# Erbium in $SiO_x$ Environment: Ways to Improve the 1.54 µm Emission

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Si:(Er,O) based light emitting diodes were developed and fabricated, emitting at room temperature in breakdown regime at a wavelength of 1,54 µm. We investigated doping profiles and electrical activity in order to optimize our structures for room temperature luminescence. We present data from SIMS and Hall effect investigations, which demonstrate significant deviations from TRIM simulations of the implantation profiles and the hitherto assumed electrical activity of Er in such environment.

## 1. Introduction

It is known that electroluminescence (EL) of erbium in silicon can be achieved by impact excitation with hot electrons injected in a reverse biased (r.b.) diode. Obviously, various Er centers can be excited in the impact excitation process. They can be distinguished by their characteristic luminescence line patterns. It was found, however, that the centers responsible for room temperature luminescence are contained in $SiO_x$ precipitates. Their dominance at high temperature EL becomes apparent in the transformation of the emission spectra from the characteristic sharp line spectra to a less structured band with 20 nm width. The incorporation of Er in $SiO_x$ clusters is achieved by Er and O implantation and subsequent annealing above 950 °C. The latter is necessary in order to initiate the formation of $SiO_2$:Er precipitates.

Er electroluminescence at room temperature can be realized in diodes operating both in the tunneling and in the avalanche regimes. In tunneling diodes, the Er excitation occurs only at a very small volume, within 15 nm of the depletion edge [1]. Making use of an avalanche process allows us to increase the excitation volume considerably but it is still limited to the space charge region of a pn-junction only.

The fabrication of these diode structures requires accurate control of doping gradients and thus knowledge of the electrical activity and the distribution of the implanted dopants. We present data from SIMS and Hall effect investigations, which demonstrate significant deviations from TRIM simulations of the implantation profiles and the hitherto assumed electrical activity of Er in such environment.

## 2. Design and Realization of p-n Junctions

An important property of the Er centers is their electrical activity which has to be taken into account in the design of the diodes. For isolated centers a large portion can be electrically active. Electrical activity has been seen also for $SiO_2$ precipitates. Therefore we investigated the electrical activity of our $SiO_{2-\delta}$:Er precipitates by means of Hall effect measurements on samples prepared by implanting Er into high resistivity Si substrates (Fig. 1). As a result, we estimate an electrical activity of less than 3% for this sample.

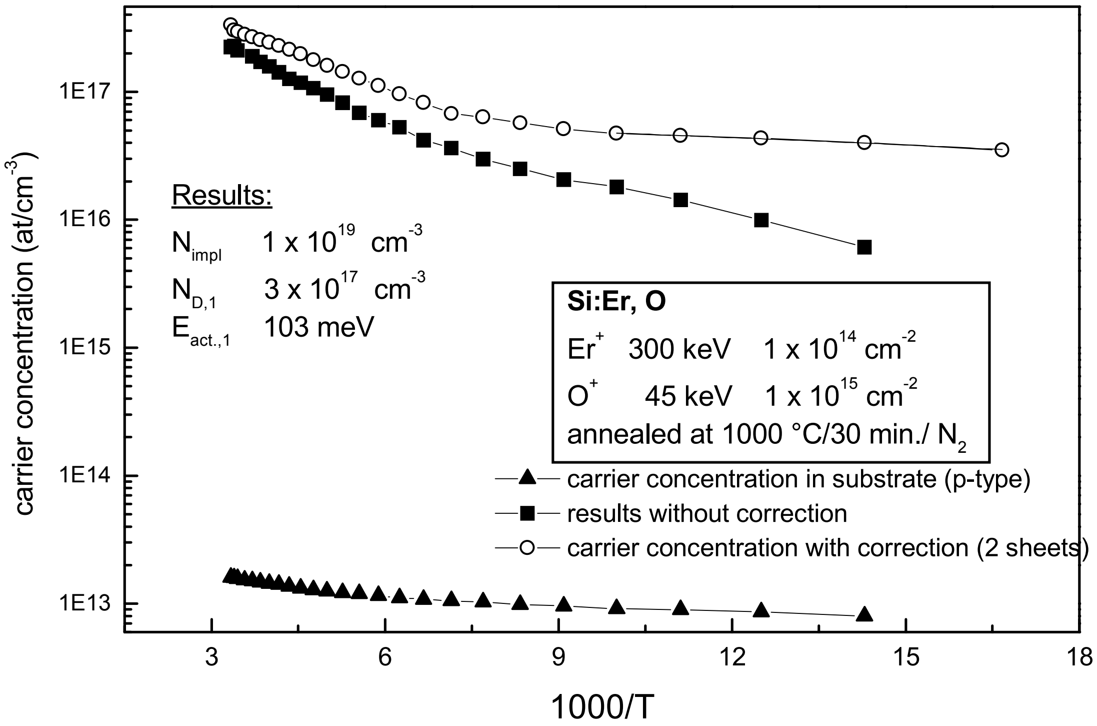
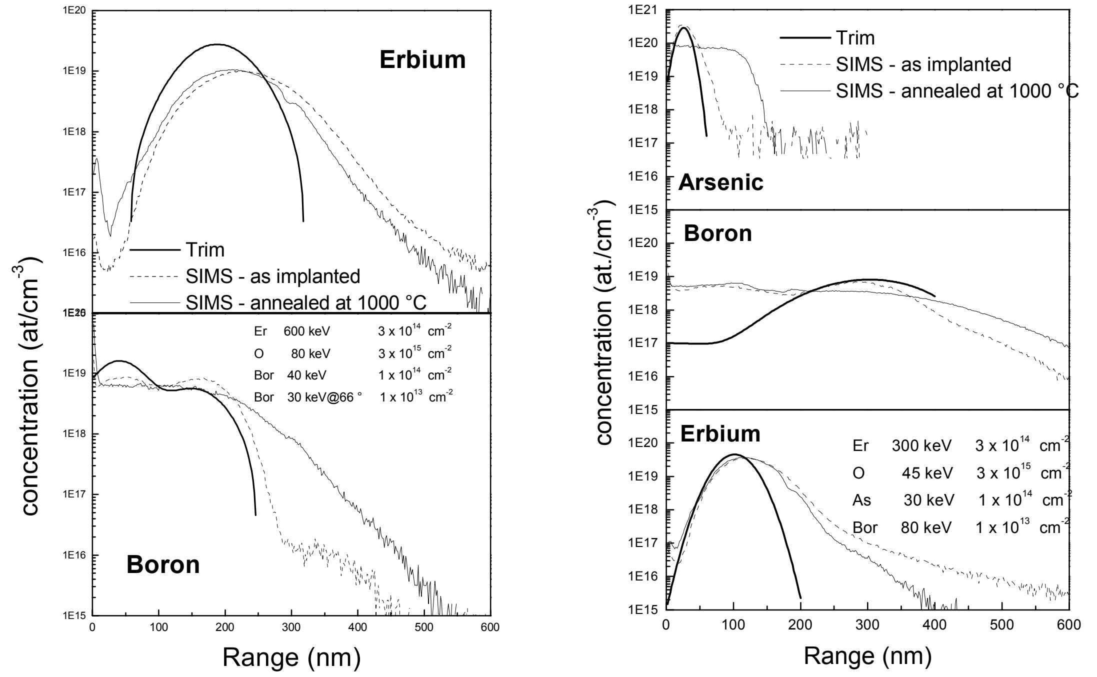


Fig 1: Arrhenius plot of the electron concentration measured by Hall effect on a sample of p-Si (ρ > 1000 Ω·cm) implanted with Er+O. For the evaluation of the electron concentration a two sheet model was applied in order to correct for the substrate contribution.

The early successful attempts to obtain EL from *r.b.* p-n junctions were performed on diodes with large doping gradients that showed tunneling breakdown [2] – [4]. The problem with this kind of excitation is the short ballistic range of electrons with a energy of more than the 0.8 eV that are required to excite Er [1]. That way only a very small fraction of the incorporated Er can be excited and the total efficiency of such a device would be rather limited. An avalanche breakdown is expected to offer considerable advantages as it occurs in a much wider volume.

The most relevant parameter deciding about the two types of breakdown is the electric field strength which in turn is ruled by the doping gradient. According to Sze, for Si at room temperature the doping gradient must not exceed a value of $10^{23}$ $cm^{-4}$ if avalanche conditions are desired [5]. This, together with the requirement of a large concentration of optically active Er centers in the avalanche region needs careful design of the implantation parameters and knowledge of the resulting implantation profiles.



(a) (b)

Fig. 2: Implantation profiles of Er and B into n-Si (a) and Er, As and B into p-Si (b) substrates.

Comparison of the implantation profiles measured by SIMS and those simulated by the TRIM code led to a surprise: the profiles of Er are substantially deeper than expected (see Fig. 2). Since the same discrepancy was found for Er implanted into amorphous $SiO_2$ [6], channeling effects can be excluded. Because of the low electrical activity of Er under the present preparation conditions this discrepancy may not be crucial for the electronic properties of a diode, but it is important for the optimal spatial overlap of the Er profile and the avalanche excitation volume. More important, however, is the fact that the shallow dopants also start to diffuse substantially at the annealing temperature of 1000 °C (s. Fig. 2). This diffusion has a strong influence on the doping gradient at the p-n junction and therefore realistic profiles have to be taken into account in the design of an avalanche breakdown diode.

Another important design consideration concerns the question of homogeneity of the field strength and thus of the generation rate in the avalanche regime across the diode cross section. It is well known that in an avalanche diode the field strength close to the edge of the contact may exceed the average field strength substantially. Consequently avalanche breakdown occurs already at lower voltage and excitation concentrates at the circumference of the diode whereas the center of the diode remains dark. This effect may lead to an early degradation of such a diode. In order to avoid this effect we apply a guard ring structure as it is also applied in the design of avalanche photon detectors.

## 3. Conclusion

At present, the only principle yielding stable emission at room temperature employs impact excitation of the Er in a reverse biased p-n junction. It has been shown that thermal quenching of the luminescence can be avoided by producing a particular type of Er center. This type of center exhibits a single inhomogeneously broadened line with two characteristic asymmetrically arranged shoulders. There are several indications for an $SiO_2$-like surrounding of Er in this type of centers. The $SiO_2$:Er centers exhibit also larger excitation cross section for hot electrons than the isolated Er centers. We have shown that in the design of such a diode it is essential to control the doping gradient in order to achieve avalanche rather than tunneling breakdown in the diode. It turns out that TRIM simulations are insufficient to describe the Er implantation profile and either diffusion of the shallow dopants has to be taken into account at the necessary formation temperature for the $SiO_2$:Er clusters of 950 °C or a second implantation and annealing step at lower temperature is necessary. As a result, almost temperature independent emission of 1.54 µm can be achieved in a diode that can be produced in a way compatible with present Si technology. The shortcoming of this type of device is the rather low yield ($mW/cm^2$), the low efficiency ($10^{-4}$) and the relatively big linewidth (20 nm).

## Acknowledgements

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