Erbium in Silicon: Design Concepts and Luminescence Enhancement by Hydrogenation

G. Kocher[1], W. Jantsch[1], L. Palmetshofer[1], A. Ulyashin[2], Margarita Stepikhova[3]

[1]Univ. of Linz, Altenbergerstr. 69, A-4040 Linz, Austria
[2]Univ. of Hagen, Haldener Str. 182, PO Box 940, D-58084 Hagen, Germany
[3]Russ. Academy of Science, Nishny Novgorod, Russia

Si:(Er,O) based light emitting diodes were developed and fabricated, emitting at room temperature in the breakdown regime at a wavelength of 1.54 µm. By adjusting the diode design we were able to increase the electroluminescence (EL) intensity by one order of magnitude. We also investigated codoping with hydrogen in order to increase the luminescence. With this we achieved an increase of the luminescence intensity at temperatures below 150 K by a factor of five.

1. Introduction

Ever since the first report on the observation of 1.5 µm photoluminescence (PL) due to Er in Si by Ennen and Schneider [1], [2] erbium doped semiconductors have attracted a lot of attention as it seemed to indicate a way to obtain temperature stable emission at a well defined wavelength [3]. Room temperature electroluminescence at 1.54 µm in Si diodes due to intra-atomic transitions of erbium is achieved via excitation of SiO_2:Er clusters by hot electrons injected in a reverse biased diode. Impact excitation of erbium and thus electroluminescence can be achieved in tunneling diodes, although at very small excitation volume, which would cover only a small fraction of a wave guide. Making use of an avalanche process allows to increase the excitation volume considerably [4]. This requires accurate control of doping gradients and thus knowledge of the electrical activity and the distribution of the implanted dopants. With 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, we were able to optimize the parameters for the design of our diodes and to increase the intensity of the room temperature EL by an order of magnitude.

In order to further increase the intensity of the luminescence, we used additional codoping of hydrogen in our samples. Hydrogen plasma treatment is widely used in semiconductor technology as a technological step in production. Hydrogen is known to enhance O_i diffusion and O_i precipitation in silicon [5]. Both characteristics should have a positive influence on Er-related luminescence in c-Si. Studies of the excitation dependence on power indicate a higher concentration of optically active Er in the hydrogenated samples. All samples showed a large enhancement of the luminescence by at least a factor of 5. The most prominent change appeared at annealing temperatures > 600 °C, with the appearance of the so-called "cubic center" which was previously observed only in samples with a low dose of Er and O [6].

2. Design Parameters for Diodes

An important property entering design considerations is of course the electrical activity of the Er centers. We investigated our SiO_x:Er precipitates by means of Hall effect measurements. The measurements were performed on samples prepared by implanting Er and O into high resistivity Si substrates. Whereas for isolated centers a large portion can be electrically active, for our sample we found that the sheet concentration of the free carriers is only a few percent of that of the incorporated Er ions after annealing.

In order to gain information on the actual structure of our diodes we applied SIMS for two different structures at various annealing temperatures. It turned out that the experimental values for the mean projected range Rp are about 20% larger than values obtained by simulation [7]. The experimental values for the range straggling, Rp, are almost twice as large as TRIM table values. The same discrepancy was found for Er implanted into amorphous SiO_2, so channeling effects appear unlikely as an explanation.

Due to the low electrical activity of Er under the preparation conditions used, this difference would not significantly change the electronic properties of a diode but it may crucially impair the optimal spatial overlap of the Er profile with the avalanche excitation volume.

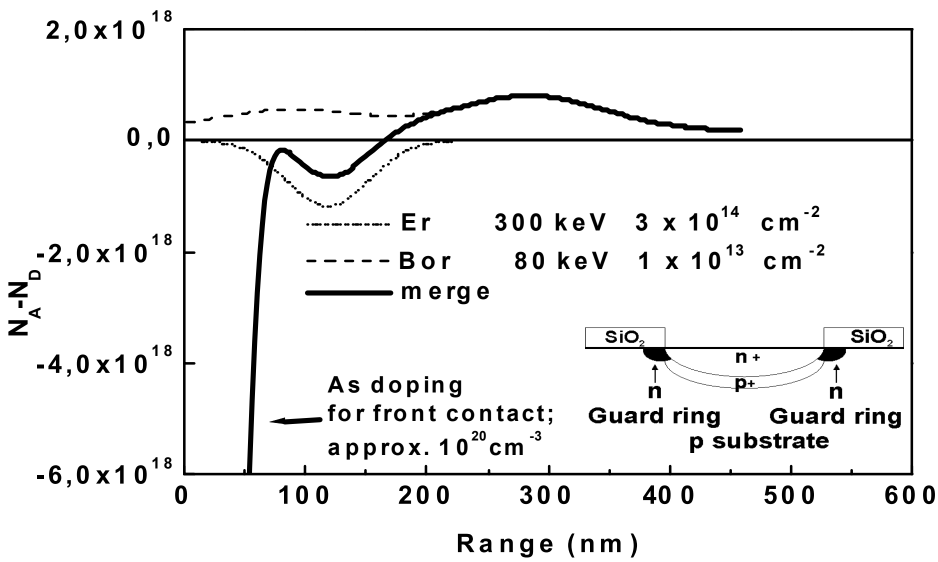

Fig. 1: Simulated doping profiles according to SIMS results. The insert shows a typical structure for an avalanche diode.

To adjust the doping gradient according to these results, we fitted the SIMS data with a Gaussian function containing exponential correction terms. A schematic diagram for our diode structure is shown as insert in Fig 1. Although the implantation energies stayed the same, the implantation doses and annealing procedure had to be changed according to the SIMS results. In order to avoid excessive diffusion of shallow dopants, a two step implantation and annealing procedure was adopted. After implanting Er and O and subsequent annealing at 1000 °C for 30 min, additional lithography and annealing steps were inserted for arsenic and boron, which provide the contact- and background doping respectively. To keep the diffusion low, the annealing temperature was lowered to 400 °C.

With the structure shown in Fig. 1 we were able to get room temperature luminescence of Er for excitation in reverse bias. The intensity of the luminescence increased at least one order of magnitude compared to a similar diode structure designed using TRIM code simulations only.

3. Hydrogenation

After implanting Er and O in c-Si ($1x10^{14}$ cm^{-2} / $1x10^{15}$ cm^{-2}, respectively) two sets of samples – one annealed at 600 °C/15 min. in N_2 atmosphere, the other "as implanted" – were hydrogenated using a plasma treatment for 1 hour at 260 °C. The samples were then annealed at various temperatures in the range of 450 °C to 1000 °C.

All samples showed large enhancement of the photoluminescence by at least a factor of 5. Comparing the intensity with non-hydrogenated samples, the hydrogenated samples show higher intensities at low annealing temperatures (400 – 450°C), then the intensity decreases, reaches a minimum at 600 °C and starts to rise again. It is much higher than in the non-hydrogenated samples at 800 and 900 °C. At annealing temperatures higher than 700 °C the so called "cubic center", which was previously observed only in samples with low concentration of Er and O, started to become more and more visible. It was most dominant in samples annealed at 900 °C, whereas the previously observed center for high Er concentrations and similar annealing conditions due to Er-O complexes [6] was completely missing.

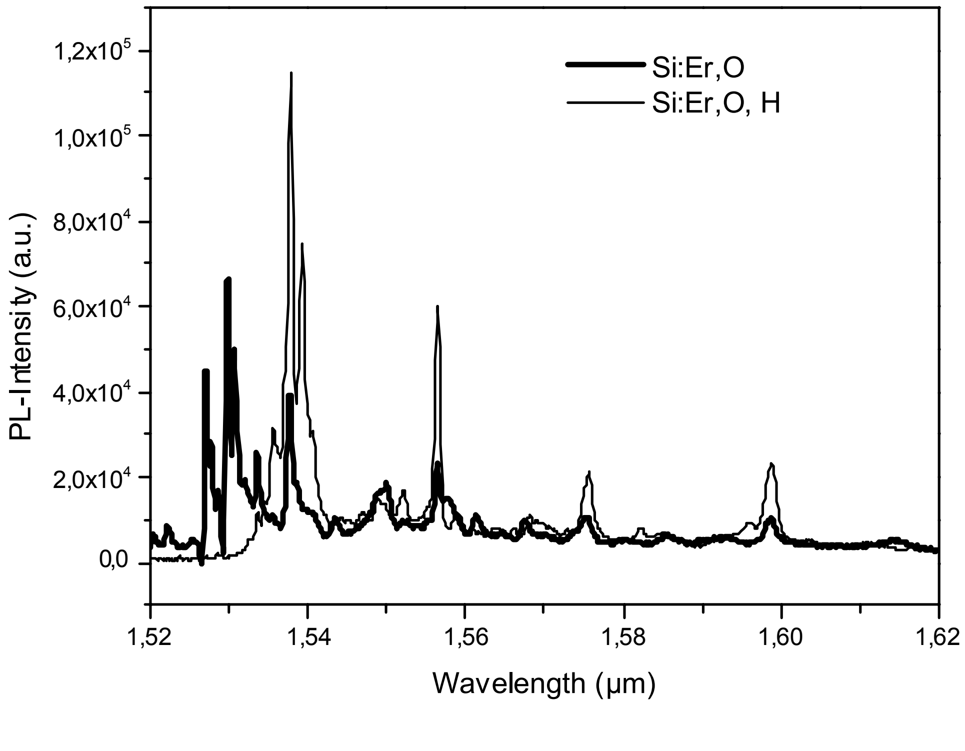

Fig. 2: Comparison of PL-spectra of Si:Er,O with (thin line) and without (thick line) hydrogenation. Both samples were implanted with the same doses of Er and oxygen treated with the same annealing procedure. The intensity is more than 5 times bigger in samples additionally doped with hydrogen.

4. Conclusion

Accurate control of doping gradients and thus knowledge of the electrical activity and the distribution of the implanted dopants are essential for the location and impurity gradient of the pn-junction. Careful consideration has thus to be put into diode design in order to achieve avalanche rather than tunneling breakdown in a diode. TRIM simulations turn out to be insufficient. After adjusting the diode design according to SIMS results the intensity of the electroluminescence at room temperature increased by at least one order of magnitude.

Hydrogenation of Si:Er, O leads to an increase in luminescence yield. We found that hydrogen enhances the solubility of Er in silicon and also suppresses the formation of other Er-O complexes as well as that of other, non-radiative Er centers, leading to an increase of luminescence yield at temperatures below 150 K. This is supported by power dependence studies which also indicate a higher concentration of optically active Er in the hydrogenated samples.

Acknowledgements

FWF, BMWV

References

[1] H. Ennen, J. Schneider, G. Pomrenke, A. Axmann, *Appl. Phys. Lett.* 43 (1983) 943

[2] H. Ennen, G. Pomrenke, A. Axmann, K. Eisele, W. Haydl, J. Schneider, *Appl. Phys. Lett.* 46 (1985) 381

[3] S. Coffa, G. Franzo, F. Priolo, *MRS Bulletin 23* (1998) 25

[4] "Erbium in SiOx Environment: Ways to Improve the 1.54 µm Emission", G. Kocher, H. Przybylinska, M. Stepikhova, L. Palmetshofer and W. Jantsch*, Physica B*, in print

[5] R. Job, A. G. Ulyashin, W. R. Fahnrer, A. I. Ivanov, L. Palmetshofer, *Appl.Phys. A* 72 (2001) 325

[6] H. Przbylinska, et.al. *Phys.Rev.B* 54 (4) (1996) 2532

[7] L. Palmetshofer, M. Gritsch, G. Hobler, , *Mat. Sci. Eng.*B B81 83 (2001) 83