SOI Back Reflectors for Tb Doped Oxide Electroluminescent Devices

By

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Abstract

Electroluminescent devices based on light emission from Tb-doped SiO₂ incorporated in a MOS capacitor structure have been formed on SOI substrates. It is shown that with appropriate choice of Si film and buried oxide thickness the SOI substrate can serve as a quarter-wave high-low-high index back reflector. Analysis predicts this back reflector can boost total light output integrated over the Tb emission spectrum by approximately 35% compared to a bulk substrate control device. Experimental devices using 100 nm thick PECVD SiO₂ emitting layers doped with 1% Tb were fabricated on substrates with nominal 32 and 108 nm Si film thicknesses (corresponding to approximately $\lambda/4$ and $3\lambda/4$ at the Tb emission peak). The Si films were doped to $10^{19} - 10^{20} \text{ cm}^{-3}$ by As implantation. Uniform bright green electroluminescence was obtained from 250 μm square devices, demonstrating that current crowding is not an issue even with such a thin Si film. The comparison of output spectra for thick and thin Si films demonstrates that optical absorption in the heavily doped Si film does not seriously degrade the light output of the devices.

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List of Abbreviations and Acronyms

MOS = Metal Oxide Semiconductor

SOI = Silicon On Insulator

PECVD = Plasma Enhanced Chemical Vapour Deposition

SSL = Solid State Lighting

LED = Light Emitting Diode

OLEDs = Organic Light Emitting Diodes

ELD = Electroluminescent Devices

ITO = Indium Tin Oxide

RE = Rare Earth

TMHD = Tetra Methyl Heptane Dionate

ECR-PECVD = Electron Cyclotron Resonance Plasma Enhanced Chemical Vapour
Deposition

EL = Electroluminescence

PL = Photoluminescence

CMOS = Complementary Metal Oxide Semiconductor

LOCOS = Local Oxidation of Silicon

LPCVD = Low Pressure Chemical Vapour Deposition

Chapter 1 Introduction

1.1 Solid State Lighting

People on earth have made tremendous progress in the field of science and technology over the last century or so, but we all have to pay a huge price for it. Rapid industrialization has impacted our climate to a large extent and all the developing as well as the developed nations are therefore seeking ways to reduce their energy loss and consumption [1]. SSL is being considered as an important step to conserve electrical energy, thereby reducing greenhouse gas emissions. It has been estimated that worldwide lighting is responsible for approximately 1900 mega tonne CO₂ emissions [2].

Lighting applications that use light-emitting diodes (LEDs), organic light-emitting diodes (OLEDs), or light-emitting polymers are commonly referred to as solid-state lighting [3]. SSL technology helps in conservation of electrical energy as it is much more efficient as compared to standard incandescent lamps and somewhat more efficient than fluorescent lights [4]. Most SSL technologies do not require toxic materials, while conventional fluorescent lights contain significant amounts of mercury [5]. The energy savings potential of SSL technology is enormous. For example, it has been estimated that with the use of LEDs in traffic signals alone, the United States could save 2.5 GWh annually [6]. Globally, it has been estimated that converting to SSL technology wherever

possible could save 860 TWh and eliminate 200 million tonnes of carbon dioxide emission annually worldwide [7].

1.2 Silicon Based Light Emitting Devices

Silicon microelectronic devices have revolutionized society and the global economy. Today there is a major research effort around the globe to try and repeat the success story of silicon microelectronics in the photonics area [8]. Much of this research is focused on using silicon in light emitters. The push to use silicon to produce light is based on two main factors. First, optoelectronics has emerged as a major industry in its own right and there is a strong and continuing desire to integrate optical devices such as lasers and detectors, and optical modulators, multiplexers, waveguides and interconnects within the established microelectronics industry. Group III-V semiconductors such as GaAs have optical properties ideal for these devices. So a lot of work is carried out on these semiconductors but due to the huge existing investment in silicon based technology, there is a great desire to use silicon material for such devices. Silicon, being an indirect bandgap semiconductor, it has weak light emission, which is considered a major drawback [9]. There are number of ways to overcome this drawback such as nanocrystalline silicon, Er doped silicon, metal-oxide-semiconductor (MOS) structure with native oxide, porous silicon based devices, polymer deposition in silicon substrates, Si⁺-implanted SiO₂, GaN growth on silicon substrates and so on [10]. GroupIV Semiconductor based in Kanata, Ontario, Canada has made considerable progress in obtaining efficient, bright EL from rare earth doped oxides on silicon.

1.3 Use of SOI Wafer as Back Reflector

SOI wafers are finding widespread application in photonics and microelectronics. Due to its easy availability and excellent optical and electronic performances SOI has received more and more attention in recent years [11]. In SOI wafers, a uniform layer of silicon dioxide is sandwiched between a thick silicon substrate and a thin surface layer of crystalline silicon [12]. As Si has a refractive index of 4.1 which is much higher than SiO_2 , so SOI makes a stack of material with High-Low-High refractive index which is ideal to get maximum reflection of visible light. This makes SOI a suitable material for use as a back reflector to maximize light emission from silicon devices. Some results on the use of SOI back reflectors for nanostructured Si emitters have been reported previously by Bogalecki *et al* [13].

1.4 Thesis Contribution.

This thesis demonstrates the use of SOI substrates to increase the light emission efficiency of ELDs produced by Group IV Semiconductor. The present generation of devices produced by Group IV are fabricated on bulk Si substrates. Half of the light emitted in the doped oxide travels towards the substrate. Simple theory [13] predicts that only 60% of the light directed towards the substrate is reflected. The remainder of the light enters the substrate and is lost to absorption. In order to increase the light output here SOI wafers are used in place of bulk Si substrates. SOI substrate acts as a back reflector thereby increasing the light output of the devices. The Tb-doped light emitting oxides produced by Group IV Semiconductor have a peak emission at 545 nm. In order to get the maximum reflection out of the SOI wafer at 545 nm wavelength, the silicon film

and buried oxide thicknesses should both be an odd integer multiple of a quarter wavelength. A $\lambda/4$ Si film corresponds to a physical thickness of 32 nm. The reflectance is integrated across the Tb emission spectrum to determine the total theoretically possible boost in optical output provided by the back reflector. Experimental devices were fabricated to test the back reflector concept. SOITEC Smart Cut SOI wafers with silicon thickness of 340 nm and buried oxide thickness of 1 μm were used and by successive oxidation the silicon film was thinned down to 32 nm [14]. Tb doped SiO_2 was deposited on the SOI wafers and then an ITO contact was made on the top. ITO is semi transparent and acts as a conductor in the device. Al metal was used to make final contact to the thin silicon film and the ITO. Electrical as well as optical testing of the devices was performed at Carleton University and at Group IV Semiconductor Kanata. It was established that SOI substrates can indeed be used to make electroluminescent MOS devices and these substrates act as a back reflector.

1.5 Thesis Organisation

This thesis has been divided into six chapters:

Chapter 1 has provided the motivation of the thesis, importance of SSL technology in today's world, brief overview of Si based ELDs, thesis contribution and thesis organisation.

Chapter 2 provides a background and review of previous literature for the project.

Chapter 3 describes theory and modelling of experimental devices.

Chapter 4 discusses fabrication of experimental samples.

Chapter 5 describes the electrical and optical testing of the experimental devices.

Chapter 6 gives conclusions and recommendations for further work.

Chapter 2 Background

In this chapter a detailed background of silicon light emitters is provided. This chapter begins with a brief explanation of the physical properties of silicon relevant to light emission, outlines different methods to obtain light emission from silicon despite the indirect band gap, summarizes the properties of SOI and describes reflection from thin film stacks.

2.1 Physical Properties of Silicon

The optical as well as the electrical properties of semiconductors are determined by their energy-band structure. The band structure relates the energy and crystal momentum (or wave vector) of electrons moving in the crystal. During the energy conversion process (electrical to optical and vice versa) electrons move from conduction band to valence band and vice versa. During the transition of electrons from valence band to conduction band and vice versa, momentum as well as energy has to be conserved [16]. Conservation of momentum cannot be achieved in indirect semiconductors unless a phonon is involved in the transition (in other words, momentum exchange with the lattice is required). Silicon has an indirect bandgap i.e. minimum of conduction band is not directly above the maximum of valence band. Transfer of an electron from the conduction band to the valence band through the emission of a photon therefore does not conserve momentum

and is not an allowed process [17]. A phonon must be involved in the process to conserve momentum, which greatly reduces the probability of the process (leading to long minority carrier lifetimes in silicon). Normally the energy released in the transition is imparted to the phonon, and no photon is emitted. Silicon light emission efficiency is therefore very low due to the indirect bandgap. Indirect bandgap is shown in Figure 2.1. Different ways to overcome this are being explored by various researchers.

Figure 2.1 Schematic of energy as a function of momentum graph for an indirect bandgap in semiconductors.

2.2 Light Emission from Silicon

In order to increase the light emission efficiency of silicon, the indirect bandgap has to be overcome [18][19]. Lockwood [20] has extensively reviewed the various methods that are being explored to accomplish this. The main methods under investigation are listed below.

1. Band structure engineering via alloying[21]
2. Luminescence via impurity centres[22][23]
3. Silicon nanostructures- Porous Silicon, silicon nanoclusters, quantum wells, wires and dots.[24][25]
4. Polymers and molecules containing silicon
5. Hybrid methods for integrating direct gap materials with silicon[26][27]

In this thesis we will focus on approach 2 to create light emission, relying on rare earth impurities to emit light from silicon-based devices.

2.3 Luminescence via Impurity Centres- Doping of Silicon with Rare Earth Metals

Doping of silicon with rare-earth elements such as Er, Gd, Tb, Ce and Eu is being investigated to generate light in the infrared spectral range. Of these Er has been the most intensively investigated [28][29]. As Er emits light at the same wavelength independently of the host, it has got a number of advantages over other Si based light emitters. Through various experiments it has been observed that solid solubility of Er is few orders of

magnitude less than the concentration needed for the LEDs [30]. There are several ways by which Er can be incorporated into silicon such as ion implantation, solid phase epitaxy (SPE), molecular beam epitaxy (MBE), chemical vapour deposition (CVD) and ion beam epitaxy (IBE).

A wide variety of interesting properties are shown by RE atoms. They have an unoccupied core shell of electrons (the 4f shell) in the interior of the atom. These inner electrons are unaffected by the ion's exterior surroundings due to the shielding effect of the outer electrons. Intra-4f transitions occur in trivalent Er atoms implanted in semiconductor or dielectric materials having an incomplete 4f electronic shell when energized by an optical source. During the implantation the silicon lattice is damaged. Thermal treatment is used to repair this damage and activate charged erbium ions.

2.4 Electroluminescence from Rare Earth Doped Silicon Rich SiO_x

Group IV Semiconductor Inc of Ottawa, Ontario has developed light emitters using RE doped silicon rich SiO_x . The basic structure of the ELDs made by Group IV is illustrated in Fig. 2.2. The devices are made on a heavily doped bulk n-type silicon substrate. The light emitting layer consists of a rare earth doped silicon-rich silicon oxide film deposited by ECR-PECVD [31]. The top contact to the device is made with a layer of transparent conductor (typically (ITO)). All of the Er-doped films were deposited from SiH_4 , O_2 and Er (TMHD)₃. Wafers were annealed at high temperatures in flowing argon. Front and back sides of the wafer were provided with metal contacts made of Aluminum. Tb doped layers were deposited in slightly different way as compared to Er doped layers. The same procedure was followed to deposit Tb as used for Er deposition with few changes. The

ECR-PECVD system used for Tb doping was slightly different, with a higher thickness and lower rare earth concentration.

Figure 2.2 Tb-doped oxide electroluminescent device structure on bulk silicon

DC bias was applied to the films while keeping the current densities below 100 mA/cm^2 before breakdown. It was observed that with DC bias, an increase in electric field and charge trapping in the oxide led to breakdown of the device. In order to operate the device at high current densities and high electric fields, AC bias with a sinusoidal drive frequency of 15 kHz was applied. ITO interface or substrate can be used to inject electrons for SRSO films to conduct. It was assumed that AC bias reduces the overall effect of the trapped oxide charge. The EL spectra obtained from Tb doped devices is shown in Figure 3.2 [31]. It has been reported that Er doped samples have a double peak at 535/545 nm and a smaller peak at $\sim 650 \text{ nm}$. Tb doping produced bright green EL as compared to Er doping EL. Also the efficiency of energy transfer from nanocrystals to RE is greater for Tb. When a high electric field is applied to the device, electrons in the

silicon substrate tunnel into the SiO₂ film doped with the RE metals (Fowler–Nordheim tunnelling). Hot electrons transfer energy to the RE ions thereby exciting the RE ions to higher energy levels. RE ions emit light as they decay to their ground states. The light emitted by the RE metal ions leaves the device through the top transparent ITO electrode.

Some studies have also been carried out on other RE elements such as Gd and Yb [44]. Strong UV EL has been observed from an ITO/SiO₂: Gd/Si MOS structure with external quantum efficiency above 1% [45]. Strong Blue violet EL at 390 nm has also been reported with Ge 3+ implanted structures [46]. EL has been observed with Yb at 980 nm with external quantum efficiency of 0.1 % [44].

2.5 Silicon on Insulator Wafers (SOI)

SOI wafers are widely used in CMOS applications and continuous research is underway to find SOI applications in photonics [32]. SOI wafer offers many advantages over silicon wafer. In SOI wafers a uniform layer of silica is sandwiched between a thick silicon substrate and a thin surface layer of crystalline silicon. The thickness of crystalline silicon and buried silicon dioxide layer depends on the fabrication process but thicknesses ranging from a few tenths of a micron to several microns are common [33]. The different ways of manufacturing SOI substrates are explained in brief in the next section.

2.5.1 SIMOX (Separation by Implanted Oxygen)

SIMOX uses a high energy (200 keV) oxygen implant at extremely high dose (10^{18} cm^{-2}) to form the buried oxide. The technique requires that the substrate be held at a temperature of approximately 600 °C throughout the implant to maintain the crystallinity

of the surface layer via solid phase epitaxy. After implantation the buried oxide is non-stoichiometric. Wafers are annealed close to the melting point (typically near 1350 °C) to segregate oxide and silicon. At the end of anneal the buried oxide is stoichiometric SiO_2 and the defect density in the Si film is low enough to support device fabrication. [34].

2.5.2 BESOI (Bond and Etch-back SOI)

In this method two oxidized silicon wafers are electrostatically bonded. One wafer is then etched back using either chemical-mechanical polishing or plasma etching to leave a thin silicon film. This technique has the advantage that almost any buried oxide and silicon film thicknesses are possible, but has the disadvantage that two bulk wafers must be consumed to produce one SOI substrate.

2.5.3 Smart Cut

In this process a silicon wafer is oxidised and then massively implanted through the oxide layer with protons (hydrogen nucleus). Another silicon wafer is bonded to the oxide layer and this wafer acts as a substrate for the SOI wafer. A stress fracture is formed along the plane of hydrogen implant during the annealing and is called smart cut. A thin layer of silicon is left behind on the top of buried oxide when the original silicon wafer is removed from the trilayer stack. Finally the SOI wafer is annealed and polished.

2.6 Thin Film Reflectors

A phase shift of 180° takes place when a light wave is reflected from a medium with lower refractive index than the adjoining medium whereas the phase shift becomes zero if the medium has higher refractive index than the one adjoining it. Depending upon the phase shift, incident and reflected light waves interfere either constructively or destructively. Reflection at the top and bottom of thin films causes the light wave to split into two components. If the relative phase shift is 180° , the resultant of the two components is the difference of their amplitudes and waves are said to interfere destructively, if the relative phase shift is zero or a multiple of 360° then the resultant of the two components is the sum of their amplitudes and waves are said to interfere constructively.

A stack of alternate high and low index films form a basic thin-film structure with each layer one quarter wavelength in thickness[35]. Low index layers provide a phase shift of 180° to the reflected waves whereas high index layers do not cause any phase shift to the reflected waves. All the components of the incident light reflected from the various boundaries of the thin-film structure interfere constructively at the front surface. The effective reflectance of the thin film structure can be optimised with the number of layer used in the structure. High reflectance can be obtained using a large number of thin films. In such kind of thin- film structures, high reflectance is obtained over a limited range of wavelengths and a big change in reflectance is observed outside this range [36]. High reflectance can be obtained from a stack of quarter-wave dielectric layers of

alternate high and low index. This is due to the constructive interference of waves at the front surface of the assembly.

Chapter 3 Theory and Modeling

In this chapter the effectiveness of the SOI back reflector for RE doped oxide light emitting devices is examined theoretically. The reflection coefficient of the SOI structure is first evaluated at a fixed wavelength assuming no absorption in the Si film. SOI structures with Si and buried oxide film thicknesses exactly matched to the RE emission peak are considered, as are structures that can be realized using SOI material available at Carleton University. The effect of loss in the Si is then added to the analysis using the best available experimental data. Finally the total increase in light emission with a SOI back reflector is estimated by integrating over wavelength, both for ideal Si and SiO₂ layer thicknesses, and for the thicknesses that could be obtained with wafers available at Carleton University.

3.1 Reflection Coefficient

Modelling of the electroluminescent devices fabricated in this project is based on the simple and well established formula of reflection. The three layers of the SOI substrate act as a multiple dielectric interface. In case of multiple dielectric interface, the electric field reflection coefficient R depends on the thickness of the different layers used in the interface. In order to get maximum reflection, the thickness of these layers needs to be optimised. The reflection coefficient formula for two layer dielectric interface with light

at normal incidence is given below [37]. Light emission in the ELD's is isotropic in nature but to make calculations simpler only normal incidence of light is considered.

$$R = \frac{n_1 - n_{234}}{n_1 + n_{234}} \quad (3.1)$$

$$\text{where } n_{234} = n_2 \frac{n_{34} + jn_2 \tan(\beta_2 d_2)}{n_2 + jn_{34} \tan(\beta_2 d_2)} \quad (3.2)$$

$$\text{and } n_{34} = n_3 \frac{n_4 + jn_3 \tan(\beta_3 d_3)}{n_3 + jn_4 \tan(\beta_3 d_3)} \quad (3.3)$$

$$\text{With } \beta = \frac{2\pi}{\lambda} \quad (3.4)$$

The power reflection coefficient is equal to $|R|^2$.

Fig. 3.1 illustrates the optical structure modelled here. Light is emitted in a Tb-doped deposited oxide film which is assumed to have the refractive index of pure SiO₂. Light emitted downwards encounters a thin Si film of index n_2 and thickness d_2 formed over a buried oxide of thickness d_3 and index n_3 on a silicon substrate of index n_4 .

Figure 3.1 Structure for optical modeling of electroluminescent devices

3.2 Reflectance Calculations for Different Values of d_2 and d_3

SOI wafer has three layers i.e. Silicon - Silicon dioxide - Silicon which make an interface having different refractive indices. Silicon dioxide is buried between the two silicon layers which results in the formation of interface with HLH indices. From equations 3.1 to 3.4 for a given wavelength λ (for example for the wavelength of peak Tb emission, 545 nm) maximum reflection will take place if d_2 and d_3 are $\lambda/4$. In order to calculate the reflectance at different values of d_2 and d_3 a Matlab program was used. Values for the complex refractive indices of Si and SiO₂ as a function of wavelength were taken from Ref. [38]. Values at the Tb peak emission wavelength of 545 nm are listed in Table 3.1.

Table 3.1 Refractive indices n for Si and SiO₂ at $\lambda = 545$ nm (Tb emission peak) [38].

Material:	n:
Si	4.10175+j 0.044
SiO ₂	1.46

The emission spectrum for Tb-doped SiO₂ is shown in Fig. 3.2. The Matlab program was modified to numerically integrate the emission-reflectance product over this spectrum. Assuming that half the light is emitted towards the substrate, and that there is perfect transmission of light through the top conductive electrode, the use of the SOI substrate allows 90% of the light emitted by the Tb to escape the device, compared to 61% emission for the bulk control.

Figure 3.2 Normalized emission spectrum for Tb-doped SiO₂ [39].

3.3 Optical Absorption in Si Film

Relatively heavy doping of the Si film is required to provide a low-resistance lateral path for current from the Si film contact into the region under the emitting oxide. Heavy doping is also required to ensure that the Si film does not deplete. Doping levels up to 10^{20} cm^{-3} were used here (details are given in ch. 4). There have been few studies of optical absorption in doped Si films. Extrapolating the data of Schmid [40], at this

doping level the absorption coefficient α at 545 nm wavelength is only about 10% higher than in undoped material, where $\alpha \approx 10^4 \text{ cm}^{-1}$.

Figure 3.3 Power reflectance versus wavelength for optimum ($\lambda/4$) Si film and buried oxide thickness.

Figure 3.3 shows the power reflectance with the use of SOI substrate having $\lambda/4$ thin silicon and silicon dioxide. It also shows the effect of optical absorption in the heavily doped thin silicon layer.

3.4 Reflection Coefficient Calculations Based On the Wafer Available In Carleton University Fabrication Lab

Two Smart cut SOI wafers from SOITEC were used for this project.

Specifications of the SOI Wafers available in the Carleton Fabrication lab are given in Table 3.2.

Table 3.2 Parameters of the SOI wafers used in the project

Name	Parameter	Value
d_2	Thickness of medium2 (Thin silicon film on SOI wafer)	340 nm
d_3	Thickness of medium 3 (buried oxide in SOI wafer)	1006 nm

Figure 3.4 shows the power reflectance for $d_2 = \lambda/4$ and $d_3 = 1006$ nm. This buried oxide thickness corresponds approximately to 7.38 quarter wavelengths at the Tb emission peak. It is observed that plot the shown in Figure 3.4 has more crests and troughs as compared to the plot generated in Figure 3.3 with SOI having $\lambda/4$ silicon film and buried oxide. This is expected, since with such a thick buried oxide a relatively small change in λ can change the optical thickness of the oxide from an odd to an even number of quarter wavelengths, shifting from constructive to destructive interference.

Figure 3.4 Power reflectance versus wavelength for ($\lambda/4$) Si film and 1006 nm buried oxide thickness.

3.5 Comparison of Light Output Using SOI Wafer and Bulk Substrate.

For the SOI substrates available for this project, the buried oxide thickness closest to an odd integer multiple of $\lambda/4$ at the Tb emission peak was 1006 nm. Use of such a thick buried oxide makes the back reflector less effective for wavelengths far from the Tb emission peak. Figure.3.5 compares the output spectrum expected for a $\lambda/4$ Si film thickness over 1006 nm buried oxide to that of a bulk substrate device. Even with this non-optimum buried oxide thickness, the model predicts the SOI back reflector should improve light output by $\approx 35\%$ integrated over the Tb emission spectrum.

Figure 3.5 Predicted output spectrum for $\lambda/4$ Si film thickness over 1006 nm buried oxide.

Chapter 4 Device Fabrication

In this chapter a detailed explanation of the steps involved in the fabrication of SOI-based ELDs is given. The specifications of the SOI starting material are also covered in this chapter.

4.1 Device Structure

The cross-section through a typical device of the type reported here is shown in Fig. 4.1. Unlike earlier electroluminescent SiO_2 devices [39], the devices fabricated here must be contacted from the front surface, not through the bulk. This requires that current flow laterally through the thin silicon film into the device. To obtain maximum light emission the Si film in the emitting region must be an odd integer multiple of $\lambda/4$ thick, where λ is the wavelength of peak emission. If the film is too thin, resistive voltage drops will block emission from the center region of the device. Conversely, as the film thickness is increased more light is absorbed in the silicon. For the Tb emission peak at 545 nm, a $\lambda/4$ film thickness corresponds to a physical thickness of just 32 nm. Current densities of approximately 100 mAcm^{-2} at bias voltages of near 30 V are expected in operating devices [39]. An upper bound on the resistive voltage drop across the Si thin film can be obtained by assuming that all the current required by the device must flow from one edge to the other. For a typical device with square layout geometry, this corresponds to the

current flowing through one square of Si film resistor. The largest voltage drop will be found for the largest device area- in this case 1 mm^2 , giving a current of 1 mA . The Si film doping used here is estimated to be between 10^{18} and 10^{19} cm^{-3} . In the latter case the electron mobility is approximately $100 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ [41], giving a sheet resistance R_S of about $2 \text{ k}\Omega/\square$. The larger value of R_S gives a resistive voltage drop of just 2 V , which should be negligible compared to the 30 V supply. For this reason relatively thin Si films were used here. The Si film was first uniformly thinned to $3\lambda/4$, and then the Local Oxidation of Silicon (LOCOS) technique was used to selectively thin the active areas of some devices to $\lambda/4$, as shown in Fig. 4.1. This was done to provide information on how strongly the Si film attenuates light.

Figure 4.1: Tb-doped oxide electroluminescent device structure on SOI.

4.2 Device Layout

A mask set for the formation of SOI electroluminescent devices was prepared using the L-Edit mask design software. The overall layout is shown in Fig. 4.2. The chip contains test devices with sizes ranging from $250 \text{ }\mu\text{m}^2$ to 1 mm^2 . There are also rectangular devices with length much greater than width to examine the effect of Si film sheet

resistance, and test structures to estimate layer sheet resistances and contact resistance.

All device sizes have examples with $\lambda/4$ and $3\lambda/4$ film thicknesses. Fig. 4.3 shows a close-up view of the layout for a typical $250\text{ }\mu\text{m}$ square device. Contact to the Si thin film and ITO top electrode surrounds the active area.

Figure 4.2: Overall layout of the SOI Electroluminescent devices.

Figure 4.3 Layout for a typical 250 μm square device

4.3 Substrate Preparation

Two 100 mm diameter SOI wafers with nominal 10 Ωcm Si film resistivity from SOITEC Corporation were used as starting material for the experiments reported here. These substrates were manufactured using the Smart cut technique, which produces very uniform silicon film thickness. The buried oxide thickness was 1006 nm and the initial silicon thickness was 340 nm.

From the results obtained from the calculations done in chapter 3, the silicon must be thinned down to an odd integer multiple of $\lambda/4$ to obtain maximum light emission. Here silicon film thickness of 32 nm and 108 nm were used. The initial silicon thickness of 340 nm was reduced to the desired values by oxidation. For better control, and to minimize the oxidation times required, a total of four oxidations were used. After each oxidation, the oxide film was completely removed by etching in hydrofluoric acid to hydrophobia. Details are given in Table 4.1. Oxidations were carried out at 1000 $^{\circ}\text{C}$. An initial 20 min dry O_2 cycle was used to grow a thin oxide to protect the silicon surface, after which the bulk of the oxide was grown in pyrogenic H_2O , since wet oxidation provides a far higher growth rate than dry. Initial estimates for oxidation times required

were obtained by Suprem4 simulation [42]. After each oxidation the thickness of oxide grown on a lightly-doped p-type test wafer included in the run was measured to determine the amount of silicon consumed, noting that growth of a thickness t_{ox} of dry oxide consumes $0.45t_{\text{ox}}$ of silicon. The first two oxidations were intended to remove equal amounts of silicon. The time of the second oxidation was adjusted slightly based on the oxide thickness measured after the first oxidation. The short third oxidation was used to introduce a slight variation in the oxide thickness across each wafer. This was done by using a photoresist mask to remove the oxide grown in the second oxidation from only half the wafer. This slows the oxidation rate in those areas already covered by oxide. It is estimated that this procedure resulted in a silicon film thickness difference of 20 nm across the wafer. The purpose of this deliberate variation was to ensure that at least part of the wafer would come close to the target $\lambda/4$ or $3\lambda/4$ thickness. For the final oxidation, the Local Oxidation of Silicon (LOCOS) technique was used. Standard deviation of 3-4 nm is estimated in the computed Si film thicknesses based on the variation in ellipsometer readings for the monitor wafers.

Table 4.1 Oxidation Details

Time	Desired oxide	Silicon consumed	Residual silicon thickness
20 min dry	224 nm	98 nm	242 nm
23 min wet			
55 min dry	244 nm	108 nm	134 nm
29 min wet			
10 min dry	45 nm	20 nm	114 nm

4.3.1 Local Oxidation of Silicon

LOCOS was used to produce split oxide thickness on the same chip. LOCOS [43] begins with a pad oxidation required to reduce the stress caused by the mismatch in the thermal expansion between the silicon nitride and silicon substrate. Here a 50 nm pad oxide was grown by 11 min of dry oxidation at 1100 °C. The pad oxide is then overlaid with a nitride layer that protects the silicon surface from the oxidizing species. Deposition of nitride layer is done using low pressure chemical vapor deposition (LPCVD) technique which involves the reaction of the following gases:

80 nm of nitride was deposited using LPCVD technique at 820 °C for 13 min.

4.4 N + Arsenic Implant

After thinning the silicon on SOI wafer to the required thickness wafers were subjected to heavy arsenic implants to convert the lightly doped p-type Si film to heavily doped n+ type. Wafers were shipped to Kroko Implant Services in Los Angeles, CA for implantation along with some test wafers. Relatively heavy doping of the Si film in the device of Figure 4.1 is required to provide a low-resistance lateral path for current from the Si film contact into the region under the emitting oxide. Heavy doping is also required to ensure that the Si film does not deplete. Wafers were implanted with arsenic using two different doses of 10^{15} cm^{-2} and 10^{14} cm^{-2} at 30 keV energy. Two different implant doses were used to examine the effect of film doping on optical absorption. The implant was annealed in N_2 at 1000 °C for 10 min. Suprem4 predicts a final doping concentration in the film of approximately 10^{19} cm^{-3} for the lighter and 10^{20} cm^{-3} for the heavier implant. Suprem4 appeared to drastically overestimate the As concentration for thin silicon, predicting values in excess of 10^{21} cm^{-3} , probably as the result of an overestimate of As segregation from the buried oxide into the Si film.

Figures 4.4 and 4.5 shows the Suprem4 simulation doping profiles of thick silicon with different doping concentration before annealing. Figure 4.6 and 4.7 shows the Suprem4 simulation doping profiles of thick silicon with different doping concentration after annealing. The doping profiles for thin silicon were similar to the doping profiles of thick silicon.

Figure 4.4 Suprem4 simulation of doping profile on thick silicon with low doping before annealing.

Figure 4.5 Suprem4 simulation of doping profile on thick silicon with high doping before annealing.

Figure 4.6 Suprem4 simulation of doping profile on thick silicon with low doping after annealing.

Figure 4.7 Suprem4 simulation of doping profile on thick silicon with high doping after annealing.

4.5 Emitter Dielectric Deposition

Initially the Tb-doped light emitting oxide deposition was to have been carried out at the Canadian Photonic Fabrication Center (CPFC) of the National Research Council using standard processes specified by Group IV Semiconductor. The depositions would have been done on complete 100 mm diameter wafers to industrial tolerances for repeatability and uniformity. Unfortunately, Group IV Semiconductor ceased technical operations before this deposition could be completed. A direct approach was made to the CPFC to arrange for the deposition, but we were informed that it would be necessary to re-install and re-calibrate the Tb source at a cost we could not afford. Finally arrangements were made with Prof. P. Mascher's research group to carry out the deposition at the Centre for Emerging Device Technologies at McMaster University in Hamilton, Ontario. The PECVD system used to produce the first light-emitting films in Group IV Semiconductor's initial research was employed. Unfortunately the system only had a 50 mm diameter chuck, so the samples had to be broken into small pieces for the deposition. Six separate deposition runs were required to coat all the samples, and there may have been some variation in film properties from deposition to deposition. The system was not housed in a clean room, which may account for the high density of particulates seen in the completed films. A 10 nm thick light-emitting oxide film was deposited with nominal 1 atomic percent Tb doping. A 30 nm LPCVD nitride layer was next deposited as described above to encapsulate the emitting oxide and serve as an etch stop in the subsequent process step. A 1 μm thick LPCVD oxide film was then deposited from

SiH_4/O_2 at 410 °C to provide device isolation. Windows were etched through this deposited oxide to define active device areas.

4.6 ITO and Aluminum Deposition

A 230 nm thick ITO layer was deposited by reactive sputtering using Semicore SC943 sputtering system and patterned by wet etching in HCl/HNO_3 to form a transparent top electrode. Argon was used in the process with base pressure of 2.4×10^{-7} Torr and process pressure of 5 mtorr.

A- 1 μm thick Al layer was deposited by e-beam evaporation and patterned by lift-off to provide contact to both the ITO and doped Si film. The lift off process is based on two-layer resist structure. A special lift-off resist LOR10B was used in the project. Another resist S1811 was applied over the lift-off resist LOR10B. The S1811 was exposed and developed. The developer undercuts the LOR10B resulting in a “lip” structure. Here Microposit remover 1165 at 60 °C was used to dissolve the LOR resist.

Chapter 5 : Optical Testing and Discussion

This chapter covers the optical testing of the ELDs fabricated as described in Ch. 4. Detailed information is provided about the test equipment used and the measurement-results.

5.1 Experiment Setup

First testing of ELDs was carried out in Carleton University's semiconductor device testing facility. A Wentworth wafer probe station and Agilent HP4155 Semiconductor Parameter Analyzer were used. The voltage applied to the devices was ramped while watching for light emission through the prober microscope. Devices of various sizes were tested, although most measurements were done on 250 μm by 250 μm square samples. Devices were biased with the ITO as the positive electrode to place the Si surface in accumulation. Characteristic bright green emission was observed from some devices, although many samples showed catastrophic electrical breakdown before any visible light was emitted. The cause for this variability in device performance is not known, but it is probably associated with the particulate contamination visible in the PECVD oxide. The emission was observed to be completely uniform across all devices for both silicon thicknesses and doping levels, even for high aspect ratio 250 μm wide, 500 μm long devices contacted from one narrow edge. The uniformity of light emission

from the samples was judged by human eye. This result indicates that even with the thinnest, most lightly doped Si layer current crowding is not an issue. A current of $10\ \mu\text{A}$ was injected at biases in the range 70 to 100 V. Figure 5.1 shows the typical I-V curve of a test device.

Figure 5.1 Typical I-V curve of test device.

The next step in testing was quantitative measurement of light output from the devices. At this point T.W. MacElwee of Group IV Semiconductor offered access to that company's test facilities, which were already set up to measure ELD light power output. Testing at Group IV was initially carried out using excitation from a Keithley current

source. A current of 25 μA was injected at biases in the range 70 to 100 V. Unfortunately lifetimes under electrical excitation were found to be very short (typically less than 1 minute) making it difficult to record output spectra. A picture of a failed device with fracture lines visible in ITO is shown in Figure 5.2

Figure 5.2 Picture of failed device

Picture shown in Figure 5.3 shows the test equipment used at Group IV Semiconductor.

Figure 5.3 shows the test setup at Group IV semiconductor, Kanata.

To obtain spectra, devices were therefore excited with a 325 nm Kimmon HeCd CW laser providing an output power of approximately 15 mW at the target. The output spectra obtained with PL for best and worst cases with SOI wafers and also for a bulk substrate control device are shown in Figure 5.4. Although the best SOI device gave higher light output than the control, the variation between samples was too great to

conclusively demonstrate the advantage of the back reflector. This variation in light output is believed to be the result of non-uniformity and variability in the properties of the Tb-doped PECVD oxide.

Figure 5.4 Output spectra under photoexcitation (arbitrary units on y-axis)

Figure 5.5 compares typical output spectra for devices with thin ($\lambda/4$) and thick ($3\lambda/4$) Si layers on the same chip. The two devices are spaced less than a millimeter apart and have PECVD oxides formed in the same deposition cycle, so the light emission characteristics of the oxides should be very similar. The light output of the thick Si

device is only about 10% less than that of the thin device, indicating that light absorption in the Si film is not having a major impact on the devices, particularly for $\lambda/4$ films.

Figure 5.5 Comparison of output spectra for thick and thin Si films on the same chip (arbitrary units on y-axis).

Since sample-to-sample variability precluded direct demonstration of the advantage of the back reflector, using comparisons of the output spectra, our attention was turned to the detailed shape of the spectral peaks to provide some validation of the theory of Section 2. In particular, the relative magnitude of the 495 and 545 nm peaks in the Tb spectrum is quite sensitive to changes in thin-film interference effects resulting from changes in the Si film thickness. The model of Section 2 predicts that ratio of peak

heights should differ by only 1% for the 32 and 108 nm Si film thicknesses used here.

Far larger differences in peak height ratio are predicted for other film thicknesses.

Table 5.1 gives the ratio of the 495 to 545 nm peak heights for the devices measured here, and indeed the ratio is very similar for the thick and thin devices in every sample.

Table 5.1 Ratio of 545 to 495 nm peak height for different samples.

Sample:	Si Film (nm):	Implant Dose (cm⁻²):	Peak ratio:
HS1L1	32	1e14	1.16
HS1L1	108	1e14	1.16
HS1L2	32	1e14	1.36
HS1L2	108	1e14	1.21
HS2L1	32	1e15	1.61
HS2L1	108	1e15	1.60
HS2L2	32	1e15	1.31
HS2L2	108	1e15	1.25

Chapter 6 Results: Conclusion and Discussion

6.1 Thesis Summary

To our knowledge this thesis reports the first rare-earth doped oxide MOS capacitor ELDs with SOI back reflectors. Analysis predicts an SOI back reflector with buried oxide and Si film thicknesses of $\lambda/4$ (where λ is the wavelength of the Tb emission peak) should provide a total 35% increase in light output for a device with a Tb doped oxide layer. Test devices were fabricated on SOITEC substrates with initial Si thicknesses of 340 nm and buried oxide thickness of 1006 nm. Selective oxidation was used to thin the Si film to thicknesses of 32 nm ($\lambda/4$) and 108 nm ($3\lambda/4$). The film was doped in the range 10^{19} - 10^{20} cm⁻³ by As implantation. The emitting oxide was deposited by PECVD at McMaster University and contained 1% Tb. The emitting oxide was overlaid with a Si₃N₄ cap layer and then with an ITO transparent conductor top electrode. Most testing was done on 250 μ m square devices using a 25 μ A current drive at approximately 75 V. Uniform EL was observed across the device area, indicating that current crowding is not an issue even for the thinnest, most lightly doped Si films. Unfortunately many devices suffered destructive breakdown before EL was observed, and even in those devices which emitted light time to destructive failure was usually less than one minute. For these reasons light output was measured using PL rather than EL, with devices excited using a HeCd laser.

Comparison of the output spectra for thick and thin Si films demonstrated that light absorption in the Si film has a relatively minor effect on the emission efficiency, particularly for a $\lambda/4$ film.

6.2 Recommendations for Future Work

This thesis has provided a first demonstration of the use of back reflectors with Tb-doped oxide ELDs. The limited number of samples which could be processed and variation in the properties of the deposited oxide from sample to sample precluded a direct demonstration of enhanced light emission from devices with back reflectors. Fabrication of more samples with a better controlled doped oxide deposition system to verify the advantage of the back reflector would be highly desirable.

The SOI structure lends itself to the integration of control electronics with ELD emitters to produce a light emitting array. Experimental demonstration of such an array would be a very interesting project.

Appendix A - Fabrication Run Sheet

Starting material: Two 4" SOITEC wafers 1 μ m buried oxide 340 nm Si, label HS-1, HS-2

1. FIRST SI THINNING OXIDATION (blanket) 1000 °C 20 min dry, 23 min wet
target oxide thickness: 224 nm target Si removal: 98 nm
include 2 - 4" P type test wafers

a) RCA clean

b) Oxidation tube temperature 1000 °C

5 min preheat	O ₂
2" every 6 sec push	O ₂
20 min oxidation	dry O ₂
23 min oxidation	O ₂ + pyrogenic H ₂ O
5 min anneal	N ₂
2" every 15 sec pull	N ₂
10 min cool	N ₂

Target thickness: 224 nm

Thickness measured on test wafer 204.1 nm

2. OXIDE THICKNESS ASSESSMENT ON TEST WAFER, OXIDE ETCHBACK

confirm time for second oxidation

a) remove oxide

etch in 10% HF until oxide removed

estimated etch time: 5 min

actual etch times : 6 min 30 sec

3. SECOND SI THINNING OXIDATION (blanket) 1000 °C 20 min dry, ~23 min wet
(based on first oxidation)

target oxide thickness: 224 nm target Si removal: 98 nm

a) Oxidation tube temperature 1000 °C

5 min preheat	O ₂
2" every 6 sec push	O ₂
20 min oxidation	dry O ₂
29 min oxidation	O ₂ + pyrogenic H ₂ O
5 min anneal	N ₂
2" every 15 sec pull	N ₂
10 min cool	N ₂

target thickness: 250 nm

thickness measured on test wafer: 236.2 nm

3.1 TOP UP OXIDATION FROM 236.2 nm TO 244 nm-246 nm, 1000 °C 35 min dry

5 min preheat	O ₂
2" every 6 sec push	O ₂
35 min oxidation	dry O ₂

5 min anneal	N ₂
2" every 15 sec pull	N ₂
10 min cool	N ₂

4. ETCH OXIDE FROM HALF THE WAFER

Half & Half P.E. Mask ½ and ½ mask

- a) dehydration bake, apply, prebake, expose,
develop, postbake, descum S1811 photoresist
- b) remove oxide on half the wafer
etch in buffered HF until
oxide removed
estimated etch time:
actual etch time: 2 min 30 sec
- c) strip PR in PlasmaPreen

5. THIRD SI THINNING OXIDATION 1100 °C 10 min dry

target oxide thickness: 45 nm target Si removal: 20 nm
include test wafer

- a) RCA clean
- b) Oxidation tube temperature 1100 °C

5 min preheat	O ₂
2" every 6 sec push	O ₂
10 min oxidation	dry O ₂

20 min anneal	N ₂
---------------	----------------

2" every 15 sec pull	N ₂
----------------------	----------------

10 min cool	N ₂
-------------	----------------

target thickness: 45 nm

thickness measured on test wafer: 45.5 nm

6. STRIP ALL OXIDE

a) remove oxide

etch in 10% HF until oxide removed

estimated etch time:

actual etch times: 10 min

7. PAD OXIDE GROWTH 1100 °C 11min dry O₂

target oxide thickness: 50 nm target Si removal: 22 nm

include test wafer

a) RCA clean

b) Oxidation tube temperature 1100 °C

5 min preheat	O ₂
---------------	----------------

2" every 6 sec push	O ₂
---------------------	----------------

11 min oxidation	dry O ₂
------------------	--------------------

20 min anneal	N ₂
---------------	----------------

2" every 15 sec pull	N ₂
----------------------	----------------

10 min cool	N ₂
-------------	----------------

target thickness: 50 nm

thickness measured on test wafer: 52.5 nm

8. NITRIDE DEPOSITION 80 nm

include test wafer

LPCVD tube temperature: 820 °C

deposition time: 13 min

target thickness: 80 nm

9. SI THINNING PE (ETCH NITRIDE AND PAD OXIDE) Mask CU-296-01

a) dehydration bake, apply, prebake, expose,
develop, postbake, descum S1811 photoresist

b) plasma etch nitride (Technics Planar Etch II)

power: 100 W source gas: freon/5%O₂

pressure: 0.3 Torr

estimated etch time: 1 min 50 sec

actual etch times:

c) remove pad oxide

etch in buffered HF until

oxide removed from device wells

10. FOURTH SI THINNING OXIDATION 1100 °C, 80 min dry

target oxide thickness: 147 nm target Si removal: 64 nm

a) RCA clean

b) Oxidation tube temperature 1100 °C

5 min preheat O₂

2" every 6 sec push	O ₂
80 min oxidation	dry O ₂
40 min anneal	N ₂
2" every 15 sec pull	N ₂
10 min cool	N ₂

11. NITRIDE / OXIDE STRIP

a) remove converted nitride

etch in 10% HF until oxide removed from top of nitride

actual etch time – 30 sec

b) plasma etch nitride (Technics Planar Etch II)

power: 100 W source gas: freon/5%O₂

pressure: 0.3 Torr

estimated etch time: 1 min 30 sec

actual etch times:

c) remove all oxide

etch in buffered HF until oxide removed from device wells

estimated etch time: 40 sec

actual etch times: 1 min 30 sec

12. SCREEN OXIDATION 1000 °C 12 min dry

target oxide thickness: 10 nm

a) RCA clean

b) Oxidation tube temperature 1100 °C

5 min preheat O₂

2" every 6 sec push	O ₂
5 min oxidation	dry O ₂
40 min anneal	N ₂
2" every 15 sec pull	N ₂
10 min cool	N ₂

13. N+ ARSENIC IMPLANT ENERGY 50keV

Ship to Kroko implant services

HS1: energy 50 keV ,dose $1 \times 10^{15} \text{cm}^{-2}$

HS2: energy 50 keV dose $1 \times 10^{14} \text{cm}^{-2}$

14. IMPLANT ANNEAL 1000 °C 10 min

tube temperature :1000 °C

a) RCA clean

b) anneal

5 min preheat	N ₂
2" every 6 sec push	N ₂
10 min anneal	N ₂
2" every 15 sec pull	N ₂
10 min cool	N ₂

15. EMITTER DIELECTRIC PRECLEAN AND DEPOSITION ~100nm

done at Mc master university , Hamilton

After dielectric deposition samples were annealed Bruce 8 stack tube 6:

25 min @ 900 °C then 60 min @ 800 °C.

16. LPCVD CAP NITRIDE DEPOSITION

Nitride deposition 80 nm
include test wafer

LPCVD tube temperature: 820 °C
deposition time: 5 min 50 sec
target thickness: 30 nm
actual thickness 32.6 nm

17. LOTOX DEPOSITION 1µm (LPCVD FIELD OXIDE)

include test wafer

tube temperature 410 °C

target thickness 1µm

actual thickness 1.04 µm

18. FIELD OXIDE PE (ETCH THROUGH LOTOX TO EXPOSE NITRIDE)

Mask CU 296-02

- a) Plasma preen , apply, prebake, expose,
develop, postbake, descum S1811 photoresist
- b) Lotox etch ~5 min BOE (buffered oxide etchant (7:1)
- c) strip PR in acetone/IPA/DI water + Plasma Preen

19. ITO DEPOSITION (CONDUCTIVE TOP ELECTRODE)

230 nm thick ITO reactive sputtering (Semicore SC 943 inline sputtering system)
Base pressure = 2.4×10^{-7} Torr, Process pressure = 5 mTorr, Gas Argon, Recipe:
ITO1pass, scan speed 12.63 cm/min.

20. ITO/EMITTER PE (patterns ITO and underlying emitter dielectric)

Mask CU 296-03

a)dehydration bake, apply, prebake, expose,
develop, postbake, descum S1811 photoresist

patterned by wet etching in HCl/HNO₃. ITO etch in Aqua Regia

Pour 200 mL of DI water into beaker and heat to 45 °C (using the thermocouple feedback to control the hotplate).

In a separate beaker dispense 160 mL of hydrochloric acid, followed by 40 mL of nitric acid. Allow the solution to age for 90 s, it should turn yellow.

Carefully add the mixture to the 200 mL of water. The solution will heat up.

Maintain a temperature of 45°C unless otherwise specified.

Slowly insert wafer holder into the solution and allow to etch as instructed in FabFlow.

WATCHPOINT: Look for uniform removal of ITO across the wafers

Upon completion, remove wafers from the solution and rinse in flowing DI water.

Inspect wafer under microscope for complete removal of ITO. In the event of incomplete etching, repeat process.

PR strip – acetone/IPA/DI water

21. CONTACT PE (etch through dielectric stack to expose Si for contacts)

Mask CU 296-04

a)dehydration bake, apply, prebake, expose,
develop, postbake, descum S1811 photoresist

5 min BOE (buffered oxide etchant (7:1) etches through LOTOX 1 μ m

2min 40 sec Technics RF plasma etching, CF₄/O₂ gas, to etch through 30 nm nitride

1 min 15 sec BOE – to etch through emitter dielectric oxide (100 nm)

PR strip – acetone/IPA/DI water. Plasmapreen 5min + 5min.

22. METAL PE Mask CU 296-05

a) dehydration bake, apply, prebake, expose,

develop, postbake, descum ,LOR 10B, S1811 photoresist

23. AL DEPOSITION AND LIFT-OFF

1 μ m thick Al layer was deposited by e-beam evaporation (Balzers)

Base pressure -2×10^{-6} torr, substrate at ambient temp. and patterned by lift-off to provide contact to both the ITO and doped Si film.

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