Silicon Photonics
矽光子學
Prospects for Silicon Light-emitting Devices (A)

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Outline

- 8.1 ERBIUM DOPING
- 8.2 LOW-DIMENSIONAL STRUCTURES

Silicon Light-emitting Devices

- The goal to fabricate silicon-based, electrically pumped, light-emitting devices (LEDs) with efficiencies comparable to those obtained from III-V semiconductor materials becomes a most hotly researched areas in semicon-ductor science
- Silicon is an indirect band-gap semiconductor with a low probability for phonon-assisted, radiative electron-hole recombination (i.e. resulting in the spontaneous emission of photons).
- Relatively fast, nonradiative recombination mechanisms - such as those via lattice defects or the Auger mechanism - dominate, hence the internal quantum efficiency for silicon luminescence is only 10^{-6}
- The global research efforts are to create silicon LEDs and ultimately silicon-based lasers.

8.1 ERBIUM DOPING

ERBIUM DOPING

- Rare-earth ions, especially erbium, have played a significant role in the development of the optical communications network.
- Trivalent erbium ions (Er^{+3}) embedded in semiconductor or dielectric materials have an incomplete *4f* electronic shell, permitting intra-4f transitions when excited (or pumped) by an optical source.
- Further, the first excited state is at an energy of 0.8 eV, hence down-transitions following optical pumping with higher-energy photons (usually from either a 980 nm or 1480 nm laser source) can occur with the emission of photons at a wavelength of 1.54 μm.
- The energy levels of Er^{+3} are shown schematically in Figure 8.1.

ERBIUM DOPING

- In the 1980s it was shown that erbium-doped optical fibers could be used as optical amplifiers when pumped by a laser source [2].
- At that time, the need for efficient amplifiers for the telecommunications network was paramount, and erbium-doped fiber amplifiers (EDFAs) addressed this requirement.
- Subsequent developments led to widespread deployment of EDF as, fixing the communication wavelength at 1.54 μm.
- The same principle of photon emission as used in fiber amplifiers can be applied to erbium-doped silicon.

ERBIUM DOPING

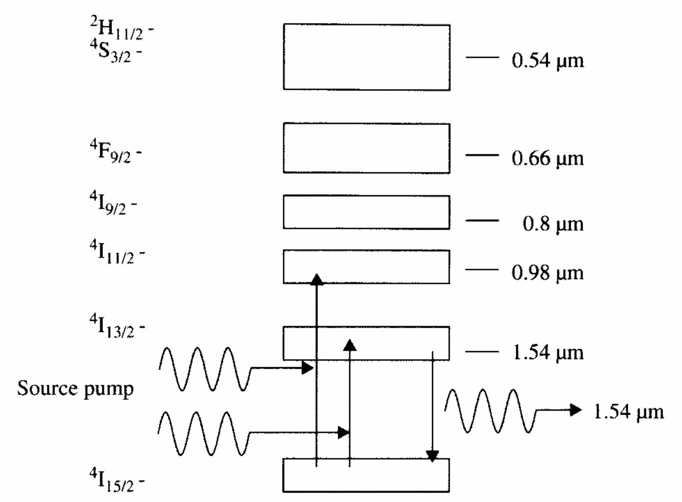

Figure 8.1 Representation of Er^{+3} electronic energy levels. Pumping sources of 980 nm and 1480 nm are shown together with the emission of photons at a wavelength of 1540 nm

Erbium Ion Implantation

- A significant restriction on the fabrication of silicon optical sources is the need for the fabrication methods to be completely compatible with processing techniques used in the manufacture of more standard devices in an ultra-large-scale-integration (ULSI) process flow.
- Many of the current approaches utilize ion implantation for the formation of the optically active medium.
- Ion implanters are ubiquitous in silicon device fabrication facilities and devices using implant technology usually meet the requirement for ULSI compatibility.
- Implantation is a convenient method for introducing erbium into silicon [3], although erbium's high atomic mass restricts the projected range to about 15 % of that for a boron ion of equivalent energy.

Erbium Ion Implantation

- Therefore, many of the experimental reports in the research literature describe setups using implanters capable of producing ions with energies of > 1 MeV.
- Erbium doping of silicon progresses in a similar manner to that for more common dopants such as boron.
- Following ion implantation, a thermal treatment repairs the silicon lattice damage while activating the charged erbium ion. Subsequent fabrication of a *p-n* junction allows the generation of charge carriers which can recombine via energy transfer to the Er^{3+} ion.
- Once excited, the Er^{3+} ion can in turn decay with the emission of a 1.54 μm photon (see Figure 8.2).
- The efficiency limits of this electroluminescence mechanism were described by Xie et al. [4] who concluded that, for performance comparable with InGaAsP/InP devices, researchers should concentrate their efforts on increasing the concentration of active erbium incorporated into silicon.

Luminescence spectrum for erbium-doped silicon

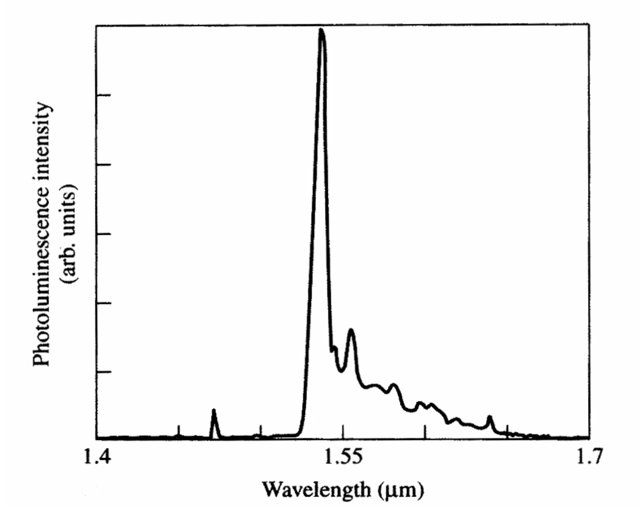

Figure 8.2 Typical luminescence spectrum for erbium-doped silicon.

Erbium Ion Implantation

- Ion implantation is a non-equilibrium process and as such can be used to introduce large concentrations of any dopant into the near-surface region of a silicon wafer.
- However, the thermal step required to reconstruct the silicon lattice does not guarantee all of the dopant is incorporated into the silicon matrix in a useful manner.
- For common electrical dopants, the limit of solid solubility is >5 x 10^{20} cm^{-3}, but for erbium it is only 1 x 10^{18} cm^{-3}.
- Polman et al. [5] used a low-temperature (600°C) anneal to reconstruct an amorphous layer created by the Er implantation (a process known as *solid-phase epitaxy),* they were able to incorporate a concentration 1 x 10^{20} cm^{-3} Er ions.
- However, they observed a complex interaction of the implanted ions and implant-induced defects, resulting in the segregation of a large proportion of the erbium out of the crystalline structure, thus rendering it of no use in the formation of optically active centers.

Erbium Ion Implantation

- A significant discovery related to Er incorporation was the role played by oxygen.
- In a subsequent report to [5], the same group co-implanted 1-MeV Er^{+} ions to a dose of 1.6 x 10^{15} cm^{-2} and 160-keV O ions to a dose of 5 x 10^{15} cm^{-2}, such that the implantation profiles of Er and O overlapped.
- Following solid-phase epitaxy of the implanted amorphous layer, almost no segregation was observed with the annealed Er profile being coincident with the as-implanted profile.
- It appeared that the erbium formed a bond with the oxygen and this so-called complex was less easily segregated from the silicon crystal [3]

Optical Efficiency of Er-implanted Si

- After description of erbium incorporation into the silicon crystal our attention is necessarily drawn to luminescent efficiency.
- Following the recipe for high concentration incorporation described in [5], photolumi-nescence measurements (i.e. measurement of optical emission following optical excitation) were performed on as-prepared samples and those subjected to a further anneal at 1000°C for 15 seconds [6].
- The results are shown in Figure 8.3
- The spectrum includes peaks resulting from Si band-edge recombina-tion (1.13 μm), and from the de-excitation of Er^{3+} at 1.54 μm.
- The data show that both the band-edge and Er luminescence can be increased by three and five times respectively by the 1000 °C anneal.

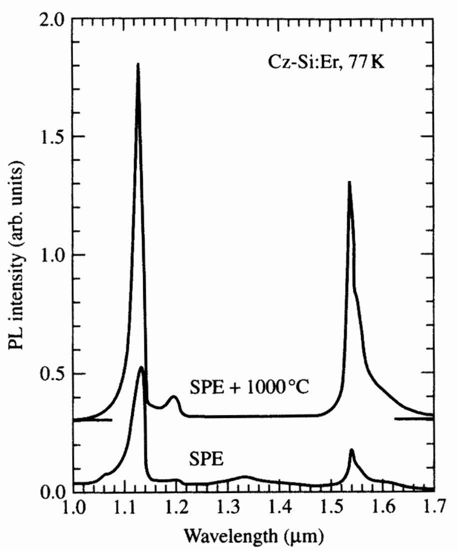

Figure 8.3 Photoluminescence spectra taken at 77 K for Er-implanted Si after solid-phase epitaxial recrystallization at 600°C (lower spectrum) and after subse-quent thermal annealing at 1000°C for 15 seconds.

Optical Efficiency of Er-implanted Si

- This is attributed to the reduction of crystalline defects which are still present following the solid-phase epitaxial growth at 600°C. Reduction in defect concen-tration and hence competitive nonradiative recombination, increases the efficiency of the Er^{3+} excitation.
- The photoluminescence intensity as a function of implanted erbium dose was obtained in the same study and is reproduced in Figure 8.4.
- It is plotted together with the Er photoluminescence lifetime. These data show that there is a clearly defined limit as to the concentration of optically active erbium that can be incorporated into a silicon device. In the case of [6] this limit was deduced from data fitting to be 3 x 10^{17} cm^{-3}, much less than the concentration of 1 x 10^{20} cm^{-3} which is incorporated into the silicon crystal.

Optical Efficiency of Er-implanted Si

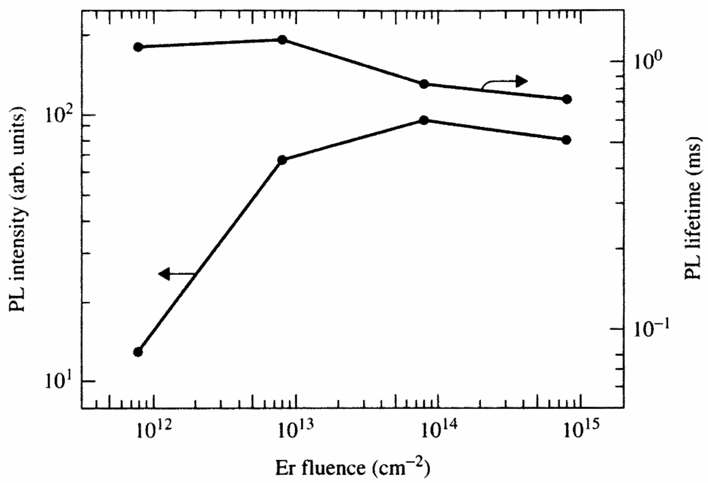

Figure 8.4 Photoluminescence and lifetime at 1.54 μm as a function of Er fluence, measured at 77K. The pump power at 514.5nm was 160mW.

Optical Efficiency of Er-implanted Si

- The nature of the optically active erbium was shown to be related to the presence of oxygen.
- The data shown in Figure 8.4 were obtained from silicon samples containing a background concentration of oxygen of 1.7 x 10^{18} cm^{-3}.
- Assuming that each optically active Er ion forms a bond with 4-6 oxygen atoms (as suggested by experimental observation), a maximum optically active concentration of between 2-6 x 10^{17} cm^{-3} can be derived, in close agreement with the measured data.
- The important conclusion is then that the active limit is determined by the concentration of oxygen co-doping, and not the total amount of embedded erbium.
- Further, one can estimate the internal quantum efficiencies for radiative recombination to be 10^{-3} and 10^{-6} for the erbium-oxygen complex and erbium-only centers respectively [3].

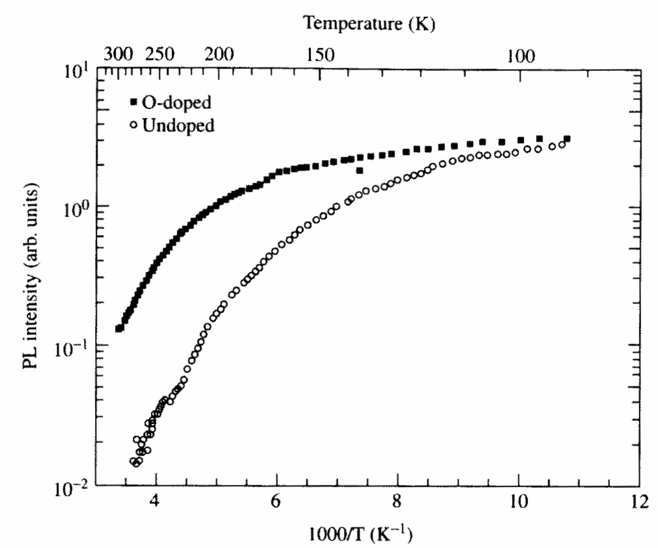

Figure 8.5 Temperature dependence of the photoluminescence intensity at 1.54 μm for both erbium-only doped (referred to in the figure as undoped) and erbium and oxygen co-doped (referred to in the figure as O-doped) samples.

Optical Intensity Quenching

- A significant problem associated with erbium-doped silicon LEDs is the severe signal quenching observed at room temperature.
- Figure 8.5 shows a plot of photoluminescence (PL) intensity versus measurement temperature for silicon either implanted with erbium and oxygen, or with just erbium.
- Post-implantation thermal treatments were similar to those outlined previously [7].
- For the erbium-only doped sample a significant reduction in PL intensity is observed as the measurement temperature is increased from 77 K to 300 K.
- At room temperature, the intensity is so weak as to be unmeasurable.

Optical Intensity Quenching

- However, the presence of oxygen is found to be beneficial in the reduction of quenching effects and a small amount of luminescence is measured for the co-doped sample.
- It has been suggested that the most significant contributions to temperature quenching in (Er+ O)-doped silicon are via:
  - (1) a 'back-transfer' mechanism in which Er^{3+} ions, excited by trapped carrier recombination, relax via a nonradiative transfer of energy to valence electrons which are in turn excited to a defect level located inside the forbidden energy band-gap; and
  - (2) the Auger excitation of free carriers [3].

Electroluminescent (EL) Devices

- The creation of a light-emitting diode (LED) requires the fabrication of a *p-n* junction within an optically active medium.
- In principle, such electroluminescent devices can be made in a straightforward manner using Er- or (Er + O)-doped silicon.
- One such design was described by Libertino et al. [9] and is shown in Figure 8.6. When such Si LEDs are conventionally, electrically pumped using for-ward bias, extremely low efficiencies are observed at room temperature (Figure 8.7).
- In particular, there is a strong thermal quenching of the optical power as the temperature is raised towards 300 K.
- In EL devices under forward bias, the excitation of the Er ions takes place via the recombination of electron-hole pairs.
- This recombination suffers from a high probability of competing nonradiative processes in the form of Auger excitation of the high number of free carriers present in the vicinity of the forward-biased junction, and the likelihood of the Er ions during the fabrication of the device.

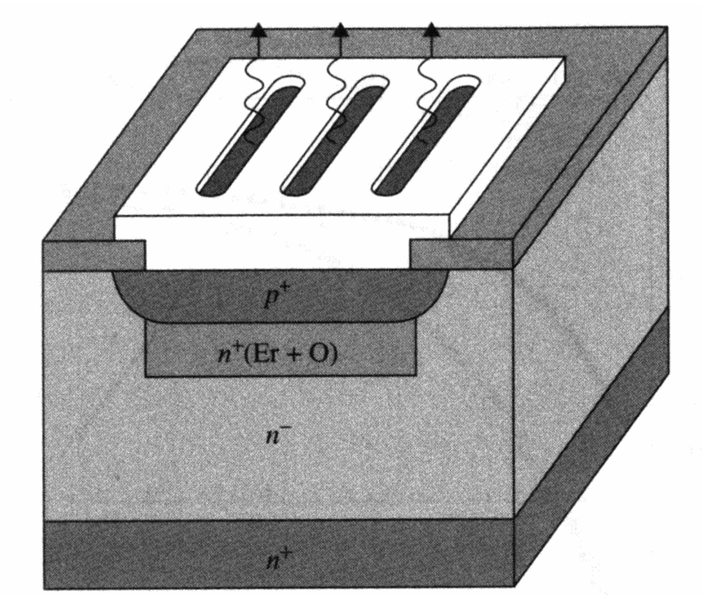

Figure 8.6 Surface emitting (Er + O)-doped Si LED.

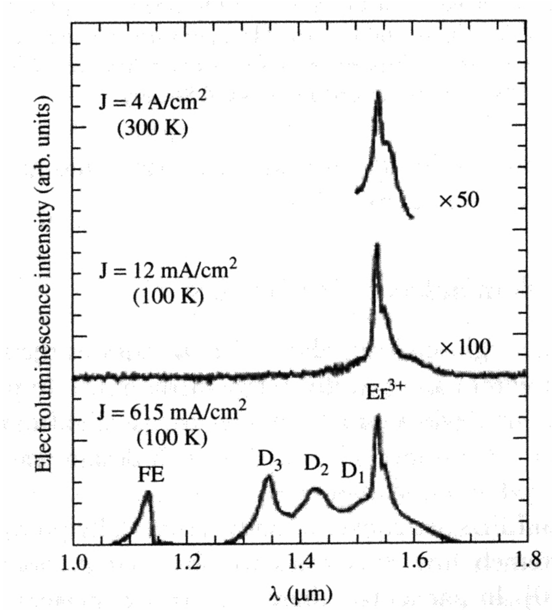

Figure 8.7 Electroluminescence spectra of a surface-emitting Si:Er LED for different current densities at 100K and at room temperature.

Electroluminescent (EL) Devices

- Following earlier work, Franzo et al. [11] discussed methods for the fabrication and optimization of electrically pumped (Er + O)-doped Si LEDs.
- They summarized the important role of oxygen in four areas (as discussed in sections 8.1.1-8.1.3):
  - 1 Oxygen increases the effective solubility of Er in Si
  - 2 It inhibits Er segregation during solid-phase epitaxy
  - 3 It enhances luminescent yield
  - 4 It reduces the temperature quenching of the luminescence.
- They also showed that reverse-biasing the devices to the point of junction breakdown (in their case >5 V applied) produces a far more efficient method (compared to forward-biasing) for generating electro-luminescence in (Er + O)-doped Si LEDs (Figure 8.8).

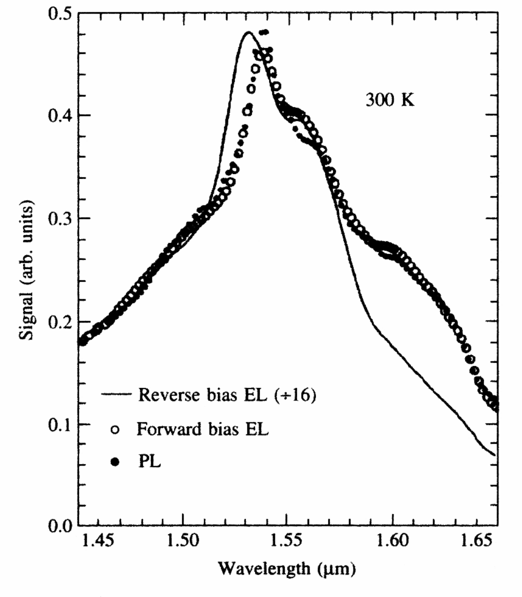

Figure 8.8 Room-temperature EL signal under both forward and reverse bias operation at a current density of 2.5 A·cm^{-2}

Electroluminescent (EL) Devices

- Notice that the reverse-biased signal is reduced in the figure by a factor of 16 for convenient comparison with the forward-biased signal. In the case of reverse-bias junction breakdown, Er ions are excited by impact ionization.
- Because the optically active (doped) region is inside the depletion layer of the junction there are no free carriers, so the Auger decay mechanism is severely inhibited.
- In fact, Franzo measured an Er decay lifetime of over 100 ILS, indicating that all fast, nonradiative mechanisms are suppressed in the reverse-biased diodes.
- The fabrication of reversed-biased Si LEDs was a significant step forward towards the goal of efficient electroluminescence.
- We shall return to the same excitation mechanism in section 8.2.4.

8.2 LOW-DIMENSIONAL STRUCTURES

LOW-DIMENSIONAL STRUCTURES

- The indirect band-gap of silicon and corresponding low probability for radiative recombination is the main reason why nonradiative transitions dominate the relaxation of excited carriers.
- One way to prevent carrier diffusion to nonradiative centers during their relatively long lifetime is to confine them in low-dimensional structures.

Porous Silicon

- In 1990, Canham [12] published a pioneering paper demonstrating efficient room-temperature luminescence from silicon samples which had been exposed to an anodization process.
- Specifically, silicon was placed in an electrochemical cell consisting of hydrofluoric acid through which a current of several milliamps was passed.
- The resulting structure of the samples consisted of an array of small holes that ran orthogonally to the sample surface.
- The dimension of the holes was shown to be controlled by the anodizing conditions. If the holes were made so large as to overlap, isolated pillars formed on the sample surface.
- Following exposure to aqueous HF acid, this so-called porous silicon exhibited efficient room-temperature photolumi-nescence (PL) upon irradiation with Ar laser lines at 488 and 514.5 nm (Figure 8.9).

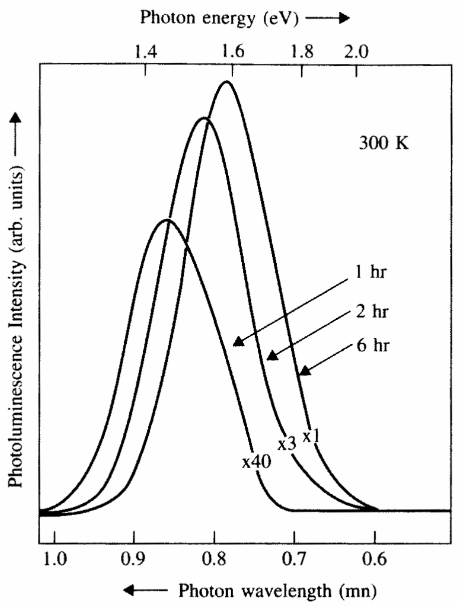

Figure 8.9 Room-temperature photoluminescence from anodized p-type silicon following subsequent immersion in aqueous HF acid. The optical pump consisted of 200mW at a wavelength of 514.5nm.

Porous Silicon

- The efficient PL is a direct result of the small width of the silicon pillars.
- As the pillars are reduced in dimension to below a few nanometers, quantum confinement of the excited carriers results in an effective enlargement of the silicon band-gap, increasing the probability of recombination.
- In addition, the localization of the carriers prevents their diffusion to possible nonradiative recombination centers, thus increasing the chances of radiative down-transitions.
- The first electroluminescent porous silicon device was demonstrated by Richter et al. [13].
- Following the fabrication of a 75-μm thick porous layer in an n-type silicon wafer, a thin film (12 nm) of gold was deposited on the porous silicon layer.

Porous Silicon

- After the formation of an ohmic contact to the reverse of the wafer, a current of 5 mA was passed through the device.
- A voltage of 200 V was required to achieve this modest current flow.
- A small but observable emission (with the eye in a darkened environment) was recorded and is shown in Figure 8.10.
- Efficient photoluminescence from a similarly prepared sample is shown for comparison.
- Considerable progress in the fabrication of EL porous silicon LEDs is evidenced by a recent paper of Gelloz and Koshida [14].
- In it they describe the fabrication of a 1-μm thick porous silicon layer, subsequently oxidized using an electrochemical process.

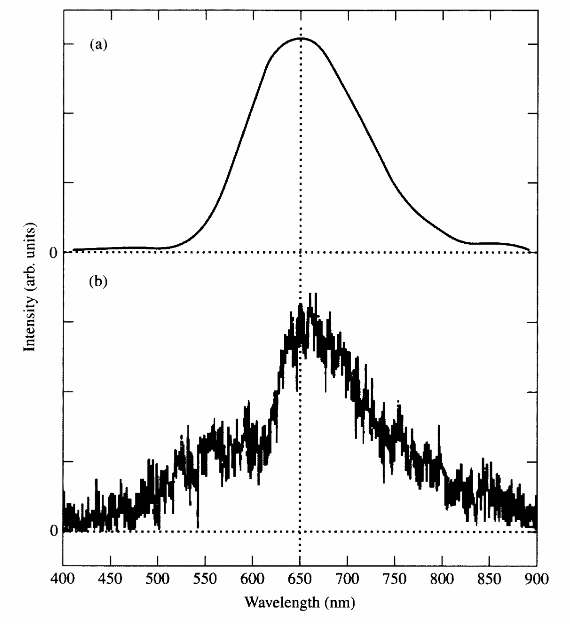

Figure 8.10 Spectra of light-emitting porous silicon pumped (a) optically and (b) electrically.

Porous Silicon

- Indium tin oxide is used as the electrode material for the porous silicon layer with aluminum providing an ohmic contact to the wafer backside.
- Room-temperature EL with an external quantum efficiency approaching 1 % for an applied bias of 5 V is reported, although the exact nature of the carrier excita-tion process is not known.
- These devices are the most efficient porous Si LEDs reported to date (Figure 8.11).
- Since Canham's original paper there has been an enormous interest in porous silicon research (for a comprehensive review see [15]).
- One reason for the plethora of published work is the low-cost fabrication method available even for those with the most modest research budgets.

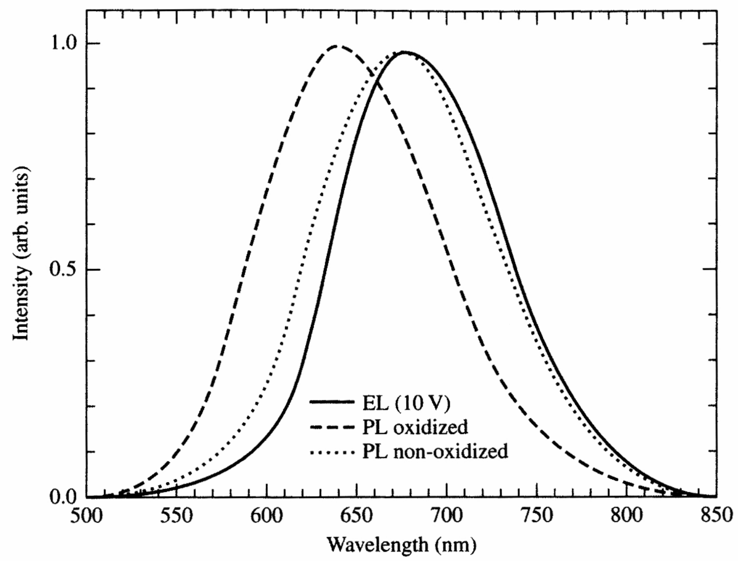

Figure 8.11 Electroluminescence at an applied voltage of 10V for porous silicon, anodically oxidized LEDs. Normalized photoluminescence spectra for similar struc-tures is shown for comparison.

Porous Silicon

- Indeed this cost-effective fabrication route is an advantage of porous silicon, although concerns exist as to the compatibility of porous silicon with more mainstream silicon processing.
- A further issue with this technology is the emission wavelength which is restricted to a range associated with sub-band-gap energies.
- This makes porous silicon unsuitable for use as a signal source for long-haul telecoms, but does not preclude it as a potential pump source or for communication over short distances.

Nano-crystals

- An approach that combines the advantages of low-dimensional silicon with a robust ULSI-compatible fabrication process is the use of silicon nano-crystals (Si-nc) embedded in a dielectric matrix, most commonly SiO_2.
- A straightforward fabrication technique involves the formation of a silicon-rich, sub-stoichiometric SiOx (x < 2) film on a silicon substrate, followed by a high-temperature anneal in the region of 1200˚C for several minutes.
- The thermal energy promotes the phase separation of Si and SiO_2 and the final structure consists of small silicon nano-crystals whose size and distribution depend on the original film properties and the subsequent thermal anneal.

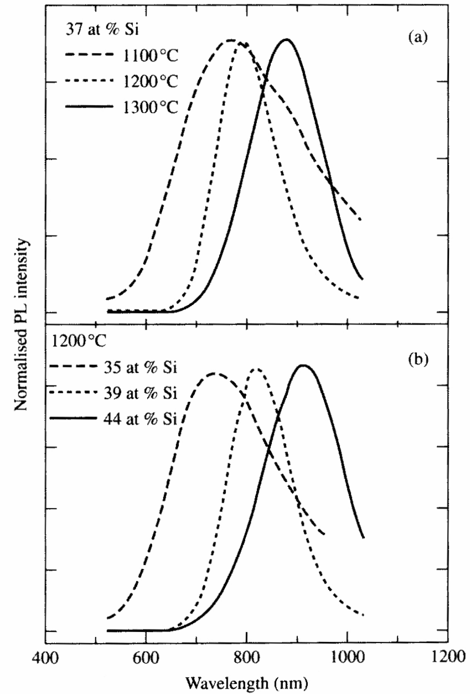

Figure 8.12 Normalized room-temperature PL spectra of (a) a SiOx film having a Si concentration of 37 % after thermal annealing processes performed at 1100, 1200 and 1300˚C for 1 hour; and (b) SiOx films having Si concentrations of 35, 39 and 44 % after thermal annealing performed at 1200˚C for 1 hour.

Nano-crystals

- Iacona et al. [16] produced silicon-rich films by plasma-enhanced chemical vapor deposition (PECVD) with *x* varying between 1 and 1.75.
- The thermal treatment consisted of an anneal at between 1000 ˚C and 1300 ˚C for one hour.
- The resulting Si-nc structures were reported to have a mean radius of between 0.7 and 2.1 nm.
- Photoluminescence measurements following excitation with a 488-nm Ar laser are reproduced in Figure 8.12.
- The authors exhibited repeatable control over both the emission wavelength and the PL intensity, with the peak wavelength shifting from 650 nm to 900 nm as the percentage of silicon in the deposited film was increased from 35% to 44%.
- Annealing at 1250˚C produced the greatest PL intensity, with an increase of nearly two orders of magnitude compared to samples annealed at 1000˚C.

Nano-crystals

- A different method for embedded Si nano-crystal fabrication was demonstrated by Min et al. [17].
- They implanted Si^+ ions into a 100-nm thick thermally grown SiO_2 film.
- The implantation energy was 50 keV and the doses ranged from 1 to 5 x 10^{16} cm^{-2}.
- The implanted sam-ples were annealed at temperatures in the range 1000-1200˚C for 10 minutes.
- In addition to demonstrating efficient PL, the authors were able to address issues relating to the origin of the luminescence sig-nal.
- By comparing results from Si^+ and Xe^+ implanted SiO_2 films they distinguished signals emanating from the Si-nc and those originating from SiO2 defects.

Nano-crystals

- This study also highlighted the advantages of using ion implantation to form the nano-crystals; namely the precise control of excess Si concentration and the concentration profile of the formed Si-nc structures, allowing fabrication of samples with predictable and repeatable luminescence characteristics.
- Devices in which the optically active medium is insulating (as is the case for SiO_2) would seem incompatible with electrical excitation.
- Indeed the fabrication of LEDs using this medium has proven troublesome.
- Even so, by utilization of a current tunneling between the embedded nano-crystals, efficient electroluminescence has been demonstrated.
- In these devices it is likely that control of the Si-nc structure dimensions is compounded by the need for sufficient current densities (dependent on the Si-nc distribution) to create efficient EL.

Nano-crystals

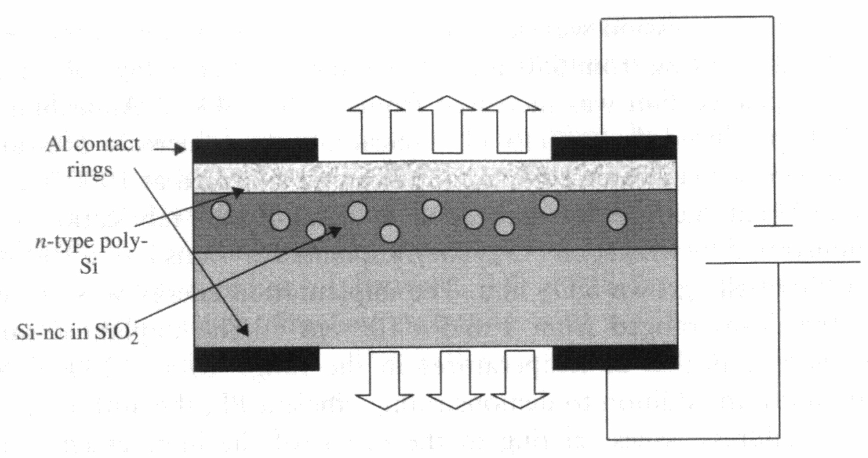

Figure 8.13 Graphical representation of a possible design for a Si-nc LED

Nano-crystals

- Irrera et al. [18] fabricated a Si-nc LED using silicon PECVD-deposited SiOx, subsequently annealed at 1100°C for 1 hour.
- Contact to the Si-nc containing layer was made via a poly silicon/aluminum stack.
- For a graphical representation of a device based on this design see Figure 8.13.
- The EL obtained from this structure is reproduced in Figure 8.14.
- It is assumed that the luminescence results from electron-hole recombination inside the Si-nc, initially excited by impact ionization from hot electron injection (somewhat similar to the mechanism used for efficient EL in (Er + O)-doped reverse-biased Si LEDs described in section 8.1.4).

Nano-crystals

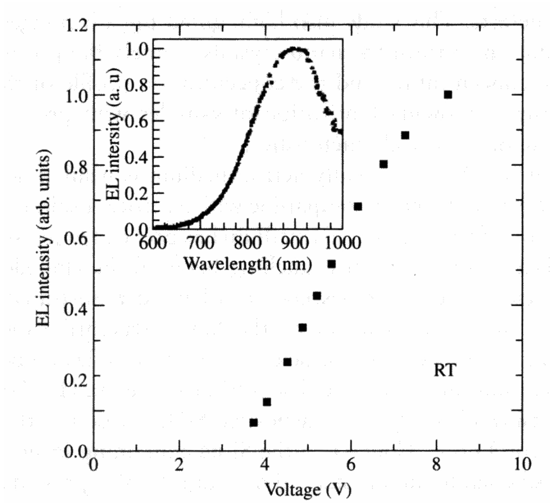

Figure 8.14 Room-temperature EL as a function of applied voltage for a Si-nc LED. Inset is the EL spectrum.

Nano-crystals

- Finally in this section, it is appropriate to highlight the ground-breaking work of the group lead by Lorenzo Pavesi from which optical amplification was demonstrated raising expectations that Si nano-crystals may provide a route to a silicon laser.
- The original report more recently Pavesi presented a complete review of all current attempts to fabricate a silicon laser device [20].
- The microscopic details of the gain mechanism is currently under debate; however, Pavesi suggests that it is related to the recombination at localized states, probably related to silicon-oxygen bonds formed at the interface of the Si-nc and the oxide, or within the oxide matrix itself.

Nano-crystals

- The confirmation of gain in Si-nc has been shown by a number of researchers. In their original experimental report, Pavesi et al. used a straightforward pump-probe arrangement shown schematically in Figure 8.15.
- The sample was prepared using the method of high-dose (1×10^{17} cm^{-2}) Si^{+} ion implantation of a high-purity quartz, followed by an anneal of 1l00°C for 1 hour.
- The use of quartz (as opposed to a silicon substrate) was required because of the transmission geometry of the experiment.
- The sample was pumped by an intense laser beam at 390 nm, strong enough to provide the population inversion conditions required for optical gain (mean power of $2kW/cm^2$).

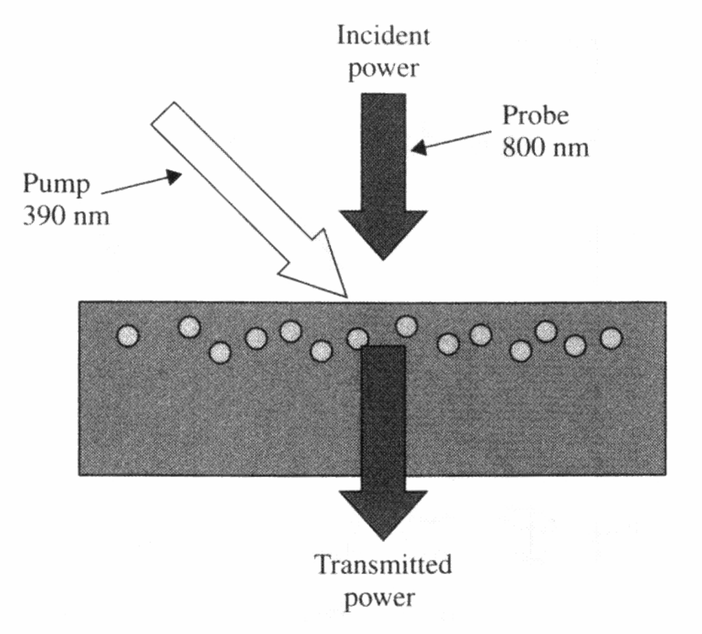

Figure 8.15 Pump-probe experimental setup to measure optical gain of Si-nc

Nano-crystals

- A relatively weak probe signal of 800 nm was passed through the layer containing the Si-nc with the difference between the incident and output power being recorded.
- The results are reproduced in Figure 8.16. Significant gain is observed in the region of $10{,}000\ cm^{-1}$.
- Further indication of gain was inferred from measurements of optical loss for power densities <1 kW/cm^2 (i.e. where population inversion is not achieved), and by the absence of gain for probe wavelengths far away from 800 nm (where the probe is no longer resonant with the optical transition).

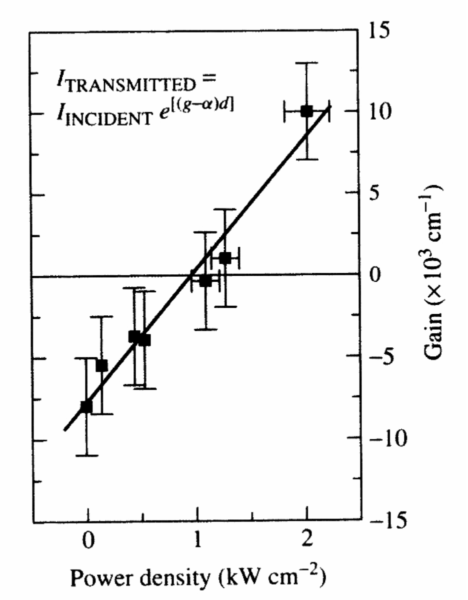

Figure 8.16 Dependence of Si-nc material gain versus pump power density for the experimental setup shown in Figure 8.15.

Nano-crystals with Erbium

- Silicon nano-crystal (Si-nc) technology shows great promise for the development of Si light-emitting diodes and optically pumped amplifiers, with the possible application to a silicon laser structure.
- However, the operating wavelengths of these devices is in a window spanning 750-1000nm.
- For use in the telecoms network it is desirable for light sources to operate at 1.3 μm or 1.5 μm.
- As we have seen in section 8.1, significant advances have been reported in the fabrication of 1.5-μm emitting devices following the incorporation of erbium into silicon.
- It is therefore a natural extension to combine Si-nc technology with Er doping.

Nano-crystals with Erbium

- Franzo et al. [21] implanted Er+ ions into a Si-nc matrix formed by PECVD deposition of silicon-rich films and subsequent annealing at 1250°C.
- Following implantation the films were further annealed at a temperature of 900°C to reduce the implant-induced defect concentration.
- They found that not only did the Er ions produce luminescence, but the process was more efficient by a factor of 100 compared to (Er + O)-implanted bulk silicon.
- Their results are reproduced in Figure 8.17. The authors suggested that the Er ions are pumped by electron-hole pairs generated within the Si-nc, but the ions themselves are located in the SiO_2 matrix.

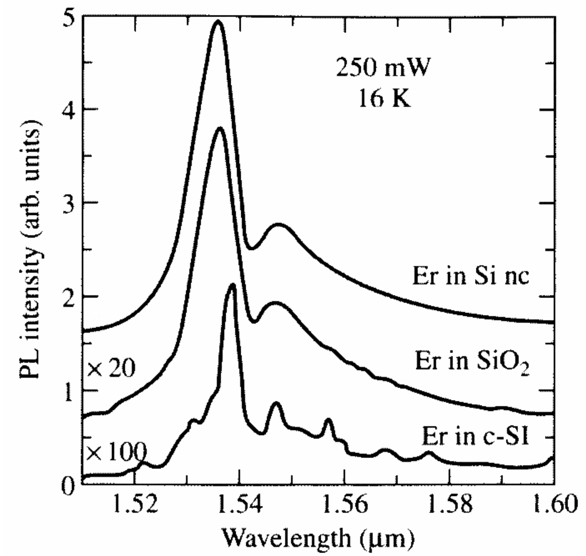

Figure 8.17 Photoluminescence spectra measured at 16 K by pumping with a laser power of 250 m W for three different samples: (Er + O)-implanted crystalline Si, Er-implanted SiO_2, and Er-implanted Si nano-crystals. The erbium concentration is 10^{20} cm^{-3} in all three cases.

Nano-crystals with Erbium

- However, correlated with increasing reliability was a decrease in the EL efficiency.
- Even so, acceptable long-life performance was achieved using samples with a small concentration of Si-nc (refractive index of 1.6 as opposed to 1.46 for pure SiO_2). showing an external quantum efficiency of 1 %.
- Recently, the group lead by Salvatore Coffa at STMicroelectronics [22] published a report of electroluminescence from Er-doped SiO^2 as a function of concentration of Si-nc.
- The device processing is compatible with a standard silicon device fabrication route consisting of oxidation, ion implantation, poly-silicon deposition, annealing and metallization, and results in a device similar in structure to that shown in Figure 8.13.

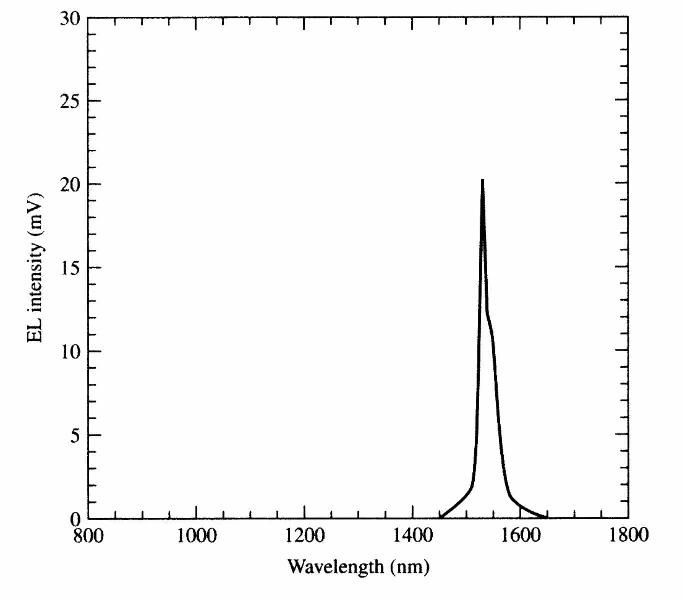

Figure 8.18 Room-temperature EL spectrum measured at 100 μA on a metal-oxide-semiconductor (MOS) device with Er-doped stoichiometric oxide.

Nano-crystals with Erbium

- A tunneling current of 100 μA was used to induce room-temperature EL with an external quantum efficiency of 10 % in a device where the Er-containing SiO_2 was thermally grown (Figure 8.18).
- The max-imum output was found to be limited only by the density of Er ions incorporated into the oxide film (approximately 1×10^{19} cm^{-3}).
- Although these Er-doped MOS devices exhibited efficiency approach-ing that of a commercial III-V LED, they were shown to be limited by their reliability and operating lifetime.
- This resulted from the use of a tunneling current through the thermally grown SiO_2 to excite the Er^{3+} ions.

Nano-crystals with Erbium

- By replacing the thermal oxide with a silicon-rich PECVD-deposited *SiOx* layer (*x* < 2) and subsequently thermally treating it to form Si-nc before Er ion implantation, Coffa's team was able to significantly improve device reliability.
- This was explained as resulting from a Si-nc mediated current passing through the *SiOx* layer as opposed to a more destructive oxide tunneling current.
- However, correlated with increasing reliability was a decrease in the EL efficiency.
- Even so, acceptable long-life performance was achieved using samples with a small concentration of Si-nc (refractive index of 1.6 as opposed to 1.46 for pure SiO_2). showing an external quantum efficiency of 1 %.