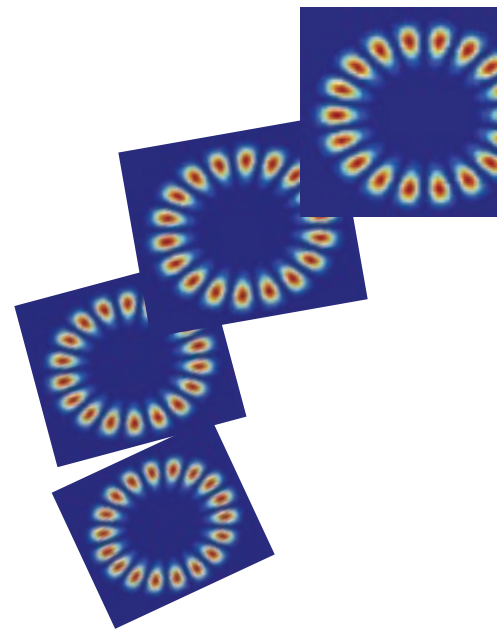


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DIRECTLY PUMPED Silicon Lasers



Jeffrey M. Shainline and Jimmy Xu

Over the past two decades, researchers have tried mightily to enhance silicon's ability to emit light. Yet electrically pumped silicon lasers remain tantalizingly out of reach. These authors review the approaches that have been tried so far and provide new insight into how these techniques might be successfully combined.

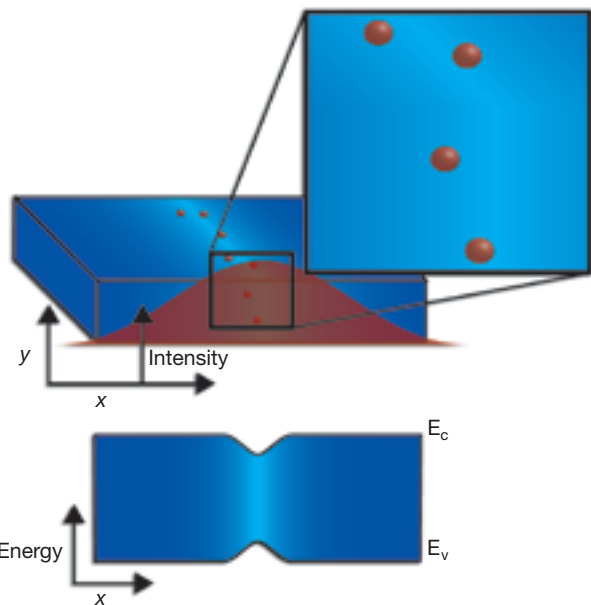
For many researchers and engineers, the challenge of developing a laser with silicon, a semiconductor that is immensely important in electronics but inherently poor at emitting light, is too delicious to resist. Others are inspired by the prospect of providing silicon-based light sources for on-chip optical signal generation, thereby extending the reach of CMOS technology. Still others are simply fascinated by the myriad manifestations of this one element.

The excitement began in the early 1990s, with the discovery that anodization of silicon in a variety of electrolyte:HF solutions leads to materials with strong photoluminescence signals. The emission generally covers a fairly broad region of the visible spectrum. Microscopic analysis of the anodized structures revealed porous material, commonly referred to as porous silicon.

Luminescence from porous silicon can be observed at room temperature, but it degrades over time and is not in the technologically important telecommunication wavelength range. Also, such anodization procedures greatly reduce the quality of the silicon, leading to a material that is difficult for monolithic integration with silicon electronic circuitry.

For some time, it was unclear whether luminescence from porous silicon was due to quantum confinement effects or silicon compounds created in the anodization process. However, more and

[Emissive silicon band structure]



When designing emissive silicon structures, it is a good idea to localize the emissive centers (shown schematically as red spheres). In so doing, you will be able to maintain high carrier lifetime and mobility elsewhere. The bandgap will be locally reduced near the emissive centers due to the strain and defects. This will draw carriers from the crystalline surroundings of long lifetime and high mobility toward the emissive centers and may help trap them at higher temperatures. Although the emissive centers themselves are localized in space, the optical mode is not, and re-absorption will be minimized.

more evidence suggests that quantum confinement can remain a principal contributor while other effects would be process- and condition-dependent.

Silicon nanocrystals

Nevertheless, researchers have developed more controlled methods for producing efficient light-emitting quantum-confined structures—especially silicon nanocrystals—and for introducing emissive centers that aid in light generation. Silicon nanocrystals in the range of 2 to 5 nm confine electron and phonon wave functions—which leads to the breaking of k -selection rules.

Thus, the limitation of the inefficient, phonon-assisted luminescence from silicon's indirect bandgap is effectively overcome. Silicon nanocrystals that are 2 nm in diameter emit blue luminescence, and emission can be redshifted to cover the visible spectrum by increasing the diameter of the nanocrystals. Surface passivation of silicon nanocrystals with nitrogen has been shown to lead to very high luminescence efficiency.

R.J. Walters and his colleagues have demonstrated an LED based on the injection of electrons into silicon nanocrystals via Fowler-Nordheim tunneling (Nature Mater. 4, 143). However,

for electrical pumping, the injection efficiency is suppressed by the small cross-section of silicon nanocrystals, the large impedance of the oxide surroundings, and the associated long-carrier dwelling time. Also, like porous silicon, the nanocrystals emit in the visible region. To date, no one has been able to demonstrate directly pumped lasers based on silicon nanocrystals.

Emissive point defects

Luminescence from point defects has been studied since the early days of silicon crystal growth as a means of gathering information about the physical nature of point defects in the lattice. These defects often give rise to states in the bandgap; luminescence is usually associated with direct electronic transitions between electric-dipole-connected states of a single defect.

Such states give rise to a four-level system, with the highest level being the conduction band and the lowest the valence band. The two electric-dipole-connected states associated with the defect center are the intermediate levels. The transition from the conduction band to the upper defect state is a fast, phonon-assisted relaxation process. The transition from the upper defect state to the lower one is slower and emits a photon directly.

Corroborated by the spectral width dependence on temperature, emission lines from the emissive point defects are treated and referred to as zero phonon lines. Transition from the lower defect state to the valence band is a fast transition, again via phonon relaxation.

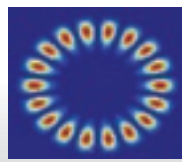
With such a four-level system, one may deploy a combination of p -type doping and separate carrier-confinement and capture mechanisms to achieve population inversion between the upper and lower defect levels. While these engineering possibilities are real and enticing, they fall more or less within the traditional domain of practice. The current challenge appears to be more on the fundamental side.

While early studies of emissive centers in silicon have focused on either pure physical aspects of the systems or on characterizing the formation and properties of the defects, recent research has used the luminescence from point defects as a means of achieving light-emitting device structures.

Introducing defects into the silicon lattice in order to create CMOS-compatible lasers may seem a bit like amputating the body to save the leg. But in several recent efforts, researchers have been able to spatially control the introduction of the defects in order to retain the crystallinity everywhere else.

W and G centers

One approach for using the optical activity of point defects while confining damage to a small volume of space made use of the 1,218 nm line resulting from the W center (a trigonal center comprised of three self-interstitials) to make an LED (Opt. Express 15, 6727). Strategic annealing by laser melting and subsequent liquid-phase epitaxy allowed the majority of the crystal to return to its pristine state while leaving a thin layer of W -center-rich material in the depletion region.



While this work demonstrated an efficient LED at cryogenic temperature, the luminescence from W centers quenches at about 40 K. This temperature limitation is a physical limitation that plagues all emitters whose electronic structure is coupled to the electronic structure of the bulk silicon lattice; excitons dissociate before radiative recombination can occur.

Another recent study made use of the zero phonon line of a point defect (Nature Mater. 4, 887); it leveraged a unique technique to locally introduce point defects to the lattice. The researchers etched an array of pores in a thin crystalline silicon layer of an electronic-grade silicon-on-insulator (SOI) wafer using an anodized aluminum oxide membrane as an etch mask for reactive ion etching (RIE). The membrane was comprised of a regular array of 50-nm-diameter pores and center-to-center distance of 100 nm.

During the RIE process, G centers—point defects comprised of two carbon atoms and one silicon atom—were produced in the side walls of the 50-nm pores. With the four-level system created by the electronic structure of the G centers in the silicon lattice, and aided by the bandgap lowering in the side wall due to the strain built in during the RIE, the investigators demonstrated an optically pumped silicon laser that showed continuous wave operation up to 80 K. Perhaps an additional reason that laser action was achieved in this situation (as opposed to many others with optically active point defects) is that the defects were created in

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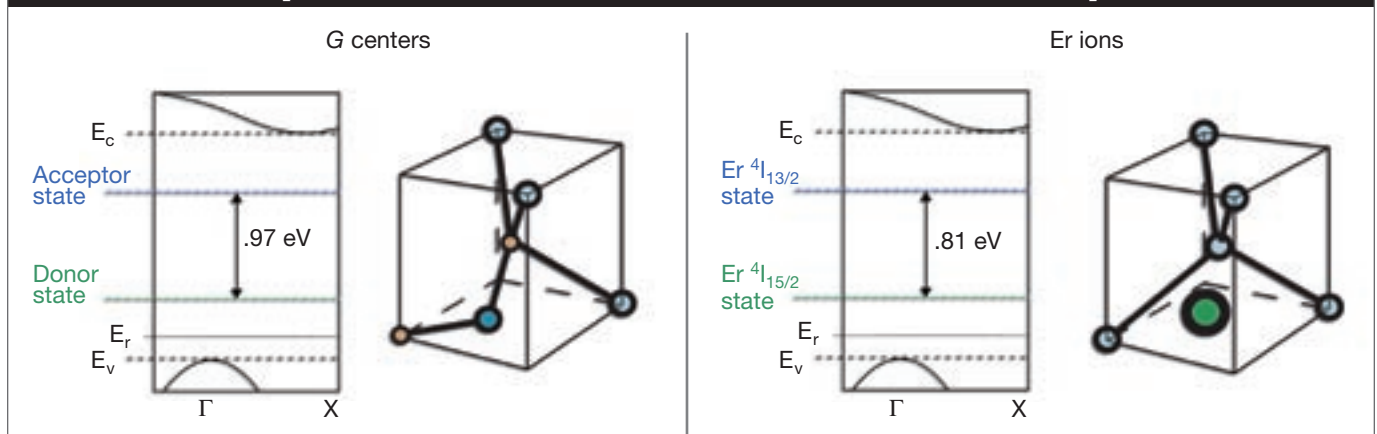
localized regions near the pore walls, while a pristine silicon lattice was maintained elsewhere and is transparent to emitted light.

Thus, the bulk of the material acted as a carrier reservoir; low carrier loss was maintained throughout most of the material, so carriers could migrate to the strained and emissive G -center-rich pore walls. Another source of loss—optical scattering and absorption—was also kept at a minimum by the crystallinity of the surrounding silicon, the high degree of uniformity and the subwavelength feature size of the nanopores, despite the distributed local structural modification.

More recently, we tried to enhance G -center luminescence by raising the G -center density; we accomplished this by increasing the carbon concentration above the solid solubility limit. A factor of 33 increase in the peak of photoluminescence from G centers was achieved (Appl. Phys. Lett. 91, 051127). Indeed, with this level of enhancement, we obtained electroluminescence in the same carbon-rich silicon platform with the nanopatterned substrate.

However, to date, no one has been able to demonstrate an electrically pumped silicon laser, with the use of the G centers created by the nanopatterning of carbon-rich silicon or by other means. The major limiting factor here is the quenching of luminescence with temperature. G -center luminescence quenches at 80 K, and electrical injection of carriers quickly heats the thin, nanopatterned substrate and raises the carrier effective temperature.

[The four-level energy structures of G centers and erbium ions in silicon]

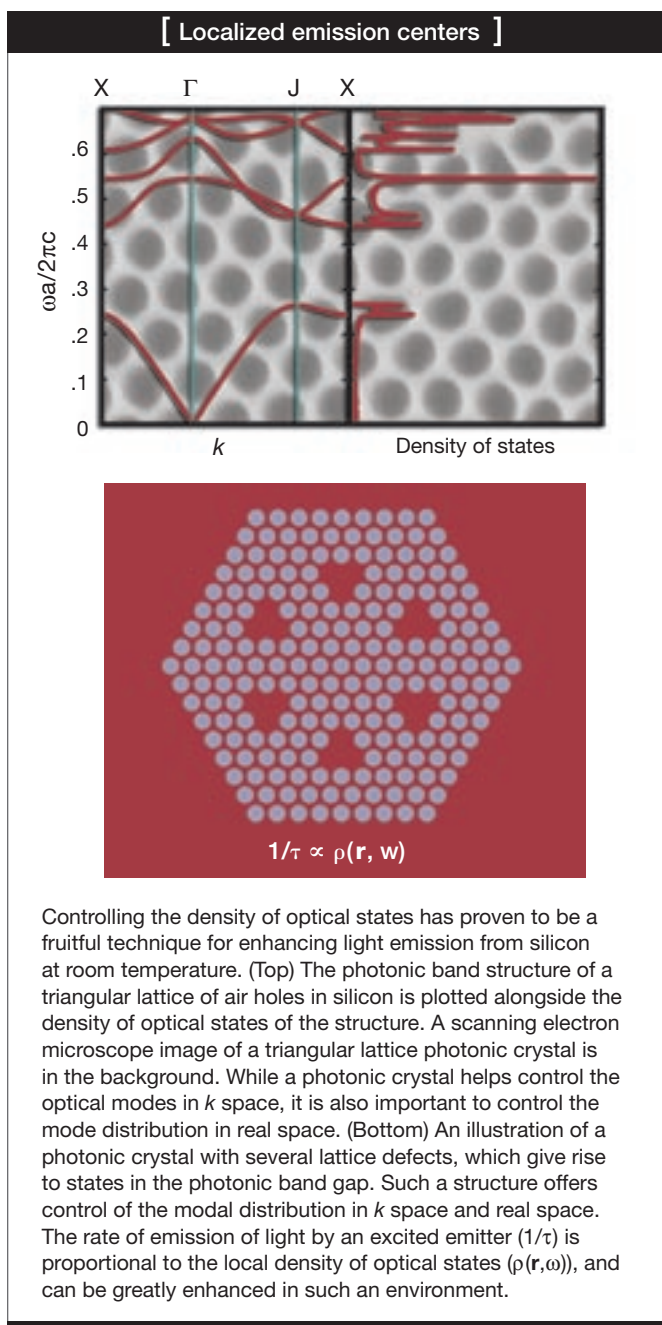


The relevant defect or atomic states involved in the optical transitions are shown in the bandgap. The atomic configuration of the G center in the silicon lattice is shown. The blue spheres represent silicon atoms, and the brown spheres represent carbon atoms. In the right half, an erbium atom is depicted in the lattice.

Extended defects

So far, in studies of luminescence from emissive point defects, luminescence has been quenched well below the temperature of liquid nitrogen. If one could only increase the lifetime of excitons at higher temperatures, this limit could be overcome. A system that utilizes extended defects—{311} defects—is capable of doing this. These {311} defects are rod-shaped accumulations of silicon interstitials that accumulate in the {311} planes of the lattice.

A great deal is known about their formation during annealing after bombardment (with ions, electrons, gamma rays, etc.).



Researchers have also extensively studied their eventual evolution into dislocation loops with persistent annealing. Although {311} defects luminesce, they do not do so in the narrow zero phonon lines of point defects. Still, at cryogenic temperatures, {311} luminescence is a great deal narrower than luminescence resulting from quantum confinement, as one would observe from porous silicon or silicon nanocrystals.

The strength of {311} defects as emissive centers is that the strain field surrounding them reduces the bandgap locally, leading to a local lowering of the exciton binding energy. This increases the exciton lifetime in the vicinity of a {311} defect. Photoluminescence from {311} defects has been shown to persist to room temperature. However, introducing {311} defects to the lattice generally results in a variety of other non-radiative pathways and leads to a material of reduced electronic and optical quality. We do not currently know of a way to locally introduce {311} defects to take advantage of the exciton trapping strain fields while maintaining a pristine lattice elsewhere.

Erbium-doped silicon

While the excitation of G centers is relatively well understood, the excitation of erbium in silicon also falls in the category of light generation in emissive centers, though with the differentiation being that in this case silicon acts merely as passive hosting material. Still, as another means of light generation in silicon, it continues to be actively investigated (see *Phys. Rev. Lett.* **99**, 077401).

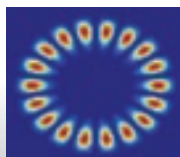
Luminescence from erbium-doped silicon has been studied in great detail. It is crucially important to telecom amplifiers and may hold promise for the future silicon laser as well. Erbium emission is appealing because it is at 1,550 nm—just right for long-haul fiber-optic applications.

The luminescence from erbium in silicon has much in common with the luminescence from point defects in silicon. For example, the luminescence from erbium in silicon suffers from the same major drawback as point defects: It is quenched at temperatures far below room temperature. However, a key difference is that the luminescent states of the Er^{3+} ion are essentially the same in the silicon lattice as they would be in vacuum, whereas it doesn't make sense to speak of the electronic nature of a point defect in a vacuum.

Photonic crystals and whispering-gallery-mode resonators

S. Iwamoto and colleagues demonstrated a technique that has overcome temperature limitations on emission from silicon (*Appl. Phys. Lett.* **91**, 211104). They used a spatially varying periodic dielectric medium (or the Bragg grating's extension to 2D and 3D, popularly named "photonic crystals") to control the local density of optical states. In this case, the source of illumination was indirect bandgap emission.

The researchers created a two-dimensional photonic crystal with a micro-lattice defect on an SOI wafer using electron



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beam lithography. The photonic crystal suppresses bandgap spontaneous emission everywhere in the structure except at the location of the micro defect, where its presence in the photonic crystal introduces optical states in the photonic band gap. Using this approach, the researchers showed that the wavelength and linewidth of emission could be tuned, and they demonstrated luminescence at room temperature.

Using an approach based on similar physical principles—controlling the density of optical states—another group of researchers has realized room-temperature photoluminescence from whispering-gallery-mode resonators (Appl. Phys. Lett. **90**, 141102). While both of these studies demonstrate the power of enhancing light emission by controlling the density of optical states, they fall short of achieving laser action. Moreover, neither marks a clear path forward for electrically pumped lasers in silicon. A major reason why such two-level systems have failed to produce lasers is that population inversion is not accessible.

Combined approaches

There does not appear to be one shiny key that will open the door to electrically pumped silicon lasers. Thus, it is essential to combine techniques. A study of silicon nanocrystals and erbium ions embedded in a SiO₂ matrix indicated that the efficiency of erbium excitation under optical pumping was significantly increased by the presence of silicon nanocrystals, indicating that the nanocrystals can transfer energy to erbium ions. It has also been shown that silicon nanocrystals have been found to be excitable via Fowler-Nordheim tunneling in an oxide matrix. Can we integrate these two ideas to arrive at a device that electrically pumps erbium ions embedded in a SiO₂ matrix?

But this leaves out the important factor of the photonic density of states. Fabrication challenges aside, would a photonic crystal cavity containing nanocrystals and erbium be a pathway to electrically pumped lasing?

The importance of controlling the density of optical states should not be underestimated. The nanopatterned silicon platform with *G*-center luminescence consisted of an array of pores. But the spacing of the pores was meant to maximize the volume density of the emissive *G* centers while keeping the optical scattering losses low, and was not exploited to control either the emission spectrum or its spatial extent. Perhaps this represents a way forward for optimal confinement and modal-guiding of point-defect luminescence. Harmonizing photonic defect states in the photonic band gap with electronic defect states in the electronic band gap may be an effective way to increase luminescence efficiency and temperature.

Strain fields could also play to our advantage. If the localized introduction of {311} defects is ever realized, it may be possible to introduce additional emissive centers—perhaps erbium ions—inside the strain fields of the {311} defects. Long-lived excitons would be trapped in the strain potential and would efficiently luminesce through the Er³⁺ at higher temperatures, possibly room temperature. Perhaps pairing this idea with a geometry that controls the density of optical states could lead to low-threshold electrically pumped lasers in a silicon medium.

None of these composite ideas has materialized yet, but they may mark potential pathways toward the creation of CMOS-compatible silicon-based lasers. Many more ideas could be conjured by creative minds, but the design constraints imposed by the requirement of electrical pumping limit the feasibility of many laser designs.

Future directions

If one is in this field to make pure, crystalline silicon emit laser light under electrical injection, the road ahead looks tough. However, if the goal is to produce lasers or even merely efficient light-emitting devices that can enable new circuit architectures and advance CMOS technology, there is reason for hope.

Indeed, there are many motivations to keep working: the promising interactions between strain, quantum-confined structures, narrow linewidth point or extended emissive centers, and structures that control the density of optical states. The newly availed capabilities of altering material structures at the atomic level offer promises of rewards that entice the imagination. ▲

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