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Optical Gain and Lasing from Band-Engineered Ge-on-Si at Room Temperature

Jifeng Liu^{***}, Xiaochen Sun^{*}, Rodolfo Camacho-Aguilera^{*}, Yan Cai^{*}, Lionel C. Kimerling^{*}, and Jurgen Michel^{*}

^{*} *Microphotonics Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

^{**} *Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755, USA*

Abstract—We present theoretical modeling and experimental results of optical gain and lasing from tensile-strained, n⁺ Ge-on-Si at room temperature. Compatible with silicon CMOS, these devices are ideal for large-scale electronic-photonics integration on Si.

I. INTRODUCTION

Electronic-photonics synergy on silicon platform calls for high volume integration of monolithic laser sources at a low cost [1]. Germanium is a particularly interesting candidate for this application due to its adequate optoelectronic properties in the near infrared regime for optical communications and compatibility with advanced silicon complementary metal oxide semiconductor (CMOS) technology. In this paper, we review the theoretical modeling and experimental studies on optical gain and lasing from monolithic Ge-on-Si devices band-engineered by tensile strain and n-type doping to compensate the energy difference between the direct and indirect conduction valleys. The demonstration of room temperature optical gain and lasing together with electroluminescence from the direct gap transition indicate that the Ge-on-Si laser is a promising candidate for monolithic electronic-photonics integrated circuits.

II. MODELING THE OPTICAL GAIN OF TENSILE-STRAINED, N-TYPE GE

Although germanium is traditionally considered an indirect gap material unsuitable for light emitting devices, it actually exhibits pseudo-direct gap behavior since the direct band gap at Γ valley is only 136 meV higher than the indirect gap at L valleys [2]. The direct band gap of Ge is 0.8 eV, corresponding exactly to 1550 nm, the most extensively used wavelength in optical communications. Tensile strain further decreases the difference between direct and indirect band gaps. However, to make Ge a direct gap material, a large tensile strain of 1.8% is required and the direct band gap red-shifts to \sim 2500 nm. To obtain optical gain from the direct gap transition of Ge while still keeping the emission wavelength close to 1550 nm, we have proposed combining a moderate tensile strain of 0.2-0.3% with n-type doping to compensate the energy difference between the direct and indirect band gaps of Ge [3]. Fig. 1 shows a theoretical modeling of net optical gain from 0.25% tensile strained Ge-on-Si vs. different n-type doping (N_d) or injection levels (Δn) in Ge at a wavelength of 1550 nm, or photon energy E_{ph} of 0.8 eV. The net gain is calculated by subtracting the free carrier absorption loss from the optical gain of the direct gap transition under carrier injection. When the n-type

doping level N_d is greater than 10^{19} cm⁻³ and the injection level Δn is greater than 10^{18} cm⁻³, the optical gain from the direct gap transition start to exceed the free carrier absorption so that net optical gain can be achieved. Notably, a large gain coefficient of >500 cm⁻¹ can be obtained under an n-type doping of mid to high 10^{19} cm⁻³ and a carrier injection of mid 10^{18} to low 10^{19} cm⁻³. These doping and injection levels are also practical to achieve experimentally. Therefore, the theoretical modeling indicates the feasibility of optical gain from tensile strained, n-type Ge-on-Si.

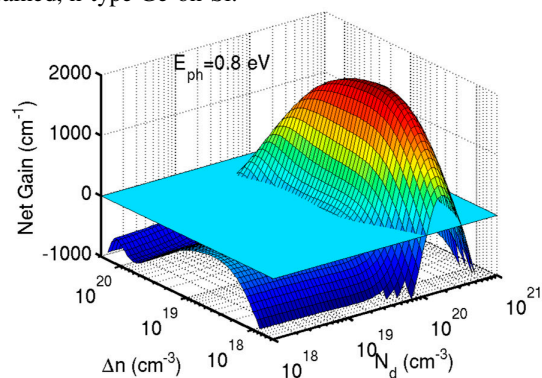


Fig. 1. Dependence of the calculated net gain of 0.25% tensile-strained germanium on the active n-type doping concentration (N_d) as well as the injected excess carrier density (Δn) at 1550 nm emission wavelength, or 0.8 eV photon energy. The color scheme (from red to blue) represents magnitude of net gain.

III. OPTICAL GAIN AND LASER EMISSION FROM BAND-ENGINEERED GE-ON-SI

To investigate the optical and lasing from band-engineered Ge experimentally, Ge mesas and 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 1×10^{19} cm⁻³ phosphorous during the growth to further compensate the energy difference between the direct (Γ) and indirect (L) conduction valleys [3-5].

A pump-probe measurement on a 500 μ m² Ge mesa with a thickness of 870 nm was used to investigate the optical gain spectrum [6]. A 1480 nm continuous wave (CW) pump laser and a tunable probe laser with an output wavelength range of 1510-1640 nm were coupled into a single mode lens-tipped optical fiber through a

wavelength division multiplexing (WDM) coupler. An InGaAs detector with an integration sphere was placed at the backside of the sample to collect the transmitted signal. The probe laser was internally modulated at 500 Hz and a lock-in approach was adopted to record the transmitted probe laser signal only. The transmittance spectra under 0 mW and 100 mW optical pumping are shown in Fig. 2a. Upon optical pumping, the transmittance at photon energies above the direct band gap (0.76 eV) increases significantly, indicating that the optical bleaching of the direct gap transition due to band filling overcomes the free carrier absorption loss. Fig. 2b shows the absorption spectra derived from the transmittance data in Fig. 2a using transfer matrix method and Kramers-Kronig relation. Negative absorption coefficients corresponding to optical gain are observed in the wavelength range of 1600-1608 nm, as shown in the inset of Fig. 2b. The error bars given here reflect the upper limit of the transmittance measurement error of $\pm 0.4\%$. Even with the most conservative estimate, a gain coefficient of $>25 \text{ cm}^{-1}$ at 1605 nm was demonstrated, which can be applied to achieve lasing.

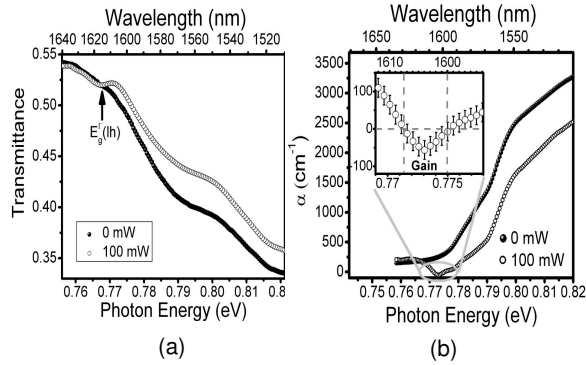


Fig. 2 (a) Transmittance spectra of a $500 \mu\text{m}^2$ Ge-on-Si mesa sample with $n=1.0 \times 10^{19} \text{ cm}^{-3}$ under 0 and 100 mW optical pumping, and (b) Absorption spectra of the n^+ Ge mesa sample under 0 and 100 mW optical pumping derived from the transmittance data. Negative absorption coefficients corresponding to optical gain are observed in the wavelength range of 1600-1608 nm, as shown in the inset. [6]

To investigate lasing, edge emission from a $1.6 \mu\text{m}$ wide and 500 nm tall Ge waveguide with mirror-polished facets was studied by optically pumping the entire waveguide area from the top with a 1064 nm Q-switched laser (1.5 ns pulse duration) [7]. Fig. 3a shows the evolution of the light emission spectra from a broad spontaneous emission band [4, 5] to sharp multi-mode lasing peaks with increasing pump power. A clear threshold behavior is shown in the inset. 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 longitudinal mode spacing of $0.060 \pm 0.003 \text{ nm}$ is in good agreement with the calculated Fabry-Perot mode spacing of 0.063 nm for a 4.8 mm -long Ge waveguide cavity. These experimental results demonstrate lasing from the Ge-on-Si waveguide at room temperature.

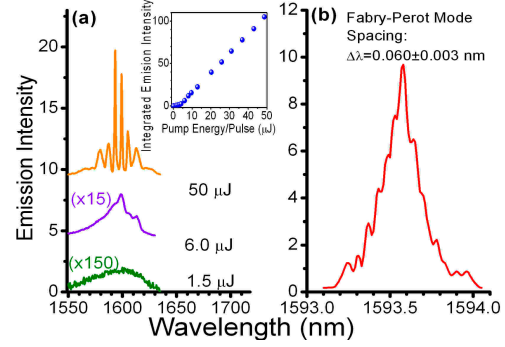


Fig. 3 (a) Edge emission spectra of a Ge waveguide. The three spectra at 1.5, 6.0 and $50 \mu\text{J/pulse}$ pumping power correspond to spontaneous emission, threshold for lasing, and laser emission, respectively. (b) High resolution scan of the emission line at 1593.6 nm (spectral resolution is 0.1 nm). Longitudinal Fabry-Perot modes are clearly observed, and the period is consistent with the Ge waveguide cavity length of 4.8 mm .

IV. CONCLUSIONS

We present theoretical analysis and experimental results of room temperature optical gain and lasing from the direct gap transition of epitaxial Ge-on-Si band-engineered by tensile strain and n-type doping. Considering that Ge has already been applied to advanced 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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