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Band-Engineered Ge-on-Si Lasers

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Abstract

We report optically-pumped Ge-on-Si lasers with direct gap emission near 1600 nm at room temperature. The Ge-on-Si material was band-engineered by tensile strain and n-type doping to compensate the energy difference between direct and indirect band gaps for efficient light emission. Modeling of Ge/Si double heterojunction LEDs shows that it is possible to achieve >10% quantum efficiency even assuming an Auger coefficient 10 times larger than reports in literature. Edge-emitting Ge-on-Si waveguide LEDs have also been demonstrated at room temperature. These simulation and experimental results strongly indicate the feasibility of electrically-pumped Ge-on-Si lasers.

Introduction

Monolithic lasers on silicon are ideal for large scale electronic-photonic integration (1). Ge-on-Si is an interesting candidate due to its compatibility with silicon complementary metal oxide semiconductor (CMOS) process and its pseudo-direct band gap behavior in the near infrared regime for optical communications. We have proposed through theoretical analysis that epitaxial Ge-on-Si can be band-engineered to behave like a direct gap material to achieve optical gain and lasing by using tensile strain and n-type doping to compensate the energy difference between the direct and indirect conduction valleys (2). In this paper we present lasing from the direct gap transition of band-engineered Ge-on-Si edge emitting waveguide devices at room temperature. The emission wavelength range of 1590-1610 nm is in good agreement with the optical gain spectrum reported previously (3). We also present theoretical modeling and room-temperature electroluminescence results on n⁺Si/n⁺ Ge/p⁺ Si double heterojunction structures for electrically pumped lasers.

Band-Engineering of Ge

Although Ge is commonly known as an indirect gap material, its direct gap at Γ valley is only 136 meV higher than the indirect bandgap (Fig. 1a). The direct gap of 0.8 eV corresponds to a wavelength of 1550 nm, the most technically important wavelength in optical communications. These properties make Ge a good candidate for photonic devices in the near infra-red (NIR) regime. The difference between direct and indirect gaps of Ge can be further reduced by introducing tensile strain, as shown in Fig. 1b. With biaxial tensile stress, both direct and indirect gaps shrink, but the direct gap shrinks faster. Therefore, Ge transforms from an indirect gap material towards a direct gap material with the increase of tensile strain. Furthermore, the top of the valence band is determined by light hole band under biaxial tensile stress, which increases hole mobility. These changes in band structure induced by tensile strain can greatly enhance the optoelectronic properties of Ge. A thermally induced tensile strain of 0.2-0.3% can be incorporated into epitaxial Ge-on-Si utilizing the difference in thermal expansion coefficient between Ge and Si (4), which extends the absorption range of Ge photodetectors from C band (1528-1560 nm) to L-band (1561-1625 nm) (5). To obtain efficient light emission from the direct gap transition of Ge, n-type doping has been applied to tensile-strained Ge in order to fill the states in indirect gap L valleys so that the energy difference between direct and indirect gaps is compensated (Fig. 1c) (6). Therefore, band-engineering by tensile strain and n-type doping enables high performance Ge active photonic devices on Si.

Optically-Pumped Ge-on-Si Laser

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 SiO₂ mask layer. 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 $1 \times 10^{18}$ cm$^{-3}$ phosphorous during the growth to further compensate the energy difference between the direct ($\Gamma$) and indirect (L) conduction valleys and significantly enhance the direct gap light emission (6-9). A cross-sectional scanning electron microscopy (SEM) picture of the Ge waveguide is shown in the inset of Fig. 2. The width of the Ge waveguide is 1.6 $\mu$m 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 (3).

**Fig. 2.** A cross-sectional SEM picture of a selectively grown Ge waveguide on Si, and a schematic drawing 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 the inset of Fig. 2. 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 $\mu$J/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 $\mu$J/pulse output power.

### C. Emission Characteristics at Room Temperature

Fig. 3a shows the light emission spectra of a Ge waveguide under different pumping levels. The spectral resolution is 2 nm. At 1.5 $\mu$J/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 (7-9). At this stage spontaneous emission dominates the spectrum. As the pump power increases to 6.0 $\mu$J/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. 3a, marking the onset of transparency. 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. As pump power increases to 50 $\mu$J/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 $\Gamma$ valley. 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. 3b 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 result indicates a longitudinal mode spacing of $0.060\pm0.003$ nm in good agreement with the calculated Fabry-Perot mode spacing of 0.063 nm for a 4.8 mm-long Ge waveguide cavity.

**Fig. 3.** (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 $\mu$J/pulse pumping power correspond to spontaneous emission, threshold for lasing, and laser emission, respectively. The arrow indicates the peak optical gain wavelength reported in [6]. 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.
Towards Electrically-Pumped Ge-on-Si Lasers

Electroluminescence is the key to practical applications of light emitters. A finite element method (FEM) is applied to investigate carrier injection in Si/Ge/Si double DH structures (10). 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 (9). 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.

Fig. 4. 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. The simulation assumed a used a conservative Auger coefficient of 10⁻³⁰ cm⁻⁶/s, one order of magnitude higher than reported values [5, 6]. 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 efficiencies as direct gap III-V materials on Si.

We then simulated the IQE of n⁺ Si/n⁺ Ge/p⁺ Si DH structures. Fig. 4 shows the effect of doping concentrations in p-type and n-type Si regions on the electroluminescence IQE for the n⁺ Si/n⁺ Ge/p⁺ Si heterojunction assuming 1×10¹⁹ cm⁻³ n-type doping in the Ge layer and 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 of the fact that 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 5×10¹⁹ cm⁻³ and n-Si doped at 1×10¹⁹ 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 (11, 12). 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 efficiencies as direct gap III-V materials on Si.

Fig. 5. Room temperature electroluminescence spectrum from an edge-emitting Ge-on-Si waveguide LED. The waveguide was fabricated by etching a blanket Ge film. Clear direct gap electroluminescence was observed in the wavelength range of 1450-1650 nm at room temperature despite of the significant edge roughness due to the die-saw process.

As a step towards electrically-pumped Ge-on-Si lasers, we fabricated an edge-emitting n⁺ Si/n⁺ Ge (n=1×10¹⁹ cm⁻³)/p⁺ Si waveguide LED by etching a blanket n⁺ Ge film on Si. Fig. 5 shows a preliminary result of edge emission spectrum at room temperature from a die-sawed sample Ge waveguide LED sample. An optical fiber is placed at the end of the Ge waveguide LED to couple emitted light into an optical
spectrum analyzer, as schematically shown in Fig. 5a. Clear direct gap electroluminescence was observed in the wavelength range of 1450-1650 nm at room temperature despite of the significant sidewall roughness due to the reactive ion etching process (RIE). Compared to previous PL and EL results, the spectrum shows a peak at 1530 nm and a shoulder around 1600 nm. One possible reason is that the junction is at the Ge/Si interface near the low temperature buffer layer, which tends to accumulate less strain then the upper layer of the Ge film. This result indicates that the emission from Ge LEDs can be tuned to cover a wide spectrum range from 1520 to 1600 nm by strain engineering.

Conclusions

Using tensile strain and n-type doping to engineer the band structure of Ge, 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. Line narrowing, polarization evolution from a mixed TE/TM to predominantly TE with increasing gain, and a clear threshold behavior have been observed. 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 heterojunction 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. As a step towards electrically-pumped lasers, we have fabricated an edge-emitting n⁺ Ge (n=1×10¹⁹ cm⁻³) waveguide LED was fabricated by etching a blanket Ge film on Si. 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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