

Erbium-Doped Silicon Based LEDs

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Abstract—A preliminary effort in Electroluminescent (EL) device fabrication using erbium-doped silicon based materials at Rochester Institute of Technology's Microelectronic Engineering Fabrication Facilities was attempted in this study. Field-assisted infiltration would be used to incorporate erbium ions into a porous silicon film. The film would be oxidized and anneal to form an erbium and oxygen rich active layer suitable for light emission. Different erbium anneals (900°C to 1100°C) would be executed and results would be thoroughly examined for any differences in the electrical or luminescent characteristics. No functional devices were fabricated, but proof of erbium activation and excitation was achieved through detection of photoluminescence (PL) in the 1100°C samples.

1. INTRODUCTION

For years, scientists have been searching for an integrated approach in producing optoelectronics on silicon chips. Such a tool would allow for further development of important applications, such as chip-to-chip interconnects and silicon based photonics³. There are a number of obstacles in achieving this goal, though, since any radiation source applicable in today's technology would have to be efficient, at a functional wavelength, able to operate in a wide range of temperatures, and still have a suitable frequency response. Since silicon is used for the vast majority of IC manufacturing, it would be an advantage if the light emitter could be fabricated using silicon process technology. Crystalline silicon by itself (c-Si) is an unsuitable source, mostly because of inefficient emission due to its indirect energy bandgap. As of late, a considerable amount of work has been done to incorporate impurities such as erbium (Er) into silicon-based films. One specific composition of interest, which is examined in this project, is Er-doped porous SiO₂.

Erbium is a rare-earth metal with an atomic number of 68 and an atomic weight of 167.62. When properly inserted into a crystal structure, Er takes a 3+ ionic state. This ion can emit photons at a wavelength of 1.54 μm , a wavelength of particularly strong interest because of its ideal applications in silica based fiber optics. The 1.54 μm

luminescence takes place due to a radiative internal 4f transition and is practically independent of the host crystal.¹ There are reasons why Er-doping directly into crystalline silicon based materials will not work. Specifically, the low solid solubility of Er in Si ($\sim 10^{16}/\text{cm}^3$ at 1300°C) prevents the incorporation of acceptable Er concentrations. Even with the use of ion implantation, Er incorporation at concentrations $\sim 5 \times 10^{17}$ is prevented by the onset of Er precipitation.² For practical applications higher erbium concentrations (at least $10^{19}/\text{cm}^3$) should be engineered. One way to inhibit Er segregation is through introduction of oxygen. Er-O structures have higher solubility limits than erbium itself, and exist in a form that promotes the excitation of the Er³⁺ ion. Two methods of excitation have been identified.

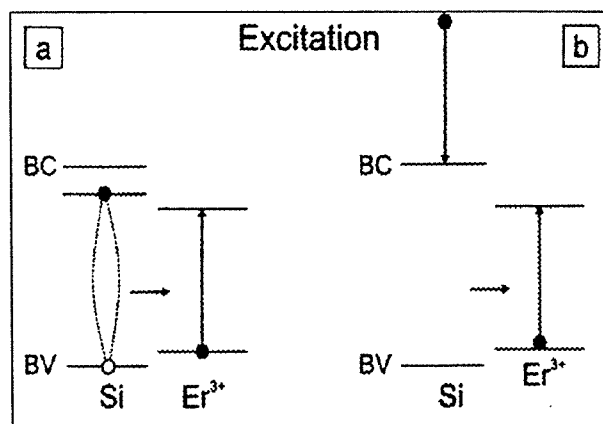


Figure 1: Methods of Er excitation in Si:O structure

The energy transfer shown as method A is based on electron-hole recombination. As a result of Coulomb interaction the energy released due to electron-hole recombination is transferred to the electron-vibrating ion system. The local vibration excitation relaxes very quickly due to decay into lattice phonons, thereby exciting the Erbium ion.¹ Method B is a schematic representation of hot-carrier impact excitation. The formation of hot carriers relies on the existence of high electric fields within an active Er-rich layer. With this knowledge, a material will be engineered with a high concentration of erbium and the ability to transport carriers. Higher fields within the

sample will enhance impact excitation. If these goals are achieved, the sample should emit measurable amounts of electroluminescence (EL). In this case EL is radiation that is emitted when the when Er ions are excited by methods associated with electric fields and current flow. Another way to detect the erbium is through Photoluminescence (PL). PL is any radiation emitted when the when Er ions are excited by an external radiation source (such as an Ar laser), with no current flowing through the device. This method is not

2. EXPERIMENTAL PROCEDURES

The silicon based LEDs were fabricated on p⁺ silicon substrates and consist of multiple thin layers as shown in Figure 2. The structure includes a top electrode, a backside aluminum contact, an active layer, and a selectively doped n-type poly-silicon layer. Note that emission will occur in the active layer and travel through the poly-silicon. The active layer is abbreviated OPNSi, for oxide passivated nanocrystalline silicon. The OPNSi is a glass that is rich in silicon and allows for current flow.

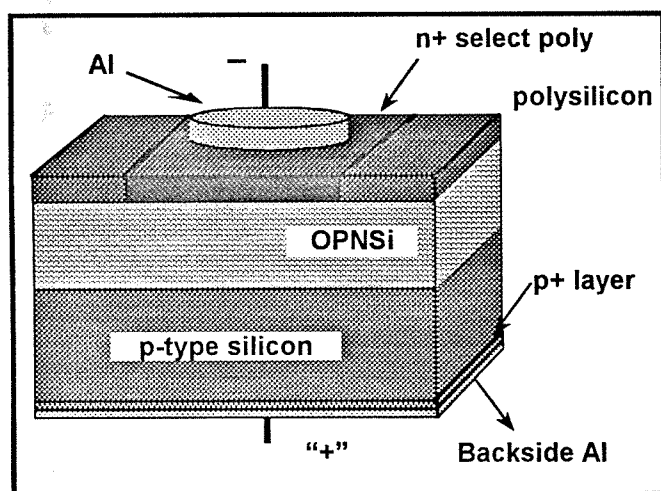


Figure 2: LED Device Cross Section

A. Device Fabrication

Bulk-film LEDs were fabricated from the OPNSi active layer in three basic process stages; substrate preparation, active layer formation, and contact formation. Substrate preparation involved backside doping of a p-type wafer, then a 950°C steam oxidation for 3.5 hours, growing approximately 5000Å of SiO₂. This oxide is removed, and followed by a backside aluminum sputter. The heavily doped backside guarantees an ohmic contact³.

Active layer formation begins when the wafer is anodized in a 49% HF / ethanol (1:1 by volume) solution at a constant current density of 3.5mA/cm for 2 min., forming a 70% porous PSI layer about 4000Å thick.

Immediately after the formation of porous Silicon, erbium was introduced via field-assisted infiltration from an erbium chloride solution (ErCl₃·6H₂O dissolved in ethanol). To do this correctly, the bias used during the anodization of the porous silicon must be reversed. After infiltration, the solution was rinsed with ethanol, submerged into DI water, and quickly moved to the SRD. The backside aluminum was removed in preparation for the following oxidation and anneal. During this furnace step, a small designed experiment would be coordinated. All samples would be pushed into an O₂/N₂ ambient at 900°C, enough to partially oxidize the active layer. Group 1 remained at 900°C for 20min after the O₂ had been shut off. Group 2 was ramped to 1100°C (in N₂) and annealed for 10 min.

Group (Wafers)	Anneal Temp	Anneal Time
1 (A, B)	900°C	20 min.
2 (C, D)	1100°C	10 min.

Table 1: Experimental adjustments in Er anneal

During both thermal variations the porous silicon is transformed into the Er-doped porous glass (OPNSi). In such a film, carrier transport is facilitated through defect states, which in turn provides the necessary means for exciting the Er ions. The concentration of Er and the efficiency of the excitation would depend on the anneal times and temperatures. The active layer is then capped with 0.25µm polysilicon deposited via low-pressure chemical vapor deposition at 610°C, forming an excellent interface to the active light-emitting material. The polysilicon is then selective doped n⁺ using contact lithography and a high-dose low-energy phosphorous ion-implant, followed by an activation anneal at 900°C for 15 min.

Finally, for the contact stage, the backside poly and any backside oxides are removed using an SF₆ reactive-ion etch, and a dilute 50:1 HF etch. Aluminum contacts are then formed to the n⁺ poly cathode areas via sputter deposition through a shadow mask, and backside aluminum is deposited to reproduce the backside substrate anode contact.

B. Device Testing

There were two areas of testing from which data were collected; the I-V characteristics, and the measurable luminescence. During electrical testing current was forced through the device while measuring voltage. The device was tested in both forward and reverse bias, using an HP4145 parameter analyzer. Characteristic plots will be examined to look for rectification and conductance. It is expected that the p-type regions of the substrate separated from the n-type poly under the Al contact by a semi-

conductive layer will have characteristics similar to a diode

The techniques used during the detection of luminescence were much more involved. To detect PL, the device was excited by an Argon laser. A germanium detector was aimed at the point of excitation and a spectrum was taken by varying the value of wavelength detection over time. The area of detection was very small and initially set up using a HeNe laser. During EL detection, the same germanium detector was used, but there was no

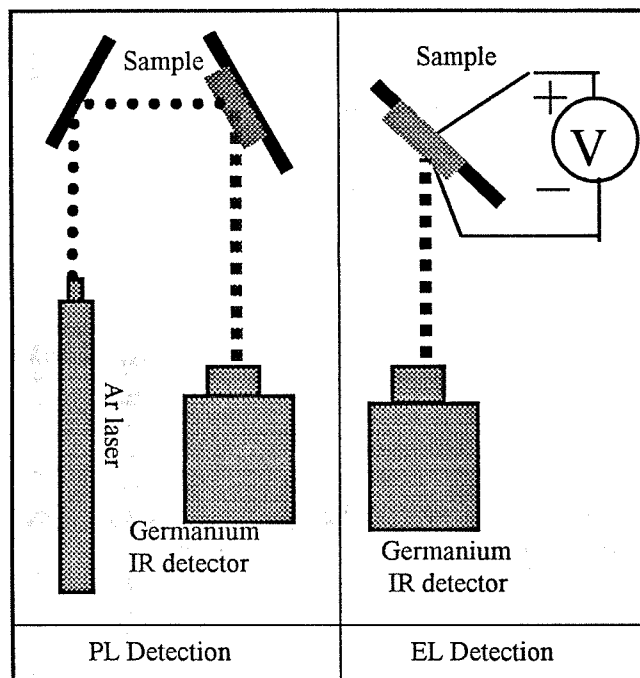


Figure 3: LED Luminescence Detection Equipment

external laser source exciting the LED. Instead, current would be forced through the device. Once again, the point of detection was aimed using a HeNe laser before the spectra was taken. Wavelengths under investigation would range from 1450nm to 1650nm, including the target 1540nm emission.

3. RESULTS AND DISCUSSION

When examining the IV characteristics of the LED, it is important that the devices facilitate carrier transport but are not overly conductive. The first test involved forcing a 20mA constant current and measuring the voltage (samples were allowed to reach steady state before V was recorded). These voltages ranged from 7.92V to 11.10V in Group 1 and from 8.31V to 17.22V in Group 2. The mean value of group 2 was significantly higher. Right from the beginning, we were able to tell that the wafers receiving the 1100°C anneal were more resistive. This test was also valuable in determining a device that is characteristic of

the entire group, since I-V curves were not drafted for each individual device. With the same set-up as this initial testing, higher currents (100mA) were forced through the devices to get a feel for the integrity. As expected, visible light was observed at levels detectable by the human eye.

Once that single device was determined for each group, the IV tests were administered and curves were generated. Log vs. Log curves are helpful in determining the different operation regimes.

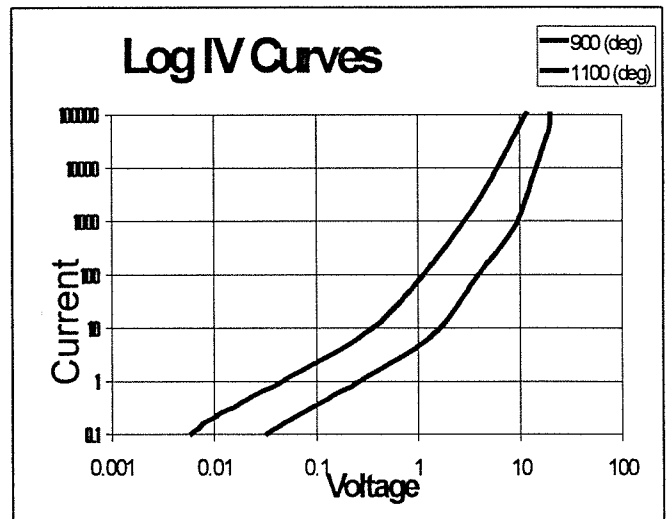


Figure 4: Log I vs. Log V

The Log vs. Log curves show that the LEDs do not have conventional diode characteristic, but still have a logarithmic response to voltage.

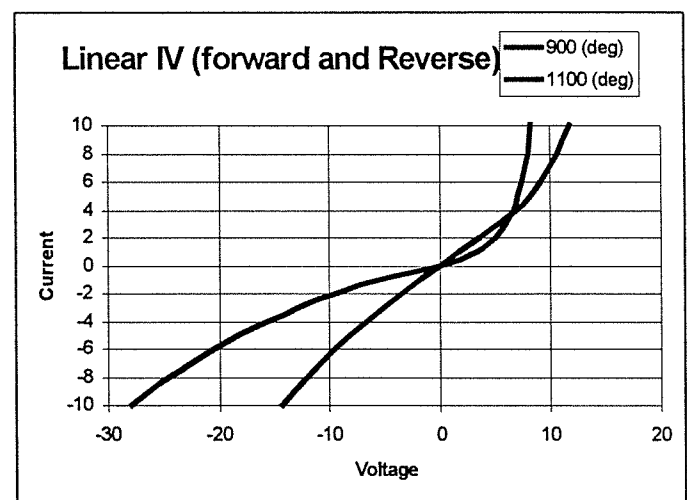


Figure 5: Linear Current vs. Voltage curve

The linear plots (more recognizable for comparison to ideal diodes) show that the 900°C anneal samples are much more diode-like, apparent in that fact that there is a greater amount of rectification and a greater increase in current at higher voltages. For the voltages (forward bias)

at which EL testing occurs, the 1100°C anneal samples will be less conductive with higher internal fields. In both groups there are non-characteristic reverse bias curves with no sign of avalanche breakdown.

In both groups, there were no detectable levels of EL. Multiple devices from all wafers were tested at current levels ranging from 20mA to 500mA. Each time, there were visible amounts of light and significant wafer heating, but the signal from the germanium detector could not be discerned from the inherent noise. What we were expecting (PL and EL) would have appeared as follows.

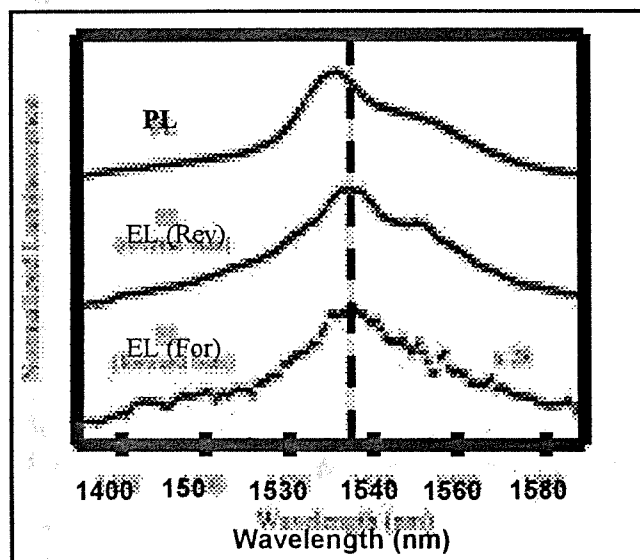


Figure 6: Expected (Non-experimental) Erbium Emission²

Instead, as stated previously, there were no detectable levels of EL. There were detectable amounts of PL from the samples annealed at 1100°C, especially when compared to those from the other sample.

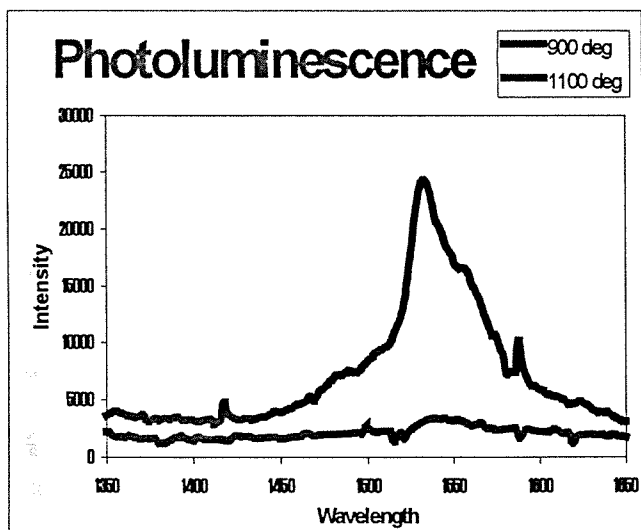


Figure 7: Comparison of PL

Figure 7 suggests that there is more activated Er^{3+} in the silicon rich silicon oxide active layer. This is accounted for because of a number of reasons. First off, there was probably a more complete anneal of the erbium within the active layer. The Er has to be bonded and in the structure for infrared emission to occur. The higher temperatures allow for more bonding to take place. Secondly, the higher oxidation and anneal temperatures allowed for a more complete oxidation of the active layer. This accounts for the lower conductivity, which would cause higher fields within the layer itself. Hot carriers would therefore have a higher probability of being generated. Since there was only a high and low setting for this designed experiment, it is impossible to tell exactly how the anneal temperature effect erbium concentrations. It is possible that higher temperature may have been too much, causing that active layer to be too resistive.

4. CONCLUSION

Even though there were no measurable levels of EL, it is reassuring to see that there were detectable levels of PL. The PL was higher in the samples annealed at 1100°C, suggesting that there were higher concentrations of Erbium and higher fields within the light-emitting active layer. It is possible that an anneal between temperatures of 900°C to 1100°C could produce even more desirable results. This experiment helped to show that erbium could be activated within the OPNSi film. Ion concentrations higher than those achieved through the field-assisted infiltration could be achieved through ion implantation. Still, large strides will have to be taken to make this film applicable in today's opto-electronic applications.

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