Electrical Properties and Infrared Luminescence of Er:SiO$_2$/nc-Si Multilayers under Lateral Carrier Injection

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Dedication

First of all I would like to thank my advisor, Professor Philippe Fauchet. His critical thinking, physical insight and dedication to details have kept driving me. I have learned so much from him and still benefit from it.

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Biographical Sketch

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Journal Publications


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1. Karl Ni, Krzyzanowska, H.; Yijing Fu; Fauchet, P.M., “Electroluminescence from Er doped SiO$_2$/nc-Si multilayers under lateral carrier injection”, Group IV Photonics (GFP), 2011

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Abstract

The work described in this thesis presents investigations of Er-doped SiO$_2$/nc-Si (nanocrystalline silicon) multilayers operating under a novel lateral electrical pumping geometry. The motivation for this study is to design and prototype an efficient Si-based light emitting p-i-n device working at 1535 nm, in the forward bias regime.

The first part presents the electrical properties of Er-doped SiO$_2$/nc-Si multilayers where each layer is a few nm thick. The current – voltage characteristics taken from samples fabricated under various depositions as well as annealing conditions are presented. It is also demonstrated that lateral current can flow through multilayers with nm-thick layers. A space charge limited current model was used to explain the collected I-V relations.

The next part of this work is focused on investigations of infrared electroluminescence (EL) from Er-doped multilayers. When electrons and holes are injected in the intrinsic region of a p-i-n device, they can excite the Er ions in the SiO$_2$ layers via energy transfer from the Si layers. The precisely defined Er-Si distance guaranteed by the very good controllability of the deposition method is one of the most crucial parameters to achieve an effective energy transfer from nc-Si to Er. The major advantage of the proposed lateral carrier injection approach, compared to vertical carrier injection through multiple SiO$_2$ layers, is that transport is much easier and more efficient. The infrared electroluminescence (EL) and photoluminescence (PL) spectra show identical features, which leads us to the
conclusion that the mechanisms of Er excitation via energy transfer and relaxation are similar in these two experiments. The observed strong PL under Er off-resonance excitation and EL under forward bias are very promising for Si-based light sources - the missing link in an all-silicon on-chip optical interconnection system.

The final part of the work focuses on optimizing parameters of the structure to design a stable, strong and efficient infrared electroluminescent device. The final goal of this work is to achieve electrical gain from the proposed device. Increased infrared transmission at 1535nm under electrical pumping indicates that gain has been achieved for TM polarized light.
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The members of the dissertation committee are as follows:

1. James Fienup (chair)
   from Institute of Optics
2. Philippe M. Fauchet (advisor)
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The following chapters of this dissertation were jointly produced. My participation and contribution to the research is as follows:

Chapter 2: Multilayer samples deposition rate characterization were done by Yijing Fu

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1 Introduction

1.1 Silicon technology

Modern life has been dominated by innumerable products that rely on integrated electronic circuits fabricated on silicon wafers. The success of silicon technology is not only caused by the dramatic improvements of performance, but also by the exponentially decreasing per-component manufacturing costs. The performance of a chip is usually equated to the transistor count, which has exponentially increased by time and is predicted by Moore’s law [1]. Fig. 1-1(a) shows the evolution of transistor gate length (minimum feature size) and the density of transistors in microprocessors over time [2]. Today’s chips already contain more than one kilometer of wiring per square centimeter of chip area [3]. Transmission of information along these wires consumes significant power in resistive waste heat and introduces the majority of the speed-limited circuit delay in a modern integrated circuit. Scaling exacerbates both of these problems by decreasing the cross sectional area of each wire, proportionately increasing its electrical resistance. Electric signal attenuation and power dissipation rise dramatically with a high data rate transmission. Cross talk between metal lines is also an origin of problems when their size decreases [4,5,7]. Fig 1-1(b) shows global interconnection and gate delay versus technology nodes. When devices keep shrinking, interconnect delay increases dramatically and outweighs the gate delay benefit. Even if we use low-K and high conductive material for interconnect, we will still have big problems in future
technologies. One possible solution of this problem could be employing optical interconnect, in which the information signals are carried by photons instead of electrons [6].

Fig. 1-1 (a) Moore’s Law, Ref [2], I. Ferain1 et al., Nature, vol. 479, p.310, 2011

Fig. 1-1 (b) Improvement in global interconnect time delay versus technology node for advanced materials, Ref [7], Bohr et al., IEEE International Electron Devices Meeting, p.242, 1995
1.2 Silicon Photonics – light from silicon

Optical communication is widely used in the long-haul telecommunications industry. Millions of miles of fiber optic cable now stretch between cities and continents. However, the photonic components fiber system used are still packaged separately and mainly based on III-V semiconductor materials [6]. Microelectronics is mostly made by silicon because it is one of the most abundant elements on the earth’s crust and the oxide of silicon has good insulating properties. The legacy of silicon microelectronics has made silicon the most studied material. In order to cost down photonic devices and also integrate them with electronic circuit, using silicon as an optical medium for the study and application of photonic systems is emerging.

Silicon photonics, pioneered by Soref in the 1980’s [8], is a technology that can merge both electronics and photonics in a single chip to take an advantage of both technologies, namely the high computation capacity of electronics and the high communication bandwidth of photonics. The goal of silicon photonics is to create high performance optical devices from the set of “CMOS compatible” materials used in electronic integrated circuits so that photonic components can be made using mature silicon fabrication technology.

There has been much research involved in developing silicon-based photonic devices. All-silicon photonic devices with all kinds of applications and functions have already been proposed and experimentally demonstrated, such as low-loss waveguides [9], high speed modulators [10], high speed detectors [11], sensitive bio-
sensors [12], etc. However, there is still no an efficient Si-based light emitting device. The merging of Si-based electronics with photonics has largely required hybrid technologies for light emitters and modulators, which are often both expensive and complicated to produce.

The design of silicon optical amplifiers and lasers has been considered almost impossible because of silicon’s indirect band structure which has the conduction and valence bands at different values of crystal momentum as shown in Fig. 1-2. The radiative recombination of an electron and a hole requires the assistance of a phonon to conserve momentum. Therefore the spontaneous emission or radiative lifetime in silicon is very long (millisecond range) while in direct gap III-V semiconductors it is short (nanosecond range) [13]. When excited carriers relax, non-radiative recombination compete with radiative recombination. In silicon, non-radiative recombination such as Auger recombination will eliminate inverted populations easily because of the long radiative lifetime. Therefore, silicon is considered out of the list of light emitter candidates.
Despite those limits, many strategies have been proposed to overcome them and make all silicon photonics possible. We will briefly cover some interesting approaches here.

A. Silicon Raman Amplification

The Raman scattering coefficient in silicon is orders of magnitude higher than in silica. Using a p-i-n structure in the silicon waveguide to sweep away the free carriers, which cause strong two-photon absorption (TPA), silicon Raman
amplification by stimulated Raman scattering has been achieved. Raman lasing has been demonstrated in silicon-based integrated-optical waveguides by Jalali's group at the University of California in Los Angeles in 2004 [14]. Silicon Raman lasers that operate in the cw regime have also been demonstrated [15]. However, optical pumping is still needed for this system.

B. III-V active materials bonded to silicon substrate

III-V materials which have a direct band gap and good radiative efficiency have been bonded to a silicon substrate. In this approach, the high optical gain from III-V compounds is coupled with a silicon waveguide by bonding them together. The laser cavity is defined by silicon waveguides. Electrically pumped lasers have been demonstrated [16]. However, the bonding process is not compatible with traditional “CMOS” processes and may limit its application.

C. Silicon/Germanium (nc-Si/Ge) alloy

nc-Si/Ge alloy has been demonstrated as a good optical material. The Ge band diagram can be modified by tensile stress between Ge and Si interfaces or n/p doping. With carefully controlled alloy fabrication processes and doping levels, the Ge band diagram can be modified to form a direct band diagram. Optical gain from Ge has been demonstrated [17]. An optically pumping nc-Si/Ge alloy laser has also been reported [18]. However, growing Ge on Si is a greatest challenge due to the lattice mismatch of 4.2% between the two elements. High surface roughness and threading dislocations are the two issues that occur because of lattice mismatch [19].
D. Silicon nanocrystals

According to the Heisenberg uncertainty principle, when an electron is localized, its momentum becomes uncertain. This phenomenon may offer a solution to the indirect bandgap of silicon. A popular approach to quantum confinement has been the use of silicon nanocrystals that occur naturally in a silicon-rich oxide (SRO) film [20]. When a SiO$_x$ (x<2) film is subjected to high temperature annealing, the excess silicon segregates from the oxide matrix and forms nanocrystalline silicon (nc-Si). Photoluminescence (PL) and electroluminescence (EL) are observed in these structures [21]. However, the emission wavelength is in the range from 800 to 900 nm, which is outside of the two standard telecommunication bands centered at 1320 and 1550 nm.

E. Er-doped silicon nanocrystals

Erbium doped fiber amplifiers (EDFA) have been widely used in optical fiber communication industry. Optical fiber is made from SiO$_2$, the main constituent of silicon-rich oxide (SRO), suggesting that erbium doped SRO should be considered as the optical gain medium. One of the erbium (Er) emission lines covers the technologically important wavelength of 1550 nm. In fact, EDFA devices are based on long and lightly Er doped fibers and high-power laser diodes to pump them. The good news is that nc-Si has a broadband optical absorption spectrum, and the absorption cross-section of nc-Si is five orders of magnitude higher than that of Er ion in silica [22]. Fuji et al. have shown that erbium can be excited via Si nanocrystals [23]. Fig. 1-3 shows a diagram of Er excitation process [24]. The excitation of Er ions
occurs via energy transfer form electron-hole pairs that are created in nc-Si either optically or electrically.


1.3 Er:SiO$_2$/nc-Si multilayer

The free carrier absorption losses and low Er absorption cross section in an SiO$_2$ matrix are the two main obstacles to achieve net optical amplification [8]. To significantly increase the number of Er excited ions in a SiO$_2$ matrix, it has been proposed to use of nc-Si as energy donors [23]. The free carriers in silicon introduced additional optical loss which decreases the probability of net optical gain. The number of active Er ions limits the performance of this system. The distance between Er ions and nc-Si determines the efficiency of energy transfer: if the distance is too large, energy transfer becomes impossible.

In order to suppress free carrier absorption and also provide good control over the distance between nc-Si and Er ions, we propose nanocrystalline silicon/erbium
doped silicon dioxide (Er:SiO$_2$/nc-Si) multilayer waveguides [26]. In general, photons tend to stay in regions of high refractive index, in this case, Si. However, using the idea of the slot waveguide, we are able to confine photons in the SiO$_2$ layers. Fig. 1-4 shows the power mode profiles of multilayers for TE and TM modes, calculated by the transfer matrix method [27]. It can be seem that photons are confined in the SiO$_2$ particularly for the TM mode. This approach not only avoids high free carrier absorption in silicon by “hiding” the photons in SiO$_2$ but also benefits optical gain by putting photons in gain medium (Er:SiO$_2$) region. [28,29]

In our group, we have already shown by pump-probe experiments that SiO$_2$/nc-Si multilayer structure can suppress free carrier absorption significantly under TM polarization. Fig. 1-5 clearly shows that free carrier absorption for the TM mode is ~1.7 times less than for the TE mode [25, 29].

Fig. 1-4 Typical power mode profiles of nc-Si/SiO$_2$ multilayer. Yellow regions are Er:SiO$_2$ and white regions are Si. Ref [28], H. G. Yoo et al., Optics Express, p. 8623, 2008.
Fig. 1-5 Pump-probe transmission spectra for TE and TM modes from nc-Si/SiO$_2$ multilayer structure Ref. [25], Y. Fu, et al., Optics Letters, Vol. 38, p. 4849, 2013
2 Infrared luminescence under lateral electrical carrier injection and optical pumping

For a number of years, quantum confined Si structures and rare-earth doped silicon media have been recognized as a promising approach [22, 24, 30]. In our group, we used SiO$_2$/nanocrystalline (nc)-Si multilayers formed by UHV RF magnetron sputtering to provide excellent control at the nanoscale [31]. We have already presented some works about photoluminescence in our multilayers [29, 32]. All groups working on electroluminescence of Er-doped multilayer structures use vertical carrier injection, in which the multilayers are sandwiched between two electrodes and form a MOS like structure [33, 34, 35, 36, 37]. Carriers are injected through Si and Er:SiO$_2$ layers. Because SiO$_2$ is an insulator, carrier injection efficiency is limited. There also is a reliability issue because hot electrons tunnel through the SiO$_2$ layers. We propose a more efficient way of carrier injection in nc-Si layers using lateral carrier injection. Carriers are directly transported within the Si layers which makes current transport easier and more efficient. These two carrier transport geometries are shown in Fig. 2-1. We will model carrier injection in our system in the following chapters. In this chapter, we study how optical and electrical pumping interact with each other and propose a new optical loss term in rate equations [38,39] due to carrier drifting when the applied voltage is high.
2.1 Sample fabrication

2.1.1 Er:SiO$_2$/nc-Si multilayer fabrication

A UHV RF magnetron sputtering system was used for Er:SiO$_2$/nc-Si deposition. Fig. 2-2(a) shows the layout of our sputtering system. There are three different targets in the system, silicon, silicon dioxide, and erbium. Both Si and SiO$_2$ targets are put on RF guns, and the Er target is put on a DC gun. The power of those guns during deposition is 300W, 350W and 40W for Si, SiO$_2$ and Er, respectively. During deposition, the substrate was heated up to 150 °C, the chamber was filled with Ar using 3 sccm flow rate, the substrate was rotated at ~30 rpm, and the vacuum level was 3 mTorr. Si alone was deposited solely to form the nm thick layers, and Er and SiO$_2$ were co-sputtered to form Er:SiO$_2$ layers. By switching the shutter and the power of different targets sequentially, Er:SiO$_2$/nc-Si multilayers could be made. The
layer thicknesses and deposition rate were calibrated by spectroscopic ellipsometry and TEM. Fig. 2-2(b) is a TEM picture of a multilayer structure. It shows sharp boundaries between Si and SiO$_2$ layers and the layer thickness agrees well with the result of spectroscopic ellipsometry [29].

After deposition, a furnace was used to anneal the samples at 1050°C for 1 hour. During annealing, a-Si crystallizes and nc-Si is formed [31]. Thermal treatment also help to activate Er ions in SiO$_2$ film [22, 23, 40].

Fig. 2-2(a) Schematic of our sputter systems, (from http://www.ajaint.com)

(The actual system can accommodate five targets)
Fig. 2-2(b) Representative TEM picture of a SiO$_2$/Si. The SiO$_2$ layer thickness is ~5.5 nm (brighter regions) and the Si layer thickness is ~ 4 nm (darker regions). Ref. [29], Yijing Fu, University of Rochester, Institute of Optics Ph.D. thesis, 2012.

2.1.2 p-i-n diode fabrication

In order to electrically pump the structure, we fabricated “p-i-n” diodes. A schematic of a p-i-n diode is shown in Fig. 2-3. Si thin films were used as conduction layers, where carriers were directly injected. The excitation of nc-Si in the i-region of the device produces energy transfer to nearby Er ions.
After the Er:SiO$_2$/nc-Si multilayer was formed, traditional semiconductor procedures were used to make a p-i-n diode. Fig. 2-4 illustrates the flow of those processes. At the beginning, we used contact aligner lithography to define trenches. HPR-504 photoresist was used for lithography processes. Subsequently, a reactive ion etching (RIE) was used to etch out those trenches. The etching conditions are: CF$_4$ gas with a flow rate at 20 standard cubic centimeters per minute (sccm) in a 100 mTorr pressure chamber and a 200W RF power supply. A Tencor profilometer was used to study the etching depth. For a 20min etching time, the trench depth is ~400nm. Next, we used the contact aligner again to define the n region, followed by ion implantation to dope phosphorous in two step process: 120 keV and 90 keV. In each step, the doping level is keep at $5 \times 10^{15}$ atoms/cm$^2$. We then follow the same process in the p region, in which we implanted boron at 45 keV and 33 keV with the same doping level ($5 \times 10^{15}$ atoms/cm$^2$). A 250nm Titanium (Ti) film was deposited and was patterned in electrodes by a lift-off process. Finally, rapid thermal annealing
(RTP) at 650°C for 45 seconds and 750°C for another 45 seconds activated those implanted ions and also formed silicide to reduce contact resistance [41].

Fig. 2-4 The process flow of p-i-n diode fabrication. (a) multilayer with photoresist for trench formation, (b) etch out trenches, (c) photoresist for formation of the N-region, (d) formation of the N-region by ion implantation, (e) photoresist for formation of the P-region, (f) formation of the P-region by ion implantation, (g) photoresist patterned for lift-off (h) Ti layer deposition (i) the final device after photoresist lift-off.
Fig. 2-5 (a) presents a top view picture of interdigitated electrodes on the multilayer samples. Electrode spacings are 10-40 $\mu$m, and electrode widths are 50 and 100 $\mu$m. Fig. 2-5 (b) shows a representative picture after ion implantation and after the photoresist is stripped out, the $n$ and $p$ implantation profiles can be clearly seen.

A typical cross-sectioned SEM view is presented in Fig. 2-6. In this picture, an etching angle $\sim 36^\circ$ between the side wall and substrate can be clearly seen. Its benefit is a good metallic contact to nc-Si layers.

Fig. 2-5 (a) Top view of interdigitated electrodes (b) Top view of trenches after ion implantation. The trench width is 31.75$\mu$m, the trench spacing is 16$\mu$m, and the i-region is in the range of 3.75-4.75$\mu$m.
2.2 Experimental setup and result

Fig. 2-7 illustrates the experimental setup to measure photoluminescence and electoluminescence. For optical pumping, we used an argon laser and a band-pass filter to select the 514.5 nm line, which is off-resonant with erbium ions. For electrical pumping, we used a source meter which is also used to collecting voltage-current characteristics. The luminescence signal was collected by an objective lens and passed through a monochrometer and picked up by a PMT with lock-in amplifier.
Fig. 2-7 Argon laser (514.5 nm) and source meter were used for optical and electrical pump respectively.

Fig 2-8 shows current/voltage characteristics with different optical pumping power. The small decreased observed degraded on the right of the chart (>120V) is due to current clamping and thermal issues. When the pumping laser was off, the current was higher. The reason may due to the space charge potential created by the optical excited carriers that limit the current.
Fig. 2-8 Voltage and current characteristics for different laser power optical pump

Fig. 2-9(a) shows the luminescence signal under different pumping conditions. When the optical pumping was off or low, the luminescence was mainly from electroluminescence. Once optical pumping went up, photoluminescence started to play a role, but the interaction is not clear to see. From Fig. 2-9(b), when the laser power went high, the delta luminescence graph (luminescence minus luminescence at 0V), indicates a decreased luminescence when the voltage increases from 0 to 80V, and then an increased luminescence when voltage exceeds 80V.
Fig. 2-9 (a) Luminescence (@1535nm) result with different optical and electrical pumping (b) delta luminescence (@1535nm) with different optical and electrical pumping (Sample is the same as in Fig. 2-8)
2.3 Discussion

The energy level scheme for the interaction between nc-Si and Er$^{3+}$ is shown in Fig. 2-10. The nc-Si is represented as a two-level system and Er$^{3+}$ ions are depicted as a three-level system. The highest energy level of the Er$^{3+}$ ion is sensitized by the nc-Si which could be pumped optically or electrically. Research on the rate equations for this system only focused on one pumping source [38,39]. Here we propose a rate equation for nc-Si which includes both optical and electrical pumping and their interaction term.

\[
\frac{dn_b}{dt} = -\frac{n_b}{\tau_{nc}} + \frac{n_a}{\tau_{nc}} e^{-\sigma_{nc} \phi_a(t) n_a} - \frac{n_a}{\tau_{nc}} e^{-\sigma_{nc} \phi_e(t) n_a} - C_{nc-Er} n_b N_1 - \frac{n_B}{\tau_{dr}}
\]

\[
\frac{dn_a}{dt} = \frac{n_b}{\tau_{nc}} - \sigma_{nc} \phi_a(t) n_a - \sigma_{nc} \phi_e(t) n_a + C_{nc-Er} n_b N_1 + \frac{n_a}{\tau_{dr}}
\]

\[
\frac{dN_3}{dt} = -\frac{N_3}{\tau_{32}} - \frac{N_3}{\tau_{31}} + C_{nc-Er} n_b N_1
\]

\[
\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}}
\]

\[
\frac{dN_1}{dt} = \frac{N_2}{\tau_{21}} + \frac{N_3}{\tau_{31}} - C_{nc-Er} n_b N_1
\]
They are modifications of ref [39] and we add two additional terms (highlighted in red boxes): electrical pumping flux \((\sigma^{e}_{nc}\phi_{e}(t)n_{a})\) and drift velocity induced loss \((n_{b}/\tau_{dr})\).

Other parameters are: \(n_{b}\) is the nc-Si upper level population, \(n_{a}\) is the nc-Si lower level population, \(N_{1}\) \(N_{2}\) and \(N_{3}\) are Er ion density on ith energy level \((1=e_{I_{15/2}}, 2=e_{I_{13/2}}, 3=e_{I_{11/2}})\), \(\tau_{nc}\) is the nc-Si lifetime, \(\sigma^{o}_{nc}\) is the nc-Si optical pumping cross section, \(\sigma^{e}_{nc}\) is the nc-Si electrical pumping cross section, \(\phi_{o}\) is the optical pump flux, \(\phi_{e}\) is the electrical pump flux, \(C_{nc-Er}\) is the coupling coefficient between the excited nc-Si and the highest Er\(^{3+}\) level, \(N_{1}\) is the lowest level population of Er\(^{3+}\) ion, and \(\tau_{dr}\) is the carrier transit time in the system due to drift current.

The luminescence would be proportional to \(n_{b}\), since a larger \(n_{b}\) means more energy transfer and light emission. The electrical pumping term is \(\sigma^{e}_{nc}\phi_{e}(t)n_{a}\), which is positive for luminescence and will be proportional to the injected current. Fig. 2-11 shows the delta luminescence versus current. The slopes are independent from different optical pumping power. It confirmed this positive term. The higher current, the more luminescence emitted.

The additional optical loss term and electrical pump interaction term is \(n_{b}/\tau_{dr}\), which is negative for luminescence and will be proportional to \(n_{b}\) and reciprocal to voltage. Since the loss term has \(n_{b}\), a normalized luminescence graph will help us to learn. Fig. 2-12 shows a normalized delta luminescence versus voltage graph. It clearly shows that when the voltage is lower than 80V the decreased slope with
different laser pump power is the same which justifies this interaction term. Therefore, we can conclude that when the voltage is lower than 80V, the carrier drift velocity is a loss term for photoluminescence, and when voltage gets higher and the current is high enough, electroluminescence adds to the signal and the total luminescence increases.

Fig. 2-11 Delta luminescence (1535nm) v.s. current characteristic
2.4 Rate equation simulation

We proposed two additional terms in the rate equations for both optical and electrical pumping and their interaction for infrared luminescence in Er-doped SiO$_2$/nc-Si multilayer structure. In order to learn more from those rate equations, we will solve them using parameters presented by other groups. Table 2-1 is the summary of the parameters we will use [39]. The nc-Si optical pumping cross-section (\(\sigma_{nc}^o\)) is two order less than nc-Si electrical pumping cross-section (\(\sigma_{nc}^e\)) [39]. The pumping flux in the following will be optical flux and/or 100 times of
electrical flux. Fig 2-13 (a) and (b) show the excited fraction of nc-Si and Er under a flux of $10^{20}$ and $10^{21}$ cm$^{-2}$s$^{-1}$. It shows ~66% of the Er ion are excited to level E$_2$ in steady state. Fig 2-14 shows the excited fraction of nc-Si and Er in steady state as a function of pumping flux. It suggests that it is possible to achieve population inversion of the Er ion when pumping flux is higher than $6 \times 10^{20}$ cm$^{-2}$s$^{-1}$. The carrier density we injected in the previous section would be $\sim 10^{20}$ cm$^{-2}$s$^{-1}$ (total nc-Si layer cross section: $\sim 5 \times 10^{-5}$ cm$^{-2}$, 1 mA), which is still in the linear region in Fig 2-14. In this range, the Er ion excited fraction is proportional to the pumping flux and it is consistent with the experimental data in the previous section. The nc-Si concentration is assumed to be $10^{19}$ cm$^3$, and the assumed Er concentration is $2 \times 10^{20}$ cm$^3$, chosen to be just below the onset of concentration quenching [39]. When increasing pumping flux, the excited Er ion fraction first increases rapidly and then saturates when the pumping flux is higher than $5 \times 10^{21}$ cm$^{-2}$s$^{-1}$. It is because the pumping flux is too high for the nc-Si and Er ion concentration. The excited nc-Si fraction keep increasing after the excited Er ion fraction saturated. Those excited nc-Si fraction will introduce more optical loss by free carrier absorption because of excited nc-Si.
Fig 2-15 shows the excited fraction of Er ions in steady state with increasing pumping flux with different carrier transit time. Fig 2-16 shows excited fractions of nc-Si and Er ions in steady state under different carrier transit time with a $10^{21}$ cm$^{-2}$s$^{-1}$ pumping flux. A faster carrier transit time decreases the fraction of excited Er ion could lead to less luminescence. It is consistent with what we found in the previous section. It suggests that we need to keep the voltage as low as possible to reduce the loss due to carrier moving and keep the current as high as possible to increase the pumping flux and excite more Er ions.

Table 2-1 Rate equation parameters. [39] Gerald M. Miller, California Institute of Technology, Ph.D thesis, 2012

<table>
<thead>
<tr>
<th>$\tau_{nc} (\mu s)$</th>
<th>7.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{nc}^a (cm^2)$</td>
<td>$10^{-16}$</td>
</tr>
<tr>
<td>$\sigma_{nc}^e (cm^2)$</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>$C_{nc-Er} (cm^3 s^{-1})$</td>
<td>$3 \times 10^{-15}$</td>
</tr>
<tr>
<td>$\tau_{32} (\mu s)$</td>
<td>2.38</td>
</tr>
<tr>
<td>$\tau_{31} (\mu s)$</td>
<td>714</td>
</tr>
<tr>
<td>$\tau_{21} (ms)$</td>
<td>0.291</td>
</tr>
</tbody>
</table>
Fig. 2-13 Excited fractions of nc-Si and Er ions under a pumping flux of (a) $10^{20}$ and (b) $10^{21}$ cm$^{-2}$s$^{-1}$ as a function of time. (>1.5ms to steady state)
Fig. 2-14 Excited fractions of nc-Si and Er ions as a function of pumping flux (in steady state :2ms)

Fig. 2-15 Excited fractions of nc-Si and Er ions as a function of pumping flux with different carrier transit time ($T_{dr}=10^{-4}$ s is very close to infinity) (in steady state :2ms)
Fig. 2-16 Excited fractions of nc-Si and Er ions as a function of carrier transit time (with $10^{21}$ cm$^{-2}$ s$^{-1}$ pumping flux) (in steady state :2ms)
2.5 Conclusion

In this chapter, we proposed two additional terms in the rate equations for both optical and electrical pumping and their interaction for infrared luminescence in Er-doped SiO$_2$/nc-Si multilayer structure. Optical and electrical pumping fluxes are positive terms for luminescence. The drift velocity resulting from electrical pumping is a loss term for luminescence. When applying voltage and injecting current at low range (current density less than 4 A/cm$^2$, or injection flux less than $2.5 \times 10^{19}$ cm$^{-2}$s$^{-1}$), the loss due to drift velocity decreases the luminescence. When the voltage and current get higher, the electrical pumping flux creates electroluminescence which adds to the total luminescence. With this study, we understand more about electrical and optical pumping on this system.
3 Electrical properties of silicon superlattice under lateral current injection

As the previous chapter mentioned, our approach makes use of a lateral p-i-n junction embedded into the multilayer. Charge transport takes place in the nc-Si layers and the injected charges excite the Er ions located in the oxide layers. In this paper, we report efficient lateral carrier injection as a function of electrode spacing from precisely controlled Er doped SiO$_2$/nc-Si multilayers with different thickness sets. The space charge limited current (SCLC) [42, 43, 44, 45] model is used for current-voltage characteristics and helps to explain the carrier transportation.

3.1 Current and voltage measurement

3.1.1 Before and after silicide annealing

Fig. 3-1 shows the current is dramatically increased after annealing. From the log-log plot, we can see that the slope in annealed samples will dramatically increase after a certain voltage from ~1.5 to ~5. It also shows for Er-doped samples the transition voltage step (from slope 1.5 to 5) is obscured. However, the same multilayer structures without Er doping do not demonstrate such behavior. The current in samples without Er is larger and suggests higher mobility in those samples in comparison with Er-doped samples. It may be related to energy transfer process from nc-Si to Er ions, which may occur only in Er-doped samples. A model to
explain the current and voltage characteristics is needed and will be presented in next section.

Fig. 3-1 IV characteristics of samples before and after annealing. (a) linear plot (b) log-log plot
3.2 Carrier transport model

3.2.1 Ideal diode model

For a single crystalline Si material, the current and voltage characteristics follow following the ideal diode law [45]:

\[ J = J_0 \left[ \exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (1) \]

Where \( J \) is the current density, \( J_0 \) is the reverse saturated current density, \( q \) is the electronic charge, \( V \) is the applied voltage, \( k \) is the Boltzmann’s constant, and \( T \) is the temperature in K. Considering other effects, such as generation-recombination, high injection, series-resistance, there is an ideality factor, \( \eta \), added into the equation in forward biasing:

\[ J \propto \exp\left(\frac{qV}{\eta kT}\right) \quad (2) \]

Fig. 3-2 Current and voltage characteristics of a ideal Si diode [45]
The ideality factor should be between 1 and 2. When the ideality factor approaches to 2, the recombination current dominates. When the ideality factor approaches to 1, the diffusion current dominates.

However, in our nc-Si/SiO$_2$ multilayer structure, the ideality factor is extremely high (>200), which is not consistent with the ideal diode equations. We assume that in the few nanometer thick multilayer structure, mobility is extremely low. Therefore, the traditional ideal diode current model, which is mainly based on diffusion current, cannot be used here and we need to use another model. The model we are going to use is space charge limited current (SCLC) model which is used for modeling current transportation in low mobility material [42, 43, 44, 45].

### 3.2.2 Space charge limited current (SCLC)

Current transport is difficult for low mobility materials, such as insulators with lots of impurity and defect states. Let’s consider a hypothetic circuit, where electrode contacts are perfectly made (ohmic contact) and current flow is only bulk-limited. Diffusive current is neglected because of relatively low charge gradient. The current density is determined by the drift current for large enough fields.

\[
J = -q\mu nE + qD \frac{dn}{dx} = -q\mu nE
\]

(3)

Where $\mu$ is mobility, $n$ is charge density and $E$ is applied electric field. When a voltage is applied across a material, an electric field is established, causing injected
space-charges present in the conduction band to flow from one contact to the other. If injected carriers are numerous enough, the semiconductor will no longer be quasi-neutral. For large enough biases, most of the charges contributing to current will be injected space-charge. Because of the buildup of space-charge density, the current growth is limited. The electric field from the injected space charge is given by the Poisson’s equation:

\[ \Delta E = -\frac{q(n + n_i) - (\bar{n} + \bar{n_i})}{\varepsilon} \]  

(4)

where \( \varepsilon = \varepsilon \varepsilon_0 \) is the permittivity. \( n \) and \( n_i \) are the densities of free and trapped electrons in quasi-thermal equilibrium, respectively. \( \bar{n} \) and \( \bar{n_i} \) are the values of \( n \) and \( n_i \), respectively, in thermal and electrical equilibrium (no applied voltage). \( q \) is the magnitude of the electronic charge. Electric field in the material follows the equation:

\[ \frac{dV}{dx} = E \]  

(5)

Where V is the applied voltage. The density of free electrons can be expressed as below:

\[ n(x) = N_c \exp\left[ \frac{[F(x) - E_c(x)]}{kT} \right] \]  

(6)

Where \( N_c \) is the effective density of states in the conduction band at temperature T and \( E_c(x) \) is the electron energy at the conduction band minima at position x. \( F(x) \) is the Fermi level. A set of traps of density \( N_t \) at energy \( E_t(x) \) are, in quasi-thermal equilibrium with \( n(x) \), expressing as:
\[ n_i(x) = N_i \left\{ 1 - \exp \left[ \frac{E_i(x) - F(x)}{kT} \right] \right\}^{-1} \] (7)

Fig. 3-3(a) shows the simplified energy band diagrams for injection contact of an insulator with a metal. Fig. 3-3(b) shows the relative steady-state energy level for a given current flow in an insulator with a single, discrete trap level \( E_t \).

The boundary conditions are:

\[ n(x) \to \bar{n} \quad \text{as} \quad x \to \infty \] (8)

\[ E = 0 \quad \text{when} \quad x = 0 \] (9)

Assuming \( \bar{n}_t = 0, n_i = 0 \), which means trap free, and dark density \( \bar{n} \approx 0 \), the solution of above equations becomes the Child’s Law:

\[ J_{\text{child}} = \frac{9}{8} \varepsilon \mu \frac{V^2}{d^3} \] (10)

Where \( d \) is the electrode spacing. Child’s law acts as the highest limit of current density, because no traps in the material was assumed. The lowest limit of current density follows the Ohm’s law,

\[ J_{\text{ohmic}} = \frac{q n \mu V}{d} \] (11)

Another current density restriction called traps-filled-limit (TFL) exists. It represented by the curve corresponding to the situation, where all the traps in the material have been filled prior to the application of voltage. Fig. 3-3(c) shows the log-log plot of the limiting current density versus voltage characteristics for space charge limited currents in an insulator with traps. We note that there is a voltage threshold, denoted \( V_a^{(TFL)} \), for current flow. This is due to the fact that before voltage
is applied there is already unneutralized charge in the traps which prevents the injection of additional electrons at the cathode. The voltage \( V_a^{(\text{TFL})} = qd^2 N_t / 2 \varepsilon \), with \( N_t \) the total trap density, is necessary to overcome this repulsion. The enormous steepness of the TFL curve relative to the Ohm’s law curve follows only on the assumption that the trap density \( N_t \) significantly exceeds the dark density \( \bar{n} \). The ratio of the slope of TFL curve to that of the Ohm’s law curve at the point of their intersection is \( \approx \frac{N_t}{\bar{n}} \). The TFL curve is practically vertical, for \( \frac{N_t}{\bar{n}} \gg 1 \), up to a decade or so below its extrapolated intersection with the Child’s law curve.
Fig. 3-3(a) Simplified energy band diagrams for injection contact of an insulator with a metal. The amount of downward bending of the bands at the contact is, in a simplified picture neglecting surface influences, given by the difference of work functions between the insulator and metal. $E_c, E_t, F$ are the bottom level of the conduction band, a single, discrete trap level, and thermodynamic Fermi level, respectively. (b) Relative plot of the steady-state Fermi level $F$ for a given current flow in an insulator with a single, discrete trap level $E_t$. (c) Log(V)-log(J) characteristic for SCLC, three lines in plot represent Child’s Law, Ohmic Law and trap filled Limit. [42] M. A. Lampert, Physical Review, Vol. 103, no. 6, pp. 1648, 1956.
Fig 3-3(c) shows the typical SCLC current voltage characteristic and three limit line are presented which are Ohmic Law Limit, Trap Filled Limit, and Child's Law Limit. Fig 3-4 (a) presents the current-voltage characteristic by just change \( N_t \) from \( 10^{14} \rightarrow 5 \times 10^{13} \text{cm}^{-3} \). Only Trap Filled Limit line changed. It makes the transition voltage lower because there are less traps in the system and they will be filled up quicker. Fig 3-4 (b) presents the current-voltage characteristic by just change \( N_c \) from \( 10^{24} \rightarrow 5 \times 10^{23} \text{cm}^{-3} \). Only Ohmic Law Limit line changed. It makes the current in the low voltage range smaller because there are fewer free electrons in the system initially. Fig 3-5 (a) shows the current-voltage characteristic by just change \( \mu \) from \( 1 \rightarrow 0.5 \text{cm}^{-1} \text{V} \cdot \text{s}^{-1} \). Both Ohmic Law Limit and Child's Law Limit changed. It makes the current smaller overall because both two limit proportional to mobility. Lower mobility means more difficult to transport carriers. Fig 3-5 (b) shows the current-voltage characteristic by just change electrodes spacing \( d \) from \( 20 \rightarrow 25 \mu \text{m} \). It would change all three limits. Ohmic Law Limit will decrease a little bit but Child's Law Limit will decrease more. Trap Filled Limit will increase since the volume of system increases. Fig 3-6 (a) shows the current-voltage characteristic by just change \( E_c - F \) from \( 0.75 \rightarrow 0.8 \text{eV} \). Similar to changing \( N_c \), it only changed Ohmic Law Limit because it reduced the free electrons in the system. Fig 3-6 (b) shows the current-voltage characteristic by just change \( E_c - E_i \) from \( 0.745 \rightarrow 0.7 \text{eV} \). It only changed Trap filled Limit because it reduced the trap density in the system.
Fig. 3-4 Current density – voltage characteristics for SCLC model with different parameters changed (a) $N_t$ from $10^{14} \to 5 \times 10^{13}$ cm$^{-3}$ (b) $N_c$ from $10^{24} \to 5 \times 10^{23}$ cm$^{-3}$ (other parameters: $\mu = 1$ (cm$ \cdot $ V$ \cdot $s$^{-1}$), $d = 20$ (µm), $E_c - F = 0.75eV$, $E_c - E_t = 0.75eV$)
Fig. 3-5 Current density – voltage characteristics for SCLC model with different parameters changed (a) $\mu$ from 1 $\rightarrow$ 0.5 cm$^{-1}$ s$^{-1}$ (b) d from 20 $\rightarrow$ 25 $\mu$m (other parameters: $N_t = 10^{14}$ (cm$^{-3}$), $N_c = 10^{24}$ (cm$^{-3}$), $E_c - F = 0.75$ eV, $E_c - E_t = 0.745$ eV)
Fig. 3-6 Current density – voltage characteristics for SCLC model with different parameters changed (a) $E_c - F$ from 0.75 → 0.8 eV (b) $E_c - F$ from 0.745 → 0.7 eV (other parameters: $\mu = 1$ (cm · V⁻¹ · s⁻¹), $d = 20$ (µm), $N_i = 10^{14}$ (cm⁻³), $N_c = 10^{24}$ (cm⁻³))
3.2.3 Current voltage characteristics

We fabricated several sets of multilayers with different electrode spacing on the same multilayer sample. Fig. 3-7 shows the top view of these structures. The interdigitated electrodes have 4 different spacing conditions, which are 10, 20, 30 and 40 μm respectively.

Fig. 3-7 Top view of different electrode spacing design

Fig. 3-8(a) presents the current and voltage characteristics in log-log scale. There is an obvious transition from slope ~1 to slope ~4.5. The transient voltage for the slope changes decreases when electrode spacing decreases. Fig. 3-8(b) shows the IV characteristics of different layer thickness sets. There were 3 different sets of multilayers with 10 nm (24 pairs), 15 nm (16 pairs), and 20 nm (12 pairs) thickness Si layers. Here we keep Si and Er-doped SiO$_2$ layers at the same thickness. In all
cases, the total thickness of Er:SiO$_2$/ns-Si layers was kept fixed at 480nm. It shows that the thinner Si has lower injection current. Especially with 10nm thick Si, the current density is much lower (about an order of magnitude lower) than 15nm and 20nm thick Si. The log-log slope seems independent on layer thickness. All values of the slopes are from $\sim$1.3 to $\sim$4.8 at a certain applied voltage. It exhibits similar characteristics with two transition regimes; one is related to ohmic and Child’s laws, and the other one to trap filled limit (TFL).

Fig 3-9 shows JV characteristic of different samples fitted with the SCLC model. The fitting result is very good and shows some interesting results. The fitted result reflected the electrodes spacing change while the other parameters remain fixed. The electrode spacing fitting result shows smaller than the realistic layout especially for bigger spacing. It may due ion implantation diffusion distance and process alignment variation. The thicker Si sample has higher mobility, which is expected.
Fig. 3-8 Current and voltage characteristics of (a) different electrode spacing (b) multilayers with different layers thickness with fixed electrode spacing (20 μm).
Fig. 3-9 JV relation for (a) different electrodes spacing, (b) different thickness Si and SiO$_2$
3.2.4 Substrate bias while deposition

During deposition, the applied substrate bias is a choice to improve surface roughness and have a more dense film [46]. However, during our previous PL study, we found that the applied bias was not good for the PL signal. In EL cases, efficiently injecting carriers into thin Si layer is the most important criterion. If we can inject more current into the system, this is a greater chance that those carriers can transfer their energy to Er ions and emit light out. It is good to know the current injection condition in substrate biased deposited samples.

Fig. 3-10(a) shows current voltage characteristics of different electrode spacing samples with substrate bias. Comparing with Fig. 3-8(a), without substrate bias deposition, the current and voltage log-log slopes change dramatically from ~4.5 to ~10. It indicates the trap density in substrate biased samples is higher than in samples without substrate bias. That makes sense because when applying substrate bias during deposition, plasma bombards the substrate and leads to a more dense and uniform film. This will also introduce more defect states into the film. Note that for 20 μm spacing, we observe a larger slope, which indicates the defects in this region are much higher than in the other regions. It suggests that the trap density in this sample is not uniformly distributed. 10 and 20 μm electrode spacing have relatively different result from 30 and 40 μm spacing. The reason might be that in the small electrode spacing region, traps are randomly distributed and therefore do not have a coherent result. But for larger electrode spacing, the uncertainty is averaged out, and they have similar behavior. Fig 3-10(b) shows different layer thickness IV
characteristics. Thinner Si still has less current going through the nc-Si films. Unlike without substrate bias samples, the slope changes are not similar among different thickness samples. Thicker Si have a higher slope. That may due to the distribution of traps accumulated when deposition time increase. The more deposition time, the more traps accumulated. We will discuss the role of those defect states in EL and PL in later chapter.
Fig. 3-10 Current and voltage characteristics of multilayers with (a) different electrode spacing (b) different layers thickness with fixed electrode spacing (20 \( \mu \)m).
In Fig. 3-11, J-V curves of samples with and without substrate bias are presented. We can see that samples with substrate bias have higher current density and have higher trap to free electron ratio in the system. 10 nm-thick Si layers with substrate bias have similar V-J characteristics as samples without substrate bias. It might be due to the short deposition time, during which the defects have not been accumulated. The transition voltage is also lower in the case of samples with substrate bias. It is obvious that application of substrate bias may help to increase the efficiency of carrier injection into the multilayer system.

Fig. 3-12 shows J-V characteristic of different substrate bias (S-bias) samples fitted with SCLC model. Electrodes spacings are also reflected here less so then layout distance. It may not only be due to ion implantation diffusion distance and process alignment variation but also non-uniformity due to substrate bias while deposition. Similar to non-substrate bias samples, in Fig. 3-13(a), the thicker Si sample has higher mobility, which is expected. Fig. 3-13(b) shows the fitted parameters among all different conditions. The mobility of samples with S-bias is much higher, which is also expected since S-bias helps to smooth the deposition film and increase the density. S-bias also reduces the thermal equilibrium electron density and increases the trap densities.
Fig. 3-11 Voltage and current density characteristics of all different multilayers in 20 μm electrode spacing.
Fig. 3-12 JV relation for different (a) electrode spacing (b) Si/SiO$_2$ thickness with S-bias. (Solid line are SCLC model fits)
Fig. 3-13 JV relation for different electrodes spacing (a) mobility of different multilayers (b) Trap density of different multilayers.
3.3 Conclusion

Since the Si layers are only a few nm thick, we expected the mobility in our multilayer structure to be relatively low. Traditional diode current models, based on diffusion current, will not be valid in our system. By comparing current and voltage characteristics before and after annealing, we found that the slope of current voltage log-log plots changes from ~1 to ~4. It indicates that the bulk current limited model, such as space charge limited current, is more suitable to describe carrier transport in our system. By using space charge limited current (SCLC), we understand more electrical properties of our multilayer structures.

For example: a thicker Si layer is easier for carriers to pass through and hence has higher mobility. Thicker Si layers mean longer deposition time and would introduce a higher trap density in the system. If the substrate bias is on during deposition, it helps to densify the layer and also increases mobility. However, it also introduces non-uniformity in the system and the trap density does not increase with Si thickness. SCLC helps us to understand the electrical properties and also guides us to explore different process condition in order to find a optimal one.
4 Infrared luminescence from Er doped SiO$_2$/nc-Si multilayer under lateral carrier injection

In previous chapters, we have already demonstrated that carrier injection through Si nm-thin films laterally. The SCLC model properly characterizes the current transport in a SiO$_2$/nc-Si multilayer and was used to determine important parameters of the structure such as mobility and trap density. The goal is to find ways to enhance EL efficiency. Here, it will be demonstrated infrared electroluminescence from Er doped structures.

4.1 EL characteristics

4.1.1 EL and PL spectra

Fig. 4-1 shows EL spectra from Er doped multilayers at different applied voltages in forward bias. The similarity between the EL and PL spectra clearly shows that the origin of the EL and PL is the same, indicating that Er is excited by the carriers injected in the nc-Si layers. However, we note that in PL experiments, energy is transferred from nc-Si to Er via the Forster and/or Dexter processes [51,52], whereas the detailed mechanism for excitation from the nc-Si layers in our p-i-n devices under forward bias is not yet established (e.g., energy transfer as in PL or sequential transfer of negative and positive charges).
Fig. 4-1 EL and PL spectra.

The peak wavelength of EL and PL are at 1535 nm. In the following chapters, EL means the intensity at this wavelength.

### 4.1.2 EL versus voltage

From Fig. 4-2 we can find that EL occurs at Trap Filled Limit (TFL) regime. This result indicates that until part of traps have been filled, EL is generated. We already know from previous chapters that the 10nm Si layers sample has a relatively lower trap density. It can be seen in Fig. 4-2(b) that 10nm thick Si layer sets have a lower voltage threshold than other two samples as expected.

Actually, the optimum Si layer thickness to observe efficient PL from Er-doped multilayers was estimated as in our pervious studies to be 2 nm. However, thinner Si layers mean more difficult current flow. Here, in 10nm Si layers set, the current is an
order of magnitude lower, and the slope of EL versus voltage is lower. It indicates that the efficiency of EL is also lower. So there is a trade-off process to optimize EL.

The plots in Fig. 4-3 represent EL-voltage relations from samples with substrate bias during deposition. Similar features were found for all samples, EL is observed in the TFL regime. From Fig. 4-3(b) we found that the 10nm Si sample reveals higher threshold voltage for EL and lower log-log slope than other two. We already know from previous V-J curve analysis, thinner Si layers with substrate bias have less accumulated traps and act more like samples without substrate bias.
Fig. 4-2 Current density and voltage JV characteristics for multilayers without substrate bias and (a) different electrode spacing (b) different multilayer thickness sets (20μm electrode spacing)
Fig. 4-3 Current density and voltage JV characteristics for multilayers with substrate bias and (a) different electrode spacing (b) different multilayer thickness sets (20μm electrode spacing).
4.1.3 EL versus current

Electroluminescence is generated with a help of energy transfer from nc-Si to Er. Besides studying EL voltage threshold and knowing when EL occurs, we can also examine EL and characteristics of injected carriers. In Fig. 4-4(a), a current density threshold ($\sim 10^{-0.7}, \sim 0.2\text{A/cm}^2$) for EL is observed. In this plot, different electrode spacings reveal a similar current density threshold for EL. It is well known that a density of defects does not depend on a distance between electrodes. Therefore the current density thresholds, which indicate that a fixed portion of traps are filled, are similar. From Fig. 4-4(b), the curves with different layer thicknesses show the different current density thresholds. From the analysis of V-J plots, we already know that thinner Si layers have less traps than multilayers with thicker Si layers, therefore, a lower current density threshold is expected.
Fig. 4-4 EL and current characteristics for without bias samples (a) different electrode spacing (b) different layer thickness sets (20µm electrode spacing).
Fig. 4-5 shows the EL and current density characteristics for samples with the substrate bias on during deposition. Contrary to the result presented in Fig. 4-4(a), current density thresholds for EL from multilayers with different electrode spacing shows a different behavior. The larger electrode spacing leads to lower thresholds. As it was mentioned in previous chapter, traps are not uniformly distributed while depositing with substrate bias. The larger electrodes spacing, the higher V-J log-log slopes. This result indicates the traps density increases with increasing electrode spacing. In the case of smaller electrode spacing, the defects are more randomly distributed and larger spacing has mostly identical behavior. From Fig. 4-5(b) we see that the multilayers with 10nm thick of Si layers show the lowest current density threshold. It also proof that the trap density in 10nm is much lower than others.

Electroluminescence dependencies on current density collected from samples with and without substrate bias are presented in Fig. 4-6. No significant differences between these two sets of samples were noticed. It indicates that energy is transferred from nc-Si to Er ions in a similar way in these both cases. Samples with thinner Si layers and without substrate bias have lower current density thresholds except 15 nm Si layer with substrate bias. We found 15nm Si layers with substrate bias to have higher values of voltage-current log-log slope (~11) and therefore the density of traps is higher. To observe EL, we need to apply higher current and partially to fill those traps, otherwise EL will not be generated.
Fig. 4-5 EL and current characteristics for with bias samples (a) different electrode spacing (b) different layer thickness sets (20µm electrode spacing).
Fig. 4-6 EL and current density characteristics (20 μm electrode spacing)

### 4.1.4 EL versus power

Owing to the analysis of the characteristics of EL versus voltage and current characteristics, we noticed that the density of defects is important to observe EL from multilayers. There is also the need to study conditions for efficient EL. We are going to check how electrical power, directly achieved by voltage times current, affects EL properties. Fig. 4-7(a) shows EL characteristics versus power for different electrode spacing in samples without S-bias samples. There is no significant difference between these spectra. In Fig. 4-7(b), 10nm Si layers set has the lowest power threshold for EL but also the lowest slope. It suggests that although the
minimum power required to observe EL is low and might due to lower defect density, the EL efficiency is less, also.

Fig. 4-8 shows the EL spectra versus power obtained from the sample with substrate bias. Fig. 4-8(a) shows that larger electrode spacing has lower power threshold. From V-J log-log plot we know the traps density distribution in samples with a small electrode spacing range is random and no coherent results were achieved. Here the EL versus power share the same feature. Fig. 4-8(b) indicates that the thinner Si layers have the lower power threshold. But again, the thinner Si layers set has the lower slope which indicate the EL efficiency is also lower.

Both set of samples with and without substrate bias have similar EL versus power log-log slope in individual thickness sets, which is shown in Fig. 4-9. It suggests that the mechanism of energy transfer from nc-Si to Er ions is similar in all cases.
Fig. 4-7 EL and power characteristics for samples without substrate bias and (a) different electrode spacings (b) different layer thickness sets (20 μm electrode spacing).
Fig. 4-8 EL and power characteristics for samples with substrate bias (a) different electrode spacing (b) different layer thickness sets (20μm electrode spacing).
4.2 EL time response

Fig. 4-10 shows results of EL and PL time resolved measurements. Both of them are done on the same sample. The decay time constant is \( \sim 1.1 \) ms in EL and \( \sim 1.8 \) ms in PL. Both of them are comparable to another group's result \[47\]. The rise time of EL is not easy to determine because it would be very difficult to maintain a flat voltage immediately after turning it on because of the electrical impedance match issue. However, we can say that it should be found in ms range, which is also comparable to PL result and other report \[47\]. The result indicates that the PL and EL mechanisms are similar. We point out that in both processes, energy is transferred from excited nc-Si to Er ions either radiatively or non-radiatively.
Fig. 4-10 (a) EL time resolved measurement, (b) PL time resolved measurement
4.3 Conclusion

It was found that electroluminescence from Er:SiO$_2$/nc-Si multilayers occurs in the trap filled limited regime. It indicates that EL won’t be generated until some of the defect have been filled. After the traps are filled, injected carriers would have more chance to transfer their energy to Er ions. Thinner Si (10nm) layer sets have lower voltage, current density and power threshold than others, but also have lower EL efficiency. It may be related to a lower number of defects in the sample caused by the lower thickness of Si layers. EL and PL time response seem to be similar. It suggests the same mechanisms is responsible for these two radiative processes.
5 Improving electroluminescence efficiency

In the previous chapters, we studied the electrical and optical properties of our multilayer structures. The ways to improve EL efficiency and achieve optical gain over loss is very important. In this chapter, we will demonstrate two paths forward for an EL efficiency study: Trenched before multilayers and slightly doped i-region.

5.1 Trenched before multilayer deposition

Photoluminescence studies show that thinner (~2nm) Si layers are more efficient [29, 32]. However, it is very difficult to transport carrier through thin Si layer. By increasing the Si layer thickness, we can increase carrier injection efficiency but some EL efficiency will be lost. It is very important to study how to balance these two. We proposed a trenched multilayer which has localized thin Si layers that help enhance the EL and also maintain most of region thick enough to have good carrier injection efficiency. Fig 5-1 shows the scheme of the structure. These structures may be used for light emitting diodes but not as waveguide structures.

![Fig. 5-1 Scheme of trenched multilayers. Thinner multilayer region as light emission regions and thicker multilayer regions as efficient transport regions.](image-url)
5.1.1 Sample fabrication

We demonstrated unique lateral carrier injection on Er-doped SiO$_2$/nc-Si multilayers and have demonstrated good EL results[48, 49]. Unlike the previous samples we made, we etched trenches before multilayer deposition by photolithography and reative-ion etching (RIE). Those trenches will be in between electrodes made in later process. Then the UHV RF magnetron sputter tool was used to deposit Er-doped SiO$_2$/nc-Si multilayers. After deposition, we followed the same process described in chapter 2. A furnace was used at 1050C for 1 hour to grow nc-Si. Then, reactive ion etching was used to etch trenches for electrodes. Sequential ion implantation of Phosphorous (5x10$^{15}$ atoms/cm$^2$; 120keV and 90keV) and Boron (5x10$^{15}$ atoms/cm$^2$; 45keV and 33keV) was used to create p-i-n structures. Subsequently, Ti films were deposited using electron beam evaporation and patterned as electrodes. The structures were annealed to form titanium silicide and to activate the dopants. (RTP, 600ºC 45secs and 750ºC 45secs).

Fig. 5-2 Sample preparation process: (a) etch trench by RIE (b) Er:SiO$_2$/Si multilayer sputtered on Si wafer which has a 5µm thick thermal SiO$_2$. Then furnace annealing at 1050ºC for 1 hour. (c) RIE to etch trenches and p-i-n junction creation by ion implantation. (d) Ti electrodes made by E-beam evaporator. After all, use RTP to form silicide and activate implanted ions.
Fig. 5-3(a) shows a picture after ion implantation. The pre-etch trench lie in between the trenches which will cover electrodes. The cross-sectional picture is shown in Fig. 5-3(b). It shows thinner layers on the pre-etch trench slope. Due to the sample cleaning problem after etching, there are voids on the pre-etch trenches which will limit the performance.

Fig. 5-3 (a) After ion-implantation, the middle trench in between later electrodes. The trench width is 5μm, and depth is ~250nm. (b) Cross-sectional SEM picture of multilayers.
5.1.2 Electrical and optical properties

Voltage and current characteristic of two types of multilayer is shown in Fig. 5-4(a). It shows uniformed layers have higher current than trenched samples which is expected because the Si layers would be thinner in the trenched region and carrier transport would be harder. Fig. 5-4(b) shows that the electroluminescence in uniformed samples are also higher than in trenched samples because less current passed through the trenched samples. But if we check Fig. 5-5, current versus EL plot, the slope of uniformed layers is lower than that of the trenched layers. It suggests that the trenched samples have a higher EL efficiency than the uniformed samples. For a certain EL level, trenched samples require a lower current than uniformed samples. However, we need to apply higher voltage in order to have the current for trenched samples. There are two reason: First, thinner layers in trench would limit the current. Second, film quality of trenched sample is not that good because of process cleanliness issue after etch which also limit the current. Table 1 compares the EL and carrier injection efficiency for the samples. For carrier efficiency, uniformed sample is higher. But for EL efficiency, trenched sample is higher. Both results are expected. Future works should focus on improving the device quality and finding the optimum point for these two efficiencies.
Fig. 5-4 (a) Voltage and current characteristic of two types of multilayer samples

(b) Voltage and electroluminescence characteristic
5.2 Light doping in the i-region

We used p-i-n structures for injecting carriers. Electroluminescence was generated in the i region where Er ions were excited by injected carriers and emitted light. From the electrical property study in previous chapters, we know that trap density plays an important role on EL. If we can change the i-region properties and check the EL performance, we can gain more information on how to optimize our structure and have achieved the best EL efficiency. The p and n region are heavily doped.
regions (~$10^{20} \text{ atoms/cm}^3$), because the implantation dose is $5 \times 10^{15}$ \text{ atoms/cm}^2 \text{ and the doping depth ~few hundred nm range. If the i-region was lightly doped with either n or p by three orders or less, the p-i-n structure should be maintained and we might change the EL response and know more about how to optimize the structure.}

5.2.1 Sample fabrication

All the fabrication processes are the same except an additional blanket doping after n and p doping stages. Two layer thickness samples are examined here: 15 nm and 20 nm of Er:SiO$_2$/nc-S. The doping levels for this additional blanket are at least two orders less than $n$ and $p$ region (doses of $5 \times 10^{13}$ \text{ atoms/cm}^2 \text{ and } $5 \times 10^{12}$ \text{ atoms/cm}^2) and won’t affect them. Only the i-region will sense this slightly doping. After doping, electrodes and annealing conditions are keep the same as previous samples.

5.2.2 Electrical and optical properties

Voltage and current characteristics with different i-region doping on different layer thickness set samples are shown in Fig. 5-6(a) and (b). It shows that a slightly doped i-region would decrease the transition voltage where V-I curves went from the ohmic law limit region to trap filled limit region which indicates that part of traps was filled. Current and electroluminescence characteristics showing in Fig. 5-7(a) and (b) also indicates that slightly i-region doped samples have lower current density thresholds. Doping with phosphorus shows a more significant shift than boron indicating holes traps are more than electron traps. Fig 5-8 also shows slightly doped i-region samples have lower power thresholds.
Fig. 5-6 Voltage and current characteristics of (a) Si/Er:SiO$_2$ 15nm thick and total of 16 pairs samples (b) Si/Er:SiO$_2$ 20nm thick and total 12 pairs samples
Fig. 5-7 Current and EL characteristics of (a) Si/Er:SiO$_2$ 15nm thick and total of 16 pairs samples (b) Si/Er:SiO$_2$ 20nm thick and total 12 pairs samples
Fig. 5-8 Current and EL characteristics of (a) Si/Er:SiO$_2$ 15nm thick and total of 16 pairs samples (b) Si/Er:SiO$_2$ 20nm thick and total 12 pairs samples
5.3 Conclusion

We proposed and demonstrated ways to enhance EL efficiency for Er-doped SiO$_2$/nc-Si multilayer structure. First, etching trenches in between later electrodes before depositing multilayer could have thinner Si layers in trenched slope region and keep the other flat region Si layers thicker enough to inject carrier. By that, we can inject carriers efficiently and also transfer energy to erbium ions efficiently and have higher EL efficiency. Due to the sample preparation cleanliness issue, we got less current than we expected. If we can eliminate this issue, the EL efficiency could be higher. Second, a slightly doped i-region would help to reduce the trap density in the system and therefore reduce the current density threshold for EL and also increase EL efficiency. The result is promising for the development of a Si-based light source, which is the missing link in an all-silicon on-chip optical interconnection system.
6 Transmission enhancement from Er-doped SiO$_2$/nc-Si multilayer waveguide under lateral electrical carrier injection

In previous chapters, we studied photoluminescence and also demonstrated electroluminescence through lateral electrical carrier injection with a p-i-n structure. One of the important advantages of using the Si/Er:SiO$_2$ multilayer structure is the waveguide slot effect in TM modes which helps to reduce free carrier absorption in silicon and increase optical gain by confining more photons in nanometer thin SiO$_2$ layers which have been Er ion doped. In this chapter, we will demonstrate a p-i-n ridge waveguide structure and use a prism for pump-probe experiment. It is very difficult to couple light into ridge waveguide mode of multilayers especially for TM modes because the mode profile is not continuous (see Fig. 1-4). Here prism coupler and a waveguide coupler were used to successfully couple light into waveguide. This is also the first direct evidence of gain in such structures.

6.1 Sample Fabrication

Er-doped SiO$_2$/nc-Si multilayers were formed by UHV RF magnetron sputtering technique as described in chapter 2. A 300nm SiO$_2$ film was then deposited by E-beam evaporator and patterned to form a ridge waveguide. A waveguide coupler is made for coupling slab waveguide modes excited by a prism. A p-i-n diode and titanium electrodes were then made for electrical pumping which we already
mentioned in chapter 2. Slightly doped i-region which shown benefit for EL in chapter 5 was not applied here due to time constrain. Fig. 6-1 shows the waveguide structure, including waveguide the layout, a sample picture and a cross sectional schematic. Fig. 6-2 shows a cross sectional SEM picture of the structure. A 286nm wide and 3.4µm height SiO$_2$ ridge waveguide was made in between the p and n electrodes.

Fig. 6-1 (a) Sample layout (b) Picture of sample and (c) cross sectional scheme

Fig. 6-2 Sectional SEM picture of sample.
6.2 Pump and probe measurement

Fig. 6-3 shows the pump-probe experiment scheme. A prism was used to couple light into waveguide. An objective lens was used to collect transmission light out of waveguide. Mode scans for TE and TM modes are plotted in Fig. 6-4. There is one TE mode and two TM modes. The birefringence of mode indexes are consistent with our simulation result [29]. The transmission signal was picked up by an objective lens and detected by a PMT. We measured reflection and transmission simultaneously to confirm that light was coupled properly. The transmission peaks and reflection dips align well which indicates that the transmission did pick up the waveguide modes and the waveguide coupler works.

Fig. 6-3 Pump-probe experiment scheme.
Fig. 6-4 (a) TE mode scan trace (b) TM mode scan trace
Fig. 6-5 shows a voltage and current characteristics. The rectifying behavior implies a good p-i-n structure. It also shows low turn-on voltage and high current density. When apply 5V, current is $\sim0.01\text{A}$ and the electron flux would be $2.6 \times 10^{21} \text{cm}^{-2}\text{s}^{-1}$ (total Si cross section is $2.4 \times 10^{-5} \text{cm}^2$). As we mentioned in chapter2, this level of pumping flux would have $\sim80\%$ of Er ions excited and have optical gain. Fig 6-6 shows an additional 1535nm band pass filter which has $\sim5\text{nm}$ bandwidth and can be inserted in between the objective lens and the PMT. Fig. 6-7 are transmission enhancement plots for TM$_0$ and TM$_1$ modes respectively, and Fig 6-8 is for TE$_0$ mode. The black dots represent data without the 1535nm band pass filter, and the red dots are with the filter placed before PMT. Before applying 1535 band pass filter, we see transmission enhancement in all three modes in forward bias. However, after applying a filter, only TM modes show enhancement and the TM$_0$ mode has more enhancement than the TM$_1$ mode. The voltage threshold for observing the enhancement is $\sim7\text{V}$. There are $\sim1\text{dB}$ and $0.1\text{dB}$ transmission enhancement when applying 30V for TM$_0$ and TM$_1$ modes respectively. That is because the TM modes have more photons confined in SiO$_2$ region where erbium ions exist than the TE modes. The TM$_0$ mode has more confinement in the multilayers region than the TM$_1$ mode. These results agree with our previous simulations and experiments which shows TE modes have higher free carrier absorption than TM modes [28, 29]. This is the first experimental evidence of transmission from Er:SiO$_2$/nc-Si multilayers serving as a waveguide structure.
Fig. 6-5 Current and voltage characteristic.

Fig. 6-6 Pump-probe scheme. There is an optional 1535nm band pass filter (5nm band wide) in between PMT and sample.
Fig. 6-7 Voltage and transmission characteristic for (a) TM$_0$ mode
(b) TM$_1$ mode.
Fig. 6-8 Voltage and transmission characteristic for $TE_0$ mode.

Fig. 6-9 (a) shows voltage and transmission characteristics with different probe beam powers (1535nm). If we change probe beam power, the transmission enhancement changes. When the probe beam is off, there is $\sim 2.5$dB enhancement @ 1535nm. It is because the EL scattering signals is caught since signal level is now. When probe beam is 0.02W, the transmission enhancement is $\sim 1$dB and $\sim 0.4$dB for 0.06W probe beam. If we assume the coupling efficiency is 1%, the 1535nm photon density by probe beam will be $\sim 6.4 \times 10^{22} \text{ cm}^{-3}$ and $1.3 \times 10^{23} \text{ cm}^{-3}$ for 0.02W and 0.04 W probe beam respectively, which is high compared to Er ion density (The Er concentration in SiO2 is estimated to be around 1% [32]). That might saturate the transmission enhancement.
Fig. 6-9 (a) Normalized transmission and voltage characteristic for different probe beam power (b) Transmission enhancement v.s. estimated probe photon density (assume coupling efficiency is 1%)
6.3 Conclusion

We demonstrated a ridge waveguide in an Er-doped SiO$_2$/nc-Si multilayer structure. Pump-probe experiment were performed by a prism coupler and a waveguide coupler laid on a multilayer structure and we found transmission enhancement in TM modes. There is no enhancement found in TE mode which is expected since it has higher free carrier absorption it has. There is $\sim$1dB enhancement in TM0 mode and $\sim$0.1dB in TM1 mode. The result is promising for the development of a Si-based light source, which is the missing link in an all-silicon on-chip optical interconnection system.
7 Summary and Proposed Work

The object of the studies is to achieve an electrical pumping silicon laser which is the missing part for silicon photonics industry. In this thesis, a simplified rate equation for both optical and electrical pumping and their interaction for infrared luminescence in Er-doped SiO$_2$/nc-Si multilayer structure was proposed and confirmed. The drift velocity created by electrical pumping is a loss term for luminescence. Electrical properties of the multilayers under lateral carrier geometry were discussed. This novel method of carrier injection applied to a few nm-thick layers, which form a multilayer system, show that lateral carrier flow through very thin layers is possible. For comparison, reference I-V curves for non-Er doped multilayers were also discussed. The obtained results show that lateral transport of carriers is easier in the reference sample. By analyzing the current voltage characteristics, and referring to the SCLC model, we acknowledge the phenomenon of carrier injection through our nc-Si thin layers laterally. There are traps inside the film and they will influence the charge transportation properties. There were also examined sets of multilayers prepared with and without a substrate bias voltage applied during the deposition. The results of these measurements reveal that samples with substrate bias will have a higher trap to free electrons ratio and also a higher mobility, longer deposition time will have higher trap impact, and the traps in samples with substrate bias are not uniformly distributed.

Electroluminescence spectra were obtained from samples with various parameters such as: different Si thickness multilayers (10, 15, 20 nm), with and without
substrate bias during deposition, and different electrode spacing (10, 20, 30, 40 μm).
EL and PL results at 1535 nm were compared. These two types of spectra reveal the same features. It suggests that the mechanisms of Er excitation in these two processes should be the same. Energy transfer from nc-Si to Er is needed to observe infrared radiative emission from Er. EL always happens after some of the traps have been filled. Lower trap density samples need a lower current density threshold for EL to generate, but this also lower EL efficiency. The highest EL intensity was observed from multilayers with the following parameters: 10nm thickness Si layers with an applied substrate bias, 40 μm electrode spacing, applied at 84V, and current density is 110A/cm². Although samples with substrate bias have the highest EL intensity, there are also more carriers injected into multilayers. The EL efficiency is actually lower than samples without substrate bias. Work on optimization of the multilayer’s design is still needed. Two ways to enhance EL efficiency was proposed and studied. Trenched multilayers have better EL efficiency but lower carrier injection efficiency. Improving sample cleanliness will help to find the optimum conditions. Slightly doped i-region helps to reduce trap density and also reduce the current density threshold for EL. More experimental conditions should help to find an optimal doping level for best EL efficiency. Transmission enhancement was found in TM mode but not in TE mode in good agreement with our previous waveguide slot effect study. It also indicate the possibility of optical gain for future lasing.
There is still work that needs to be done in order to have a final silicon laser. First, some paths to find out the optimal condition for best EL efficiency will be listed. Second, a scheme for an electrical pumping Si-based laser will be shown.

7.1 Increasing EL efficiency

From an application point of view, the most striking result was the achievement of electroluminescence from Er-doped SiO$_2$/nc-Si multilayers under forward bias. The minimal voltage threshold of EL is $\sim$7V (with substrate bias 15 or 20nm Si layers set). This is still too high for normal electronics operational range. We need to reduce electrode spacing to $\sim$1$\mu$m which would require a more precise lithography tool. All of the fabrication done here used a contact lithography tool which has $\sim$5$\mu$m limitation. We need to try stepper or even E-beam litho for finer pattern.

We already demonstrated two paths to increase EL efficiency: trenched multilayer and a slightly doped i-region. However, due to time constrain, we did not finish all condition necessary to find the optimal conditions. There are many other approaches which can modify film qualities and we need to try and find out the best parameters. Here are some that we can try later:

- Different annealing condition,
- Different film deposition temperature,
- Different substrate bias condition while deposition,
- Changing SiO$_2$ and Si thickness ratio,
Using SCLC model, we can gain some useful information and compare that with EL result. We should be able to optimize our system in terms of EL efficiency.

7.2 Optical cavity for electrically pumped laser

After proving optical gain by electrical pumping, we intend to make a real Si-based laser structure by adding a ring type resonator into our system. Fig. 7-1 shows the proposed scheme of the system. A straight waveguide located adjacent to a ring resonator. This straight waveguide acts as a coupler. Injecting carriers into the multilayer inside the ring resonator region and letting photons get amplified in the resonator. We will also test different shape of resonators based on the simulations.

Fig. 7-1 Scheme of our proposed electrical pump silicon laser. Ref. [29], F. Yijing, University of Rochester, Institute of Optics Ph.D thesis, 2012.
8 Bibliography


