

Routes toward silicon-based lasers

by Lorenzo Pavesi

Silicon, the material *par excellence* for electronics, is not used for light sources because of the lack of efficient light emitters and lasers. In this review, I will discuss the physical reasons why silicon is not a laser material and some approaches to make it lasing. I will start with bulk silicon, then I will discuss silicon nanocrystals and Er^{3+} -coupled silicon nanocrystals, where significant advances have been made in the past and can be expected in the near future. I will conclude with an optimistic note on silicon lasing.

Starting in September 1962, scientists reported functioning injection diode lasers from three independent laboratories – GE (two distinct groups), IBM, and Massachusetts Institute of Technology's Lincoln Lab. The groups' results appeared within three months of each other in the literature¹. Since then, the photonics revolution has begun, and nowadays injection diode lasers are widespread in everyday life.

A laser is based on three main components (Fig. 1): an active material that is able to generate and to amplify light by stimulated emission of photons, an optical cavity that provides the optical feedback to sustain the laser action, and a pumping mechanism that is able to excite the active material such that population inversion can be achieved. In an injection diode laser, the pumping mechanism is provided by carrier injection via a *p-n* junction and the optical feedback is provided by a Fabry-Perot cavity. The use of electrical injection makes the device particularly interesting for integration with microelectronics.

Limitations of Si

Among the various semiconductor materials that have been used to fabricate lasers, the absence of Si is striking. One naturally wonders why Si has not been used as a laser material. The reasons are associated with the fundamental properties of Si. The schematic band diagram of this indirect band gap semiconductor is shown in Fig. 2. The probability for radiative recombination is low in Si, which means that the electron-hole (e-h) radiative lifetime is long, of the order of some milliseconds. This is not a limit *per se*, in fact there are lasers with active centers characterized by long lifetimes. The

Dipartimento di Fisica,
Università di Trento,
via Sommarive 14,
I-38050 Povo, Italy
E-mail: pavesi@science.unitn.it

problem with Si is the fact that while waiting for radiative recombination to take place, both the electrons and holes move around. If they encounter a defect or a trapping center, they can recombine nonradiatively. Typical nonradiative recombination lifetimes are nanoseconds in Si. The ability of a material to emit light is usually quantified by the internal quantum efficiency η_{int} , which is the ratio of the probability that an excited e-h pair recombine radiatively and the probability of e-h pair recombination. Thus, in electronic grade Si the internal quantum efficiency η_{int} is $\sim 10^{-6}$. This is the reason why Si is a poor luminescent material: nonradiative recombination is more efficient than radiative. Many strategies have been researched over the years to overcome this limitation², mostly by spatial localization of carriers to decrease the encounter probability with luminescence killer centers.

Two other phenomena limit the use of Si for optical amplification (Fig. 2). The first is a nonradiative, three-particle recombination mechanism where an excited electron recombines with a hole by releasing the excess energy to another carrier and not as a photon. The other carrier is, thus, excited at a high energy while e-h recombination occurs. This recombination mechanism is active as soon as more than one carrier is excited and is known as Auger recombination. The probability of Auger recombination increases as the density, Δn , of excited carriers increases and decreases as the semiconductor band gap energy increases. For Si lasers, this is undesirable because the more excited the semiconductor the more effective Auger recombination becomes. The probability of Auger recombination is proportional to Δn^3 since it is a three-particle process. Thus the Auger nonradiative

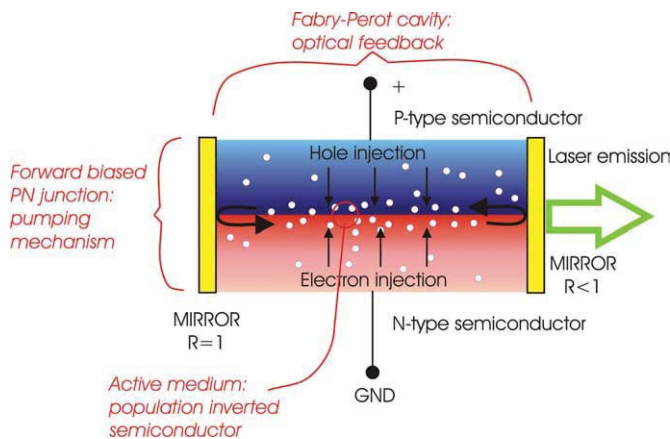


Fig. 1 Schematic of an injection laser based on a simple p-n junction.

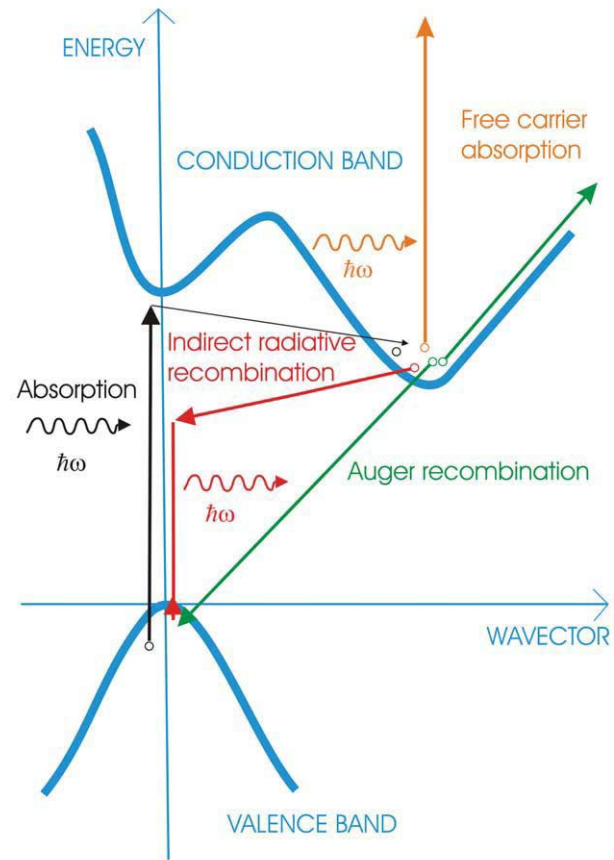


Fig. 2 Simplified energy diagram of Si. The most relevant transitions are shown. Black: absorption of a photon via a phonon-assisted indirect transition; red: emission of a photon via a phonon-assisted indirect transition; orange: free carrier absorption; green: Auger recombination process.

recombination lifetime³ is $\tau_A = 1/C\Delta n^2$, where $C \sim 10^{-30} \text{ cm}^6\text{s}^{-1}$ for Si. Auger recombination is the dominant mechanism for high carrier injection rate in Si.

The second phenomenon is related to free carrier absorption (Fig. 2). Excited carriers can absorb photons. This process depletes the inverted population and, at the same time, increases the optical losses that the photons to be amplified suffer. The free carrier absorption coefficient⁴ can be empirically related to the Si free-carrier density n_{fc} and to the light wavelength λ as $\alpha_n \sim 10^{-18} n_{fc} \cdot \lambda^2$ at 300 K. For heavily doped Si, this is the main limitation to lasing, while for intrinsic Si this contribution can be exceedingly small, unless Δn is very high as is the case for a laser.

Bulk Si

The common belief that bulk Si cannot be a light-emitting material has been severely questioned by recent work. The most interesting was published in 2001⁵. An Australian group

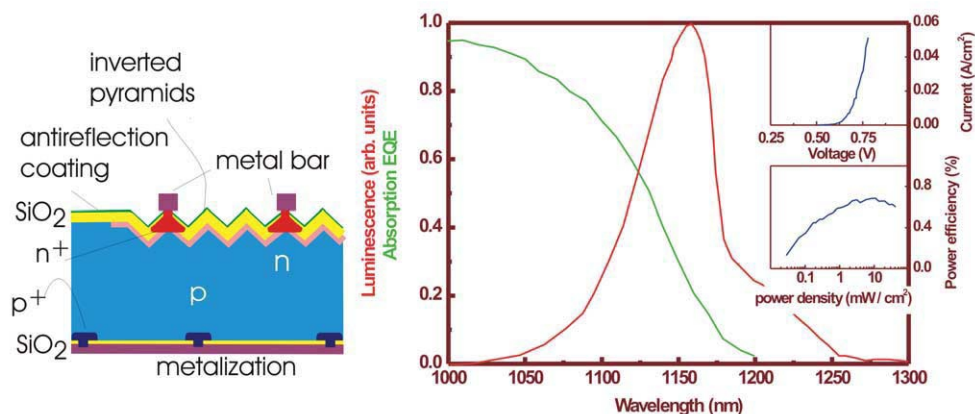


Fig. 3 Summary of the results from the Australian group on a bulk Si LED. (Left) Schematic of the LED geometry. (Right) Luminescence spectrum (red), absorption spectrum (green), power efficiency versus injected electrical power density (blue), and I - V characteristics (inset) at room temperature⁶.

noticed that some solar cells are characterized by extremely long carrier recombination lifetimes of the order of some milliseconds. That is, for these solar cells, the recombination lifetime is of the order of the radiative lifetime, hence their η_{int} is of the order of one. If the solar cell is forward biased instead of the usual reverse, the cell behaves as a very efficient light-emitting diode (LED). Fig. 3 shows a schematic of the device and a room-temperature emission spectrum. In addition, the LED surface is texturized so that most of the internally generated light impinges on the external surface of the cell with an incident angle lower than the critical angle for total internal refraction. Thus, the light extraction efficiency is increased from a few percent typical of a flat surface to almost 100% for the texturized LED. Finally, to reduce free-carrier absorption to a minimum, the electrodes, i.e. the heavily doped regions, are confined in very thin, small lines. By using these three practices, a plug-in efficiency (the ratio of the optical power emitted from the LED to the electrical driving power) larger than 1% at 200 K can be achieved⁶. Most interestingly, the turn-on voltage of the device is the same as the forward bias of the solar cell, i.e. less than 1 V.

The same group has also published a theoretical paper⁷ that questions the common belief⁸ that indirect band gap materials cannot show optical gain because of parasitic absorption processes resulting from free carriers. Indeed, they demonstrate that optical gain is theoretically possible and point out that the most suitable energy region is the sub-band-gap region where processes involving phonons could help in achieving gain. These theoretical arguments have been partially confirmed by a recent study where stimulated

emission has been observed (Fig. 4)⁹. As the limit to efficient light generation in Si is the short nonradiative lifetime, the idea is to avoid carrier diffusion and spatially localize free carriers in a small device region where nonradiative recombination centers can be easily saturated. To localize carriers, ion implantation has been used to induce dislocation loops at the junction of a p - n diode¹⁰. The dislocation loops cause local strain fields, which increase the energy gap locally producing a potential barrier for carrier diffusion. LEDs based on this idea have been realized¹¹. Other researchers have realized carrier localization by spin-on doping of small silica nanoparticles at the junction of a p - n diode⁹. The current-voltage, I - V , characteristics of the diode show rectifying behavior with a clear threshold in the light-current

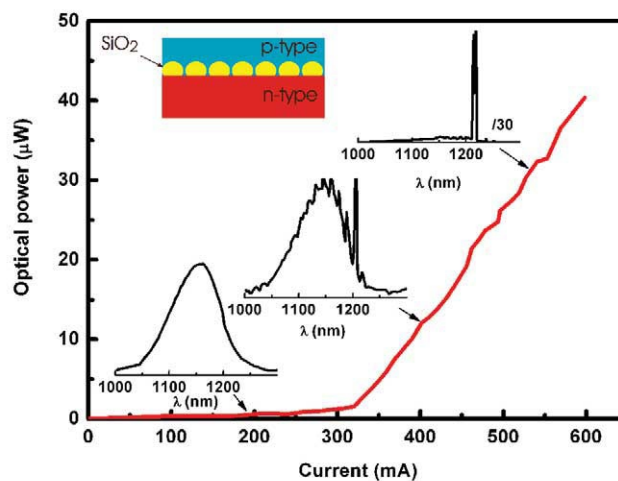


Fig. 4 Optical power versus injected current for an LED containing SiO_2 nanoclusters in the junction region (inset). Also shown are a few EL spectra for different injection rates (arrows)⁹.

characteristics. A change from the broad spectrum characteristics of band-to-band emission below the threshold to sharp peaks resulting from stimulated emission above the threshold is also observed. Stimulated emission is observed for a two-phonon indirect transition as theoretically predicted⁷. Furthermore, when the injection current significantly exceeds the threshold, a single peak dominates. These results are very encouraging since the proposed system has excellent electrical qualities as it is a *p-n* junction. The main problem with the bulk Si approach is related to the possibility of achieving a large enough gain to overcome possible free-carrier losses, which is still unclear to date. However, in the light of the present state-of-the-art, a laser made with bulk Si seems accessible.

Si nanocrystals

Another interesting approach to light emitters and amplifiers in Si is to use small nanoclusters (Si-nc) dispersed in a dielectric matrix², most frequently SiO₂. With this approach one maximizes carrier confinement, improves the radiative probability by quantum confinement, shifts the emission wavelength to the visible, controls the emission wavelength by the Si-nc dimension, decreases the confined carrier absorption because of the decreased emission wavelength, and increases the light extraction efficiency by reducing the dielectric mismatch between the source material and the air. Various techniques are used to form Si-nc, the size of which can be tailored to a few nanometers (Fig. 5).

Starting with a Si-rich oxide, which can be formed by deposition, sputtering, ion implantation, cluster evaporation, etc., partial phase separation is induced by thermal annealing. The duration of the thermal treatment, the annealing temperature, and the starting excess Si content all determine the final size of the cluster, the size dispersion, which can be significant, and the crystalline nature. The size dispersion is usually claimed as the source of the broad emission lineshape that is typical of Si-nc emission spectra at room temperature. However, both size-selective deposition¹² and single Si-nc luminescence experiments¹³ demonstrate that most of the luminescence broadening is intrinsic in nature. The active role of the interface region in determining the optical properties of Si-nc has been highlighted in a joint theoretical and experimental paper¹⁴. The origin of the luminescence in Si-nc is still unclear, but many believe it comes from confined exciton recombination in the Si-nc¹⁵, while others support a

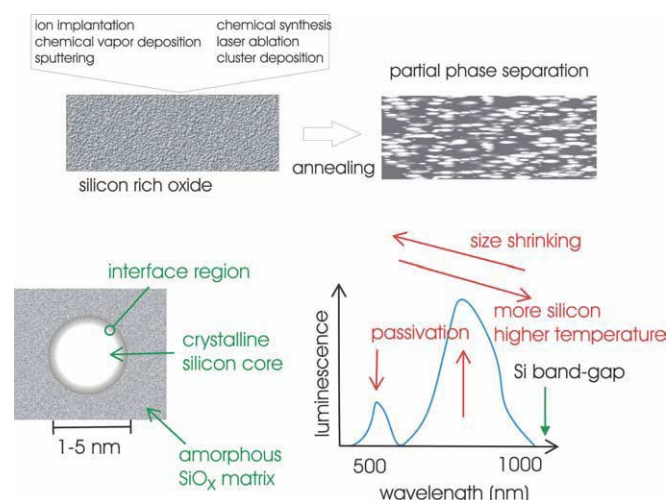


Fig. 5 Si-nc formation, structure, and luminescence spectrum.

defect-assisted recombination mechanism where luminescence is the result of the recombination of carriers trapped at radiative recombination centers that form at the interface between Si-nc and the dielectric¹⁶ or even in the dielectric itself¹⁷. One candidate for these centers is the silanone bond that is formed by double Si-O bonds¹⁸. The most probable mechanism for luminescence in Si-nc is one that involves both recombination paths: excitons at ~800 nm and trapped carriers on radiative interface states at ~700 nm. Indeed, passivation experiments show that the intensity and lineshape of the emission can be influenced by exposure to hydrogen gas or further oxidation¹⁹.

Despite skepticism, a number of papers have reported the observation of optical gain in these systems²⁰⁻²⁷. Gain has been observed in many different experiments in Si-nc formed by many different techniques. Fig. 6 gives a summary of the most relevant data taken on Si-nc formed by plasma-enhanced chemical vapor deposition (PECVD)²¹⁻²³. Two techniques are reported here: the variable stripe length method (VSL), which is shown in the inset of Fig. 6, based on a one-dimensional amplifier model, and the pump-probe technique, which is based on probe amplification in the presence of a high-energy and high-intensity pump beam. In the VSL method, by varying the pumped region extent, one can measure the amplified spontaneous emission (ASE) signal coming from the edge of a waveguide whose core is rich in Si-nc. Data in Fig. 6 shows that the ASE intensity increases sublinearly with the pumping length when the pumping power is lower than the threshold. For pumping powers

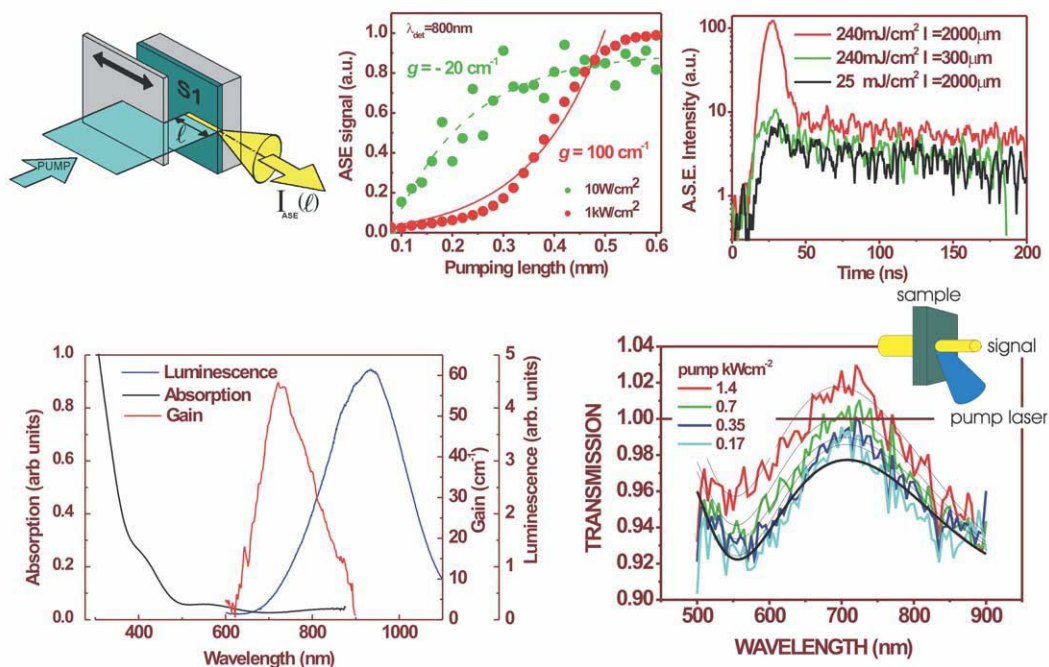


Fig. 6 Summary of experimental evidence of gain in Si-nc. (Top left) Geometry used to measure ASE; (top center) ASE versus the pumping length for two pumping powers; (top right) ASE time decay for the various pumping conditions indicated in the inset (l is the pumping length); (bottom left) luminescence, absorption, and gain spectra at room temperature for a Si-nc rich waveguide; (bottom right) transmission spectra for various pumping powers (the inset shows the experimental geometry used)²¹⁻²³.

higher than threshold, the ASE signal increases more than exponentially. In addition, if time-resolved measurements are performed (Fig. 6, top right)²², the ASE decay lineshape shows two time regimes: fast decay within the first nanoseconds and slow time decay with a typical time constant of a few microseconds. What is important is the fact that fast decay appears only if the pumping power and the excitation volume are high. If one decreases the excitation volume at high powers or the pumping power at large excitation volumes, then the fast decay disappears. This can be understood if it is assumed that fast decay is the result of stimulated emission. In fact, the Auger lifetime can be modeled in Si-nc by $\tau_A = 1/(C_A N_{ex})$, where C_A is a coefficient and N_{ex} is the density of excited recombination centers²¹. N_{ex} is directly proportional to the pumping power and not to the pumping volume. Thus decreasing the pumping length should leave the ASE lineshape unchanged. On the other hand, by simple rate equation modeling²⁸, the stimulated emission lifetime turns out to be:

$$\tau_{se} = \frac{4}{3} \pi R_{NS}^3 \frac{1}{\xi \sigma_g c n_{ph}}$$

where R_{NS} is the average radius of the Si-nc, ξ is the packing density, σ_g is the gain cross section, and n_{ph} is the photon flux density. Thus τ_{se} depends on n_{ph} , which increases as the

excitation volume increases. It is important to note that calculations show²⁹ that the Auger lifetime in Si-nc is in the interval 0.1-10 ns, which means that Auger recombination is a strongly competitive process and should be always considered. In some Si-nc systems, Auger recombination might prevail and no optical gain would be observed. Fig. 6 (bottom left) shows a summary of the wavelength dependence of the luminescence, absorption, and gain spectra in a sample with 4 nm Si-nc²¹. It can be seen that the gain spectrum is on the high-energy side of the emission band and that absorption is negligible in the region of gain and luminescence. These facts suggest a four-level model of the gain, where the levels can be associated with different Si-nc populations or to radiative states associated with Si=O double bonds for which optical excitation causes a large lattice relaxation³⁰ as in the silanone molecule.

Pump-probe measurements have been attempted with contradictory results^{23,31}. My group has shown probe amplification under pumping conditions (Fig. 6, bottom right)²³, while another group has reported pump-induced absorption probably associated with confined carrier absorption³¹. Results³² show that the confined carrier absorption cross section, σ_{fc} in Si-nc is at least one order of magnitude reduced with respect to bulk Si: $\sigma_{fc} \sim 10^{-18} \text{ cm}^2$ at

1.55 μm in P-doped Si-nc. This cross section should be further reduced at 700 nm because of the λ^2 dependence of the confined carrier absorption. Transmission measurements of a probe beam through a Si-nc slab deposited on a quartz substrate show the typical interference fringes from multiple reflections at the slab interfaces (Fig. 6). When the pump power is raised, the transmission is increased and, at the maximum power, net probe amplification with respect to the input probe intensity in air is observed in a narrow wavelength interval. Note that the probe amplification spectrum overlaps the fast luminescence spectrum measured by the time-resolved technique. Based on these results, the design of an optical cavity for a Si-nc laser has been proposed³³. In addition, very favorable results have been shown of a Si-nc-based LED where a turn-on voltage as low as few volts can be achieved using thin Si-nc active layers³⁴. Electroluminescence (EL) in these LEDs is the result of impact excitation of e-h pairs in Si-nc. Very high quality microcavities with Si-nc as the active layer show line narrowing of the emission down to a few nanometers³⁵. Channel optical waveguides with a core layer rich in Si-nc show optical losses of ~ 10 dB/cm mainly as a result of direct Si-nc absorption and Mie scattering from index mismatch between the Si-nc and the dielectric³⁶. These experiments have yet to be merged into a laser cavity structure that demonstrates a Si-nc based laser.

Er-coupled Si nanoclusters

The radiative transitions in the internal $4f$ shell of Er ions (Er^{3+}) are exploited in the Er-doped fiber amplifier (EDFA)³⁷: an all optical amplifier that has revolutionized optical communications technology. During the 1990s, various efforts² were made to develop an efficient and reliable light source using Er^{3+} in Si. The idea was to excite the Er^{3+} , which emits 1.535 μm photons, by energy transfer from electrically injected e-h pairs in a p - n Si diode. The most successful results have demonstrated room-temperature emission with an external quantum efficiency of 0.1% in a megahertz-modulated Er^{3+} -based LED³⁸. The main problem associated with Er^{3+} in Si is the back transfer of energy from the Er^{3+} ions to the Si host, which causes a lowering of the emission efficiency of the diode³⁹. This is caused by a resonant level that appears in the Si band gap from Er^{3+} doping and couples with the Er^{3+} levels. In order to reduce this back-transfer process, enlargement of the band gap of the Er^{3+} host has

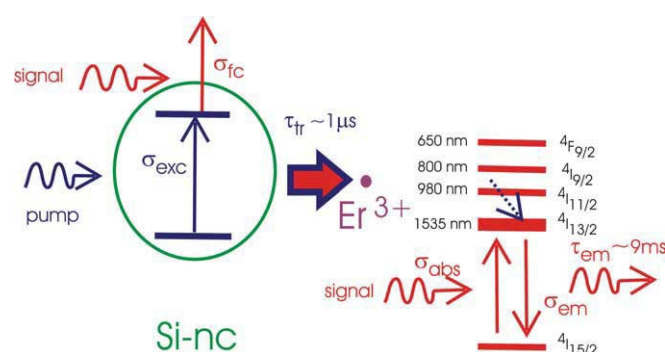


Fig. 7 Schematic of the excitation process of Er^{3+} ions via a Si-nc, with the main related cross sections. On the left, the main internal energy levels of the Er^{3+} are shown.

been proposed so that the resonance between the defect and the internal Er^{3+} levels is lost⁴⁰. Si-nc in a SiO_2 dielectric have also been proposed as the host⁴¹. Indeed, it turns out that Si-nc are very efficient sensitizers of Er^{3+} luminescence⁴² with a typical transfer efficiency as high as 70% and transfer time of 1 μs . In addition, when Er^{3+} is dispersed in SiO_2 , it finds the most favorable chemical environment. Interestingly, the transfer efficiency is maximized when the Si-nc are not completely crystallized but still in the form of nanoclusters⁴³. Some reports even claim that Er^{3+} can be excited through defects in the matrix⁴⁴. Still under debate is the number of Er ions that can be excited by a single Si-nc.

Fig. 7 summarizes the various mechanisms and defines the related cross sections for this system. Excitation of Er^{3+} occurs via energy transfer from photoexcited e-h pairs that are excited in the Si-nc: the overall efficiency of light generation at 1.535 μm through direct absorption in the Si-nc is described by an effective Er^{3+} excitation cross section σ_{exc} . On the other hand, the direct absorption of Er^{3+} , without the mediation of Si-nc, and the emission from the Er ions are described by absorption (σ_{abs}) and emission (σ_{em}) cross sections, respectively. The typical radiative lifetime of Er^{3+} is 7 ms, which is similar to Er^{3+} in pure SiO_2 ⁴⁵. Fig. 8 (left) shows the luminescence and absorption spectra from an Er^{3+} -coupled Si-nc ridge waveguide at room temperature⁴⁶. Table 1 summarizes the best results for various reported cross sections. It is important to note the five orders of magnitude increase in σ_{exc} and the fact that this value is conserved when electrical injection is used to excite the Si-nc⁴⁹. In addition, it is striking that σ_{abs} is enhanced by one order of magnitude with respect to the value for Er^{3+} in pure SiO_2 ⁵¹. A note of caution is necessary here as other work

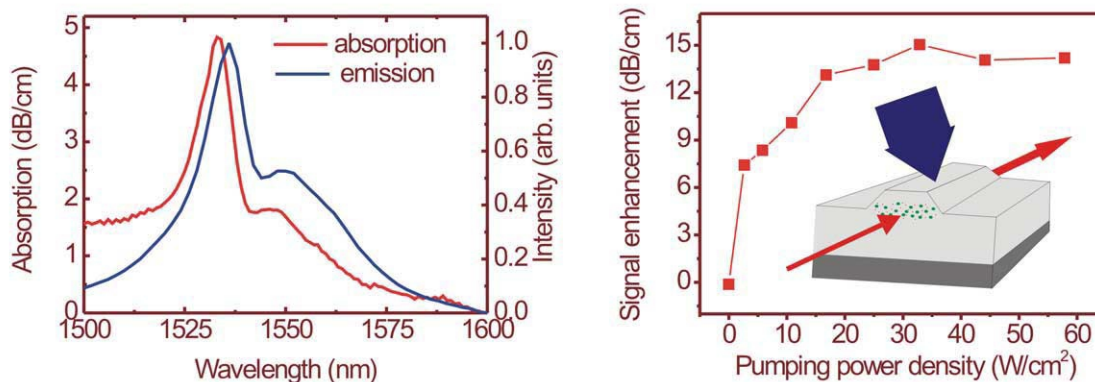


Fig. 8 (Left) Absorption (red) and luminescence (blue) spectra of an Er^{3+} -coupled Si-nc waveguide⁴⁶. (Right) Signal enhancement at $1.535 \mu\text{m}$ in an Er^{3+} -coupled Si-nc waveguide versus the pumping power density using top pumping as shown in the inset⁵⁰.

does not confirm this enhancement⁴⁶. If one places the Er^{3+} in a Si-nc ridge waveguide (Fig. 8, inset right), one can perform experiments on signal amplification at $1.535 \mu\text{m}$ with the aim of demonstrating an Er-doped waveguide amplifier (EDWA). The main advantage of an EDWA with respect to an EDFA is the reduced size, decreased pump power to achieve the same gain, and wide spectrum range to optically pump the system. A few groups have performed such experiments^{46,50,51}. The most successful⁵⁰ is shown in Fig. 8 (right). In this work, a very low Si-nc concentration was used and an internal gain of 7 dB/cm was deduced⁵⁰. The successful demonstration of pumping the EDWA with a LED battery has also been reported⁵². In other experiments, with a large Si-nc concentration, no or weak signal enhancement has been observed^{46,51}. This is attributed to the presence of a strong confined carrier absorption, which introduces a loss mechanism at the signal wavelength and prevents the sensitizing action of the Si-nc⁴⁶. Indeed, the energy transfer is in competition with confined carrier absorption at the signal

wavelength (Fig. 7). A confined carrier cross section of 10^{-18}cm^2 is usually assumed⁴². Propagation losses, saturation of Er^{3+} excitation, up-conversion of the pumped light, and confined carrier absorption make the proper design of an EDWA, where optical amplification can be observed, difficult. If the results⁵⁰ are confirmed, it seems that the right direction is to use a low Si-nc concentration, short annealing times, and a factor of 100 more Er^{3+} than Si-nc. Having achieved internal gain, electrically injected LEDs^{49,53}, and optical cavities⁵⁴, a laser that uses the Er^{3+} -coupled Si-nc system as the active material seems feasible. In this respect, it is worth noting that toroidal microcavities formed in silica doped with Er^{3+} have shown optically pumped lasing at room temperature⁵⁵.

Conclusion

As I have shown here, the prospects for a Si laser are quite good. Besides the approaches I have discussed, other directions of active research consider the use of Si-Ge alloys

Table 1 Summary of the different cross sections related to Er^{3+} in various materials. For Er^{3+} in Si-nc, the best reported results are shown, which are taken from the reference listed in the last column.

	Er in SiO_2 (cm^2)	Er in Si (cm^2)	Er in Si-nc (cm^2)	Reference for Er in Si-nc
Effective excitation cross section of luminescence at a pumping wavelength of 488 nm	1.8×10^{-21}	3×10^{-15}	$1.1\text{-}0.7 \times 10^{-16}$	47, 48
Effective excitation cross section of electroluminescence		4×10^{-14}	1×10^{-14} by impact ionization	49
Emission cross section at $1.535 \mu\text{m}$	6×10^{-21}		2×10^{-19}	50
Absorption cross section at $1.535 \mu\text{m}$	4×10^{-21}	2×10^{-20}	8×10^{-20}	51

by exploiting either Brillouin zone folding, quantum confinement, alloying effects, or nanocrystal formation^{2,56}. In addition, the Si-Ge system has been used for the band gap discontinuity that occurs at the interface and enables intraband transitions for terahertz laser emission in both simple quantum well configurations⁵⁷ and more complicated quantum cascade geometries⁵⁸. Encouraging EL results have been published for both systems. If one is not interested in having an electrically pumped system, a possible approach is based on the exploitation of Raman effects, in analogy to fiber Raman amplifiers. Indeed, stimulated Raman scattering in Si waveguides has been demonstrated by several

groups^{59,60} and a Raman amplifier integrated with an external fiber-based optical feedback⁶¹ has been shown to yield optically pumped Raman lasing in Si.

As is clear from this review, the expectations of realizing a Si-based injection laser in the near future are well founded. The variety of approaches that are now being followed, if successful, will make Si generate a rainbow of colors. **MT**

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