# Erbium Doped Waveguides in SOI Layers

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Waveguides were made in Silicon-on-insulator layers by photolithography. In order to test quality and gain we made use of the recently found increased solubility of Erbium in silicon in the presence of hydrogen. Applying the variable stripe length method we estimate a net gain of 32 $cm^{-1}$ at 10 K.

## Introduction

Among the various attempts to obtain light emission from Si, optical doping with rare earth elements like Er has been particularly fruitful at first glance as this approach is compatible with standard Si technology. Light emitting diodes emitting at a wavelength of 1.54 µm at room temperature have been successfully made. The low efficiency, however, and the slow response of such diodes limit their use to a few special applications. The main hope, namely application in optical communication systems, appears unrealistic unless laser action can be achieved.

The main problem with a possible Si:Er laser is the low gain which is a consequence of the rather low concentration of optically active Er and the small excitation cross section. Therefore any such concept requires low loss cavities. We tried to build waveguide structures involving a SiGe layer as active medium where the cladding of the active layer by Si (lower refractive index) was used to form a waveguide. It turned out however, that in SiGe structures the quenching of the Er luminescence sets in already at still lower temperatures and therefore the acceptable Ge content was lowered which reduces, however, the index contrast and thus the quality of the resonator.

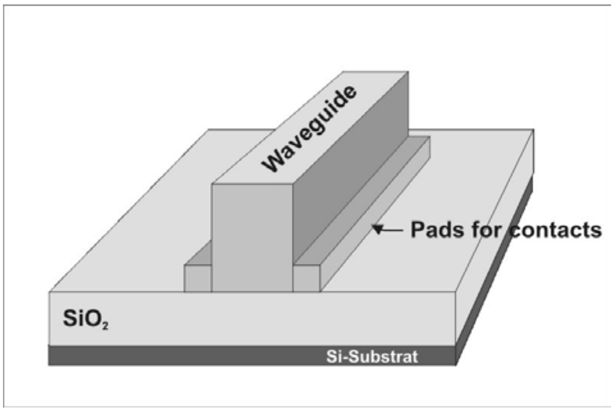


Fig. 1: Waveguide structure formed from SOI material; the dimensions are not to scale. The structure can be used for PL and EL measurements. For EL, electric contacts are put on top of the waveguide and on the pads on either side.

Therefore we recently turned to Si-on-insulator as waveguide material; thin Si-wafers bonded to an oxidized layer as available from SOITEC. In order to test waveguide structures made from this material, we first optimized photo-luminescence in that material and built waveguide structures containing Er in a p-n avalanche diode. Normally, diodes designed for room temperature operation make use of $SiO_{2-\delta}$:Er precipitates since only these allow to avoid excessive thermal quenching. We prepared different samples, however, in which Er is incorporated as isolated cubic center at high concentrations for testing purposes. The isolated cubic center exhibits very high quantum efficiency (up to 12% were reported in the literature) at temperatures up to 80 K. The reasoning behind using such centers was that they should permit to study waveguides and laser cavities, to optimize those and transfer the information gained to devices making use of the $SiO_{2-\delta}$:Er precipitates in the future.

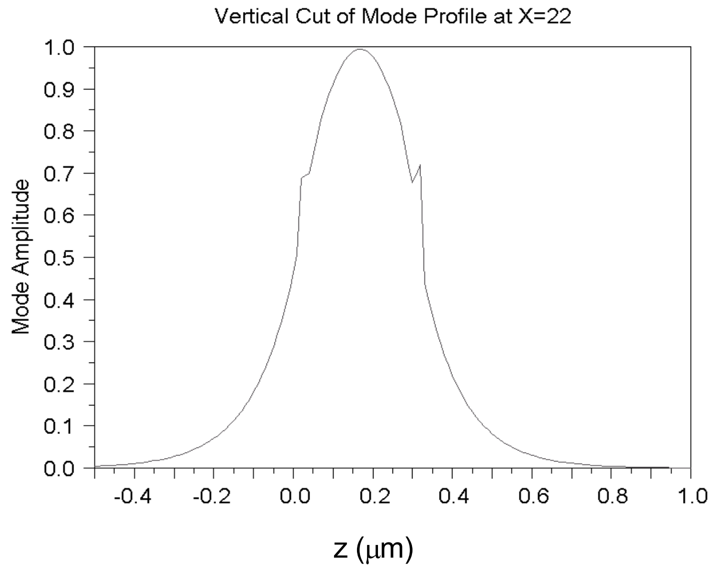


Fig. 2: Simulation of mode propagation in TE polarization in the waveguide structure shown in Fig. 1. Here "z" designates the vertical direction of the waveguide (x-axis: propagation direction).

In order to increase the concentration of optically active isolated Er we made use of a feature discovered in the course of this work. In order to lower the relatively high temperature necessary for the formation of $SiO_{2-\delta}$:Er precipitates, we added hydrogen to our samples. Hydrogenation in Si is known to increase the diffusion of oxygen. We thus anticipated formation of precipitates already at lower temperatures. We found the opposite result: After annealing samples containing Er, O and H, erbium was found to produce the sharp spectra of the isolated interstitial Er-center at the Td site. Apparently, H mobilizes the O to an extent that it is driven out of the sample at temperatures well below 900 °C already. At this temperature, the Er is still immobile and thus neither oxide- nor Er-precipitates are formed. Consequently, the concentration of the optically active cubic Er centers can be increased by an order of magnitude. This type of center is the most promising candidate for gain: its concentration is high, it has high quantum efficiency and the linewidth of its 5 luminescence lines is less than 1 nm in contrast to that of the precipitates which is at least 20 times higher.

## Experimental

Waveguides were made according to the scheme of Fig. 1, including a horizontal p-n junction and a top contact and two side contacts. The Er implantation profile was designed to include the full Si-layer thickness of 340 nm. In order to achieve recrystallization it was necessary to mask the side parts of the sample during implantation. Later on, these side parts are used for contacts for electroluminescent devices. After recrystallization, these waveguides produce photoluminescence at temperatures up to 150 K. The simulated mode distribution is shown in Fig. 2.

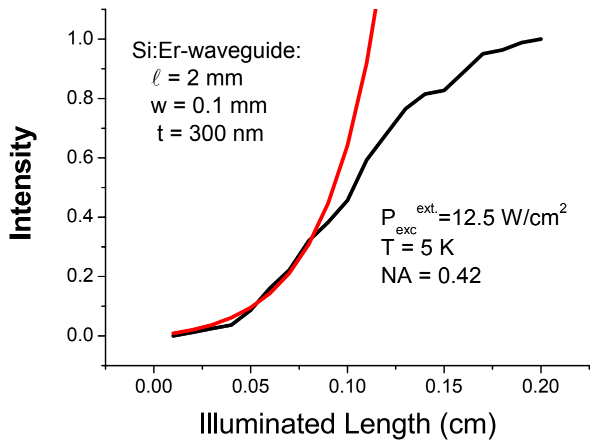


Fig. 3: Determination of the net gain of an optically pumped (λ = 514 nm) Si:Er waveguide. In this sample, Er is incorporated as cubic interstitials making use of the hydrogen co-doping method. Black curve: experimental, red curve: model. As a result a net gain of 35 $cm^{-1}$ is estimated.

In order to measure the gain a defined part of the sample is optically pumped ("Variable strip length"- VSL method). In VSL, the laser light used for excitation is focused into a rectangular shape, usually by a cylindrical lens. The elongated spot of the beam starts at the facet of the sample. The illumination of the sample is regulated by a moveable shield, which can provide controlled coverage of the specimen. The detection optics collects light emitted from the facet of the sample perpendicular to the incident laser beam. If population inversion is achieved, the illuminated (excited) stripe of the waveguide acts as a single-pass amplifier for PL photons travelling inside the stripe. The net gain is defined as a relative change of detected intensity $dI$ along the stripe. When the stripe length $x$ is increased by a length $dx$, the detected intensity $dI$ changes as well. The increment of this change in intensity $dI_{tot}$ is a sum of a gain amplification of the incoming light and of the spontaneous emission $I_{sp}(\lambda)$ from a part $dx$ of the waveguide. Solving this differential equation for the total length of the waveguide $l$, we get the "classical" VSL equation:

$$I_{tot}(\ell,\lambda)=\frac{I_{sp}(\lambda)}{G(\lambda)}\left\{\exp\left[G(\lambda)\cdot\ell\right]-1\right\} \qquad (1)$$

where the net optical gain $G(\lambda)$ is given by

$$G(\lambda)=g(\lambda)-\alpha \qquad (2)$$

with $\alpha$ representing the losses and $g(\lambda)$ as a gain coefficient or negative absorption coefficient. The results are supposed to clarify the origin of losses occurring in the waveguide and achievable gain under optimum conditions before an attempt is made using the precipitate centers. Results are given in Fig. 3.

The simple model yields a net gain of about 32 $cm^{-1}$, a value that appears very promising. A more detailed modeling is developed at present which should allow understanding also the deviations from the standard model seen at illumination lengths exceeding 0.8 mm. Such structures will allow us to test and to optimize waveguide and laser structures at low temperatures.

## Conclusion

Waveguides were made in Silicon-on-insulator layers by photolithography. In order to test the quality and gain we made use of the recently found increased solubility of interstitial (”cubic”) Erbium in silicon in the presence of hydrogen. The concentration of the optically active cubic Er centers can be increased by an order of magnitude. This type of center is the most promising candidate for gain: its concentration is high, it has high quantum efficiency and the linewidth of its 5 luminescence lines is less than 1 nm in contrast to that of the precipitates which is at least 20 times higher. VSLM was applied on these structures, leading to an estimated net gain of 32 cm-1 at 10 K.

## Acknowledgements

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## References

[1] G. Kocher-Oberlehner, W. Jantsch, A. Ulyashin, L. Palmetshofer: “On the Influence of hydrogen on the erbium related luminescence in Si”, Appl. Phys. Lett. **83**, 623 (2003)