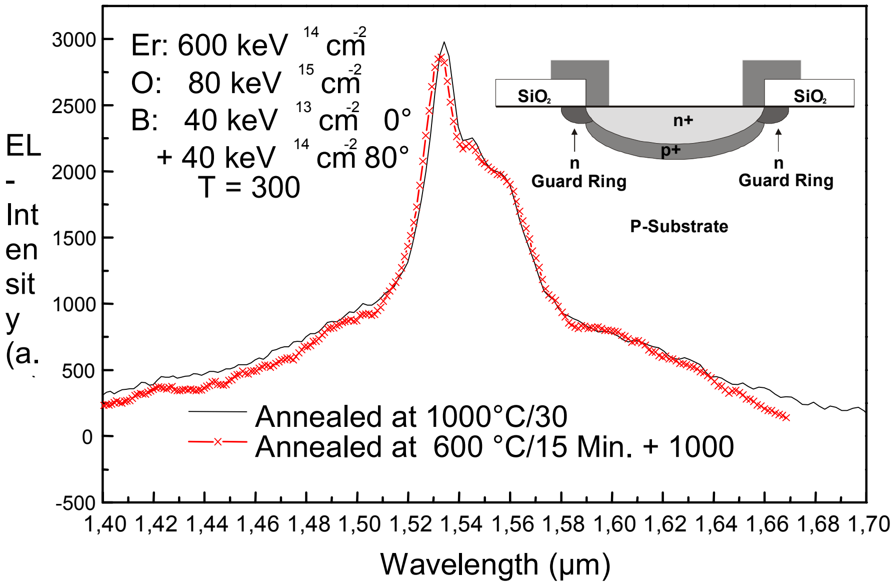

Fig. 3: Electroluminescence of two diodes operated at 300 K under reverse bias. The diodes were produced by different annealing procedures. The inset shows the diode structure schematically.

Finally, in order to optimize the excitation volume in the p-n junction we tried to design diodes for avalanche rather than tunneling breakdown. This can be achieved by a smaller doping gradient. The latter requires, however, careful design of the implantation profiles (Er is electrically active to some extent as a donor) and of the diode structure. In order to avoid breakdown at the edges, a guard ring design was used that improved both the I-V characteristics and the 1.5 µm emission at room temperature (see inset of Fig.3).

Acknowledgements

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