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# Monolithic Ge-on-Si Lasers for Integrated Photonics

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***Abstract*—We report room temperature Ge-on-Si lasers with direct gap emission at 1590-1610 nm. Modeling of Ge/Si double heterojunction structures, which is supported by experimental results of Ge/Si LEDs, indicates the feasibility of electrically pumped lasers.**

## I. INTRODUCTION

Monolithic lasers on silicon are ideal for large scale electronic-photonic integration. [1]. Previous investigations include Si and SiGe nanostructures [2-4], Er doped Si-based materials [5,6], GeSn [7,8], β-$FeSi_2$ [9], and hybrid III-V lasers on Si [10,11]. We have proposed through theoretical analysis that Ge, traditionally considered an indirect gap material, can be band-engineered to behave like a direct gap material for optical gain medium on Si by using tensile strain and n-type doping to compensate the energy difference between the direct and indirect conduction valleys [12]. The demonstration of direct gap photoluminescence (PL) [13,14], electroluminescence (EL) [15], and optical gain [16] at room temperature in tensile-strained $n^+$ Ge-on-Si confirmed our theoretical predictions. In this paper we present lasing from the direct gap transition of monolithic Ge-on-Si edge emitting waveguide devices. The emission wavelength range of 1590-1610 nm is in good agreement with the optical gain spectrum reported previously [16]. We will also discuss theoretical modeling and design of $n^+$ Si/$n^+$ Ge/$p^+$ Si double heterojunction structures for electrically pumped lasers.

## II. EDGE EMITTING GE-ON-SI LASER UNDER OPTICAL PUMPING

### A. *Material and Device Structure*

The device used in the experimental study of lasing from tensile strained $n^+$ Ge consists of trench grown multimode Ge waveguides with mirror polished facets monolithically integrated on a Si wafer. The Ge waveguides were selectively grown epitaxially on Si by ultra-high vacuum chemical vapor deposition (UHVCVD) using a $SiO_2$ mask layer. Details about the selective growth were reported earlier [17]. The Ge material was fully relaxed at the growth temperature of 650 °C, and 0.24% thermally-induced tensile strain was accumulated upon cooling to room temperature. The tensile strain shrinks the direct gap of Ge to 0.76 eV so that its difference from the indirect gap is reduced. The Ge material was in situ doped with $1\times10^{19}$ $cm^{-3}$ phosphorous during the growth to further compensate the energy difference between the direct (Γ) and indirect (L) conduction valleys and significantly enhance the direct gap light emission [12-15]. A cross-sectional scanning electron microscopy (SEM) picture of the Ge waveguide is shown in the inset of Fig. 1. The width of the Ge waveguide is 1.6 µm and the height is 500 nm. The relatively large cross-sectional dimensions were selected conservatively to guarantee >90% optical confinement in the Ge gain medium for demonstration of lasing, without optimization for the minimal threshold. The edges of the samples were mirror polished to obtain vertical facets for reflection mirrors on both ends of the waveguides. The length of the waveguides is 4.8 mm. Such a long waveguide was chosen to guarantee a mirror loss of <<10 $cm^{-1}$, which is much smaller than the optical gain of Ge [16].

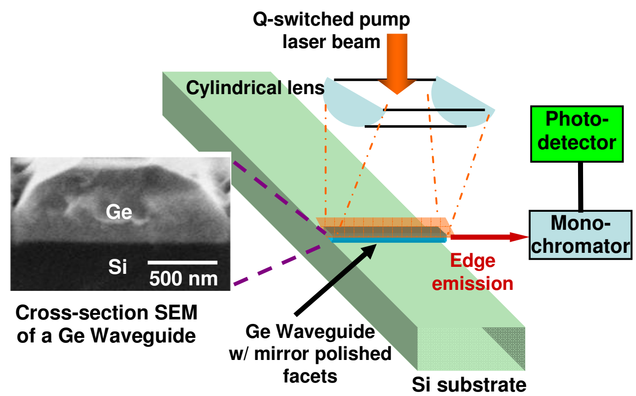


Figure 1. A cross-sectional SEM picture of a selectively grown Ge waveguide on Si, and a schematicdrawing of the experimental setup for measuring the light emission from the edge of the Ge waveguide under optical pumping.

### B. *Experimental Setup*

The experimental setup for optical pumping is schematically shown in Fig. 1. The entire waveguide was excited by a 1064 nm Q-switched laser with a pulse duration of 1.5 ns and a maximum output of 50 µJ/pulse operating at a repetition rate of 1 kHz. The pump laser was focused into a line of ~7 mm long and ~0.5 mm wide by a cylindrical lens and vertically incident on top of a Ge waveguide. The actual peak pump power density absorbed by Ge is ~300 $kW/cm^2$ for 50 µJ/pulse output power.

### C. *Emission Characteristics at Room Temperature*

Fig. 2a shows the light emission spectra of a Ge waveguide under different pumping levels. The spectral resolution is 2 nm. At 1.5 µJ/pulse, the emission from the waveguide shows a broad band with a maximum around 1600 nm, consistent with PL and EL spectra of 0.2% tensile strained Ge reported earlier [13-15]. At this stage spontaneous emission dominates the spectrum. As the pump power increases to 6.0 µJ/pulse, emission peaks emerge at 1599, 1606 and 1612 nm, respectively, and a shoulder appears at 1594 nm. This change in the emission spectrum occurs at the pump power corresponding to the threshold behavior in the inset of Fig. 2a, marking the onset of transparency [16]. The emergence of emission peaks between 1600 and 1610 nm at the threshold of lasing is also remarkably consistent with the optical gain spectrum peaked at 1605 nm reported previously [16]. As pump power increases to 50 μJ/pulse, the widths of the emission peaks at 1594, 1599 and 1605 nm significantly decrease while the polarization evolved from a mixed TE/TM to predominantly TE with a contrast ratio of 10:1 due to the increase of optical gain, as expected for typical lasing behavior. The strongest emission peak blueshifts from 1600 nm to 1594 nm, and two new peaks appear at shorter wavelengths. This result is consistent with the fact that the gain spectrum shifts to shorter wavelengths with the increase of carrier injection due to occupation of higher energy states in the direct Γ valley [12]. The two strongest and narrowest emission lines at 1593.6 and 1599.2 nm are most likely due to higher gain coefficients compared to other wavelengths. This explanation is also consistent with typical bell shapes of gain spectra where maximum material gain is achieved at photon energies slightly larger than the band gap (~17 meV above the band gap in this case). The multiple emission peaks are most likely due to multiple guided modes in the Ge waveguide. Coexistence of lasing modes can be enabled by a broad enough gain spectrum under a high excitation of 300 kW/cm$^2$ in this case. Fig. 2b shows a high resolution scan of the emission line at 1593.6 nm using the highest available resolution of the measurement system of 0.1 nm. Periodic peaks corresponding to longitudinal Fabry-Perot modes are clearly observed in the spectrum. The longitudinal mode spacing of 0.060±0.003 nm is in good agreement with the calculated Fabry-Perot mode spacing of 0.063 nm for a 4.8 mm-long Ge waveguide cavity.

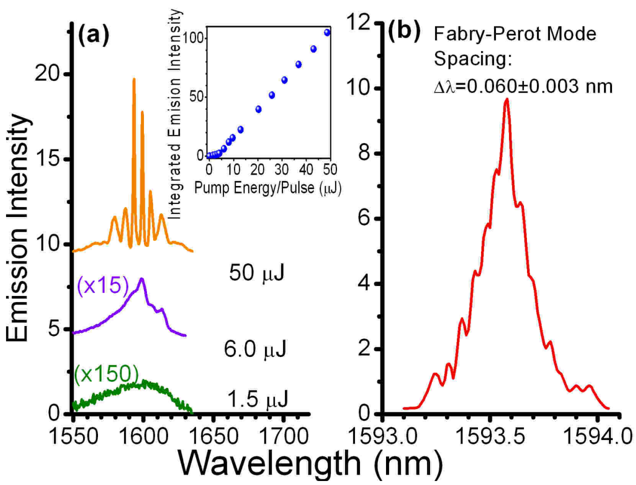


Figure 2. (a) Edge emission spectra of a Ge waveguide with mirror polished facets under 1064 nm excitation from a Q-switched laser with a pulse duration of 1.5 ns. The three spectra at 1.5, 6.0 and 50 μJ/pulse pumping power correspond to spontaneous emission, threshold for lasing, and laser emission, respectively. The inset plots the integral emission intensity vs. optical pump power, showing the lasing threshold. (b) High resolution scan of the emission line at 1593.6 nm using the highest available spectral resolution of 0.1 nm. Longitudinal Fabry-Perot modes are clearly observed, and the period is consistent with the Ge waveguide cavity length of 4.8 mm.

## III. ELECTRICALLY PUMPED GE-ON-SI LIGHT EMITTERS

The ability to achieve light emission under electrical pumping is the key to practical applications of Si-based light emitters. We have recently demonstrated the first Ge/Si heterojunction direct gap light emitting diodes (LED) [15], indicating the capability of electrical injection into the direct Γ valley of Ge. In this section, a theoretical analysis on heterojunction design is presented. The model is verified by comparing the calculated quantum efficiency of Ge/Si LEDs to the experimental results, and further applied to design n$^+$ Si/p$^+$ Ge/p$^+$ Si double heterojunction structures.

A finite element method (FEM) is applied to investigate carrier injection in Si/Ge/Si double heterojunction structures. The simulation combines SimWindows with our own carrier distribution calculation considering electron distribution in multiple conduction band valleys. The DH structure used in the simulation is composed of two 1 μm Si layers sandwiching a 0.5 μm Ge layer, and we investigate the effect of doping levels in each region on the device performance. Particularly, the internal quantum efficiency (IQE) of light emission from this heterojunction can be calculated from the ratio of the direct band-to-band radiative recombination rate in the whole active region to the carrier injection rate. The former rate is calculated by substituting the excess carrier density obtained from the simulated quasi Fermi level into the steady state rate equation, while the latter rate is calculated from the injection current density. To check the validity of our theoretical model, we first calculated the IQE of the n$^+$ Si/i-Ge/p$^+$ Si DH structure reported in [15]. The calculated IQE of 0.3% agrees with the estimated efficiency in the order of 0.1% from the experimental results of Ge/Si LEDs.

Since the band-engineered Ge involves n$^+$ doping to achieve optical gain and lasing , we then simulated the IQE of n$^+$ Si/n$^+$Ge/p$^+$ Si DH structures. Fig. 3 shows the effect of doping concentrations in p-type and n-type Si regions on the electroluminescence IQE of the n$^+$Si/n$^+$Ge/p$^+$Si heterojunction with $1\times10^{19}$ cm$^{-3}$ n-type doping in the Ge layer at 0.5 V forward bias. The result indicates that the IQE is more sensitive to the doping concentration in the p-type Si region than the n-type Si region. This result is because the Ge region is n-type so that a heavily doped p-Si region is required for sufficient separation of the quasi Fermi levels of electrons and holes. With a proper heterojunction design, e.g., p-Si doped at $5\times10^{19}$ cm$^{-3}$ and n-Si doped at $1\times10^{19}$ cm$^{-3}$, internal quantum efficiencies as high as 10% can be achieved, which is very promising for an indirect bandgap material. In the calculations above, we have used a conservative Auger coefficient of $10^{-30}$ cm$^{-6}$/s, one order of magnitude higher than reported values for both pnn and nnp processes in Ge [18, 19]. Therefore, the 10% efficiency shown here is the lower limit of Ge direct gap light emission, and it is promising for the EL efficiency of tensile-strained n$^+$ Ge to reach similar levels as direct gap III-V materials on Si.

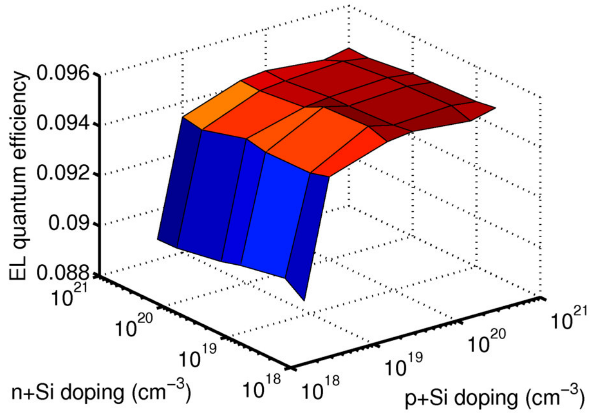


Figure 3. . Calculated electroluminescence internal quantum efficiency for a $p^+Si/n^+Ge/n^+Si$ heterojunction versus doping concentrations in the p-type and n-type Si regions at 0.5 V forward bias. The color scheme (from red to blue) represents magnitude of quantum efficiency.

## IV. Conclusions

We have demonstrated an optically pumped edge-emitting multimode Ge-on-Si laser operating at room temperature with a gain spectrum of 1590-1610 nm. Evidence of lasing consists of line narrowing and polarization evolution from a mixed TE/TM to predominantly TE with increasing gain, and a clear threshold behavior marking the onset of transparency. The gain spectrum is remarkably consistent with the band structure of tensile strained Ge observed previously. We further modeled electrical injection in Si/Ge/Si double heterojuction structures for electrically pumped devices. The calculated internal quantum efficiency of a tensile strained $n^+$ Si/i-Ge/$p^+$ Si heterojunction LED agrees with the experimental results. A conservative calculation shows that at least 10% internal quantum efficiency can be achieved from $n^+$ Si/$n^+$ Ge/$p^+$ Si double heterojunction structures. The doping concentrations of both Si regions (n-Si and p-Si) in the Ge/Si heterojunction are optimized through simulation for low optical loss in silicon without harming the light emission properties. These results indicate the feasibility of electrically pumped Si/Ge/Si double heterojunction lasers. Considering that Ge has already been applied to Si CMOS electronics and integrated photonic devices, a Ge-on-Si laser is a desirable choice for monolithic electronic-photonic integrated circuits.

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