

Optical Emission from Silicon

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CMOS circuitry growth has been largely due to the astonishing power of silicon integration technology. As miniaturization of electronic circuits progresses, the need for optoelectronic media grows. Despite silicon's popularity, bulk silicon is extremely inefficient at emitting light. Its indirect band gap only allows emission in the near IR region with external quantum efficiencies of 0.01% and even lower in the visible region. This has led to integration of more complex direct bandgap compound semiconductors (GaAs, InP) into silicon microchips. These alternatives are more expensive and degrade rapidly due to lattice mismatch, hence are kept separate from Si substrates in circuits.⁵

Addition of optical functionality to silicon-based materials has been realized through fabrication of low dimensional silicon forms¹⁰ and insertion of selected active impurities (quantum dots) and/or new phases into the silicon lattice.³

Low dimensional silicon systems include porous silicon, silicon nanocrystals, silicon/insulator superlattices and silicon nanopillars. High external quantum efficiency for photoluminescence in these systems is believed to be due to quantum confinement of excitons in the nanoscale crystallite.¹² Qualitatively speaking, confinement of carriers in real space causes the wave functions to spread out in momentum space, increasing the likelihood of radiative transitions.⁴ It also increases the size of the Si band gap resulting in stronger radiation. Silicon has also been doped with impurities in the form of rare earths (e.g. Er) causing luminescence due to internal 4*f* shell transition of the rare earth ion excited through electron-hole recombination within the silicon matrix.

Porous silicon is created by anodization of a Si wafer in hydrofluoric acid leaving a network of silicon nanowires.^{6,8,9,13,18} The resulting structure's large surface area possesses numerous dangling bonds that make it unstable. The surface is naturally passivated by fragile Si-H bonds¹⁸, but these easily succumb to ambient degradation resulting in 'dark' nanocrystals. Passivation with oxygen to form a few monolayers of SiO₂ has been shown to enable efficient and stable photoluminescence.^{7,8} Porosity is controlled by current variation, though inhomogeneity persists in porous Si with nanocrystal sizes as small as 1nm having been detected for 80-85% porosity.^{8,9} Efficient and controllable functionalization of porous silicon has also been facilitated by hydrosilylation of alkenes and alkynes.^{15,16}

More uniform silicon nanopillars (40-50 Å diameter) have been grown to several micrometers' length with a supercritical fluid solution-phase approach (fig.1). In this case alkanethiol coated gold nanocrystals (25 Å diameter) are used as 1-dimensional directional uniform seeds for Si crystallization in a solvent heated above its critical point.² Au nanoclusters have also catalyzed 1D Si nanowire growth via a vapor-liquid-solid mechanism.¹⁴

Silicon/insulator superlattices can be grown via MBE, LPCVD, oxygen implantation and sputtering. LPCVD SiO₂/Si superlattices are formed by cyclic deposition of amorphous Si and oxidation.¹² Luminescent efficiency in excess of 1% have been reported using this fabrication method and a relation between the thickness of the Si layers and the peak and intensity of the luminescence is exhibited¹¹, making it attractive for CMOS compatibility.

Silicon nanocrystals have also been formed in SiO₂ via Si ion implantation followed by thermal annealing and subsequent implantation of Er into the nanocrystal-doped SiO₂ layer. These are more efficient than the simple Er-doped quartz. The presence of Si nanocrystals in the Er-doped SiO₂ act as strongly absorbing species that can transfer energy efficiently to Er, making the Er³⁺ more sensitive.^{1,17}

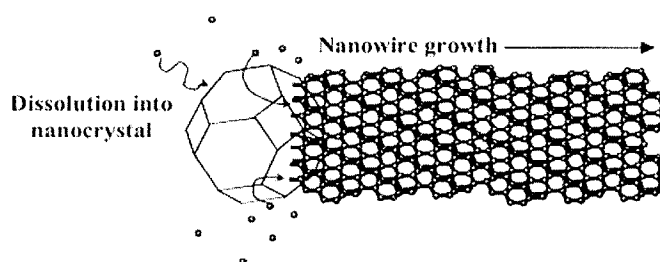


Figure 1: Nanowire growth schematic

Commercial device application has been hampered by the incompatibility of the wet processing used to form porous Si with microelectronic production techniques, and by its large, highly reactive internal surface area. Quantum dots, nanopillars and superlattice structures are as advantageous as porous Si in that they are low dimensional (1-5nm range), well passivated by SiO₂ and non radiative recombinations are eliminated by spatial localization of carriers. However, their weak electroluminescence (external quantum efficiencies ~10⁻⁵) is due to injection problems caused by the poor transport properties of the oxide.

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