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# Silicon-Based Optoelectronics: Progress and Challenges

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**Abstract**

We review the status of silicon-based optoelectronics with emphasis on light emitting diodes. Erbium-doped Si, por-Si and silicon-based superlattices and nanostructures are discussed. The origin behind light emission in silicon with feature sizes below about 60 nm still remains poorly understood.

## 1. Introduction

The development of Si-based optoelectronics has at least two driving forces: the natural scientific endeavour to understand light-matter interaction in this abundant and versatile material and the challenge posed by the reduction of silicon chips feature sizes, as far as optical interconnects is concerned.

At present silicon technology is set at 0.25 $\mu$m feature size in CMOS, which is expected to decrease to 70 nm around the year 2007. This miniaturisation is accompanied by an increasing number of logic operations per chip per second, which in turn requires a dramatic increase in input and output connections, without increasing the area and volume of the circuitry. One obvious issue arising from this increasing trend to miniaturisation is the limit of metallic strip connections given that thinner and or narrower wires will inevitably result in a larger electrical resistance and therefore a larger resistance-capacitance product. This classical electromagnetism problem is usually called the electrical wire bottleneck. The rate at which input and output connections are working at requires that signals are transferred at clock frequencies above 100 MHz. This brings the issue to the realm of transmission lines with its unavoidable baggage of impedance matching and cross-talk. At this point optical propagation comes in, since the input and output rates can be increased dramatically using optical interconnects. The arguments for optical interconnects between chips and board-to-board communications have been discussed by several authors [1, 2].

The Active Silicon integrated Optical Circuit (ASOC) technology aims to meet immediate fibre optic component market demands, considering the availability of high performance light emitters and detectors, working at high frequencies and optical communication wavelengths of 1.3 and 1.5 $\mu$m [3]. These are mainly III-V semiconductor devices compatible with optical fibres. The component propagating the light brought to the chip by the fibre is usually an integrable silicon-on-insulator planar waveguide, which relies on refractive index contrast and is flexible enough to incorporate Y-junctions, bends, mirrors and 3dB couplers. Losses have been reported to be ¡ 0.1 dB/cm operating in single mode [4,5]. The planar nature of this waveguide type permits active devices to be made, such as electro-optic modulators, by applying electric fields via gates deposited on the waveguide [6]. The main competitor of this technology is the hybrid approach based on optoelectronic III-V semiconductor devices placed or grown onto a Si CMOS platform [7].

However, the use of advanced III-V optoelectronics technology has its own drawbacks, two of which are an efficient coupling to the Si platform and heat dissipation. It is here where the optical properties of Si and related materials merit reconsideration. The reader is pointed to references [8, 9] for recent reviews. Here examples of some approaches to enhance light emission in silicon-based materials are presented. Silicon-based nanostructures with special emphasis on light emission have been the subject of a recent review [10]. The table below shows a non-exhaustive summary of approaches towards a silicon based light emitting device (LED).

This is an example of bulk material doped with a suitable impurity. Erbium atoms in their $Er^{3+}$ ionic state are responsible for the emission of photons at 1.54 $\mu$m. This emission, which results from an intra-4f shell transition, is used to amplify light in Er-doped optical fibres for optical communications and is actively investigated in silicon [21]. In a free Er ion, the transition which is otherwise parity forbidden, becomes allowed due to symmetry breakage when Er is in a suitable host material and the ensuing mixing of electronic states. Current understanding of the light emission in Er:Si suggests two possible excitation processes: (a) excitation by a photon from an electron-hole (e-h) recombination, within the Si gap, at an Er-related energy level and, (b) hot carrier impact ionisation. To relax the energy two mechanisms have been proposed: (a) back transfer of energy from an $Er^{3+}$ level to states in the energy gap of Si and, (b) transfer of energy from the $Er^{3+}$ ion to free electrons in Si via an Auger process. Two issues have to be considered: (i) the excitation-light emission process is slow (milliseconds), which presents a barrier for high frequency operation and, (ii) the emission intensity quenches rapidly with increasing temperature from cryogenic levels to 300 K. The temperature quenching issue is being addressed by codoping with oxygen [22] in order to obtain a better energy match for the back transfer of energy deexcitation process. Recently Ni et al. [23] have demonstrated room temperature emission from Er/O:Si (see Figure 1). A solution to the speed issue currently includes the use of external modulators. At present 100 MHz have been demonstrated in a diode operating in reversed bias. In addition to vertical LEDs a recent Er:Si edge emitting LED integrated with a Si-SiO2 has been fabricated [24].

**Table 1.** Compariison of different approaches towards a Si- based Light emitting diode

| System | Pumping | Growth Method $T_{Gr}$ | $T_{PL}$, $T_{EL}$ (K) | Typical emission energy (meV) | FWHM (meV) | $\eta_{EL}$ % external | $\eta_{EL}$ % internal |
|---|---|---|---|---|---|---|---|
| $Si_n Ge_m$ SL on Si(100) [11] | optical & electrical | CVD 500°C | $T_{PL}$=10 $T_{PL}$=300 | 750-1100 | 150 at RT | 0.001 | 0.01 |
| Er-O doped Si(001) a) [12] b) [13] b) [14] | electrical | a) MBE b) MBE c) Ion Implantation | $T_{PL}$= 4-300 | 800-810 | 10 at RT 20 at 300K | a) ≈0.001 at RT b) 0.003 at RT | c) 0.05 at 77K and 0.015 at RT |
| direct-gap β-$FeSi_2$ on Si(001) [15] | electrical | MBE, Ion Implantation and annealing at 900°C | $T_{PL}$= 80-300 | 730-885 | 50 at 80K | ≥0.1 | — |
| Si/SiGe/Si SL [16] and $Si_{1-x}Ge_x$ dots on Si(001)[19] | electrical | LPCVD 700°C | $T_{PL}$= 80 | 840-1100 | 2D:10 0D:26 | — | 0.01-0.1 |
| porous silicon (Si rich Si oxide) [18] | electrical | CVD 610°C Sparttering, Ion Inplantation | $T_{PL}$=300 | 1400-2500 | ≈ 600 | 0.1 at RT | — |
| Si/$Si_{1-x}Ge_x$ dots on Si(001) [19] | optical/ electrical | MBE 550°C MOCVD, MBE | $T_{PL}$= 4.2-293 $T_{PL}$=293 | 885-1079 | EL: 30 at 300K | ≈ 14 at RT | — |
| Si-$SiO_2$ superlattices [20] | optical/ electrical | MBE 550°C MOCVD, MBE | $T_{PL}$= 4.2-293 $T_{PL}$= | 885-1079 | EL: 30 at 300K | ≈ 14 at RT | — |

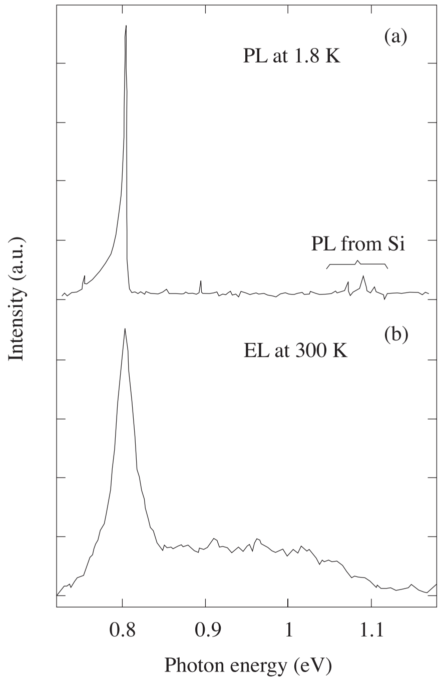


**Figure 1.** (a) Low temperature photo-luminescence spectrum from Er/O:Si grown by MBE at 420°C showing intense Er emission compared to that of Si. (b) Room temperature electro-luminescence from the sample excited by impact ionisation (Courtesy of W.-X. Ni)

Nevertheless, substantial research in Er/O:Si is required to obtain quantum efficiencies near the 1% and clocking frequencies close to 1GHz, while keeping the process CMOS compatible. Doping Si-SiGe heterostructures with Er and Er/O is a natural development under investigation in order to take advantage of bandgap engineering offered by Si/SiGe heterostructures.

## 3. Porous Silicon (por-Si), Silicon-rich Silicon Oxide (SRSO) and nanocrystals

The enormous attraction of por-Si as a light emitting material is due to its visible light emission. The science behind this process has been a rich field of investigation where surface states and quantum confinement, among others, have been called to explain the emission from por-Si. The irregular quantum wire-like structure documented by Cullis and Canham [25], which contained Si nanocrystals of a few nanometer lateral size, is thought to be partly responsible for the strong light emission. Parameters under investigation are the level of porosity, the size and distribution of pores and nanocrystallites, as well as the chemical nature of their surfaces. Recently, an efficient LED driven by an integrated bipolar junction transistor was demonstrated [18], with an operating lifetime of several weeks, although the modulation frequency of 1MHz was well below the desired level.

## 4. Superlattices and nanostructures

Silicon nanocrystals either in por-Si or embedded in a $SiO_2$, $CaF_2$ or $AlO_2$ matrix have been investigated in the quest to find volumes, albeit small, of direct gap Si. Models of silicon nanocrystallites embedded in $CaF_2$ with hydrogen and oxygen passivation of dangling bonds calculated using a self-consistent linear combination of atomic orbitals, suggest that the grain structure of nanocrytalline silicon induces the formation of a direct band gap with energies going from the bulk values for monocrystalline films, through 1.56 eV for pseudo-films, 2.38 eV for pseudo-wires, reaching 2.07 eV for pseudo-dots [26]. However, so far no LED containing these cluster-like materials has been demonstrated.

Among superlattices, Si-SiO2 grown by MBE, consisting of ultrathin amorphous Si and $SiO_2$ has attracted attention [20]. In this structure, the emission of silicon shifts to higher energies with decreasing Si layer thickness, clearly indicating quantum confinement. Evidence of a direct band-to-band recombination was said to be confirmed by x-ray techniques to measure the valence and conduction band shifts. Bright photoluminescence has been reported [20].

Si-SiGe is a lattice mismatched heterostructure with flexibility to control the concentration of Ge and the strain induced. These affect not only the band gap, but also the effective masses and the type of optical transition in real space, which is of type II for Ge concentrations of about 30% and above. The most striking result has been much improved heterobipolar transistors with better hole transport properties due to the smaller effective hole mass. The strain factor has been further studied and controlled by the addition of a few per cent of carbon to grow Si(C)-SiGe(C) by MBE [27], which has resulted in a low temperature photoluminescence increase of a factor of 10 as well as improved electrical properties. In both, Si-SiGe and Si(C)-SiGe(C), electrons are located in the Si layer, whereas holes are found in the Ge containing layer.

One of the issues driving the work on Si-SiGe and Si-Ge superlattices was the possibility to realise a Si-based direct band gap material [28]. However, unambiguous evidence of whether or not $Si_nGe_m$ superlattices had a direct bandgap was not forthcoming. Instead, from combined differential transmission and x-ray diffraction, Pearsall et al [29] concluded that the zone folded $\Gamma$-levels were too close to the indirect zone edge levels (a separation of a few meV), and therefore the standard techniques to ascertain whether the superlattice is direct or indirect did not apply. To date, there is no confirmation of the direct gap nature of Si-Ge and Si-SiGe superlattices. Moreover, this result was accompanied by observations of disorder in the superlattice structures with a correlation length of some 22 nm.

The photo- and electroluminescence work on Si-SiGe quantum dots [19] brought back the issue of what role the interface structure plays in light emission. This work is in progress and it is clear that one of the key issue in light emission from Silicon is the nature of the local environment surrounding the light emitting centre. In this respect our work [30] and that of Leifeld et al [31] are welcome developments.

## 5. Concluding Remarks

A bird's eye view of silicon-based optoelectronics has been presented, with emphasis on device-relevant properties with view to applications in optical interconnects. The physics of light emission in Si, whether interface, confinement-, localisation- or cluster-related remains unclear. This is particularly the case of nanocrystallites and Si-SiGe superlattices where simultaneous evidence of the direct and indirect nature of the energy gap is found in the same sample.

Although progress in integrable Si-based detectors and waveguides is very encoraging, electroluminescent devices have still some way to go to meet the requirements of quantum efficiency, high operating frequency and lifetime necessary to compete with the hybrid solution using III-V optoelectronic systems. Moreover, issues like compatibility with the processing steps of a Si CMOS platform, pose an enormous challenges to potential solutions involving hydrogen incorporation since this would limit processing temperatures to about 400°C. Furthermore, the need to use non-crystalline silicon would probably bring about a degrading of the unbeatable electronic properties of crystalline silicon.

Fresh thinking is required in the near future to address light emission from silicon nanoclusters and nanocomposites, before the window of opportunity for the use of silicon optoelectronics in optical interconnects closes.

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