Room temperature 1.6 μm electroluminescence from Ge light emitting diode on Si substrate

Szu-Lin Cheng,[1,*] Jesse Lu,[2] Gary Shambat,[2] Hyun-Yong Yu,[2] Krishna Saraswat,[2] Jelena Vuckovic,[2] and Yoshio Nishi[2]

[1]*Department of Materials Science and Engineering, Stanford University, Stanford CA 94305, USA*
[2]*Department of Electrical Engineering, Stanford University, Stanford CA 94305, USA*
[*]*Corresponding author: slcheng@stanford.edu,*

Abstract: We report the room temperature electroluminescence (EL) at 1.6 μm of a Ge n+/p light emitting diode on a Si substrate. Unlike normal electrically pumped devices, this device shows a superlinear luminescence enhancement at high current. By comparing different n type doping concentrations, we observe that a higher concentration is required to achieve better efficiency of the device. Thermal enhancement effects observed in temperature dependent EL spectra show the capability of this device to operate at room temperature or above. These detailed studies show that Ge can be a good candidate for a Si compatible light emitting device.

OCIS codes: (160.4670) Optical materials; (230.3670) Light-emitting diodes.

References and links

1. L. C. Kimerling, "Silicon microphotonics," Appl. Surf. Sci. **159-160**, 8-13 (2000).
2. J. Liu, X. Sun, D. Pang, X. Wang, L. C. Kimerling, T. L. Koch, and J. Michel, "Tensile-strained, n-type Ge as a gain medium for monolithic laser integration on Si," Opt. Express **15**, 11272-11277 (2007).
3. V. G. Talalaev, G. E. Cirlin, A. A. Tonkikh, N. D. Zakharov, and P. Werner, "Room temperature electroluminescence from Ge/Si quantum dots superlattice close to 1.6 μm," Phys. Status Solidi A **198**, R4-R6 (2003).
4. Y. H. Peng, C. H. Hsu, C. H. Kuan, and C. W. Liu, "The evolution of electroluminescence in Ge quantum-dot diodes with the fold number," Appl. Phys. Lett. **85**, 6107-6109 (2004).
5. M. H. Liao, C. H. Lee, T. A. Hung, and C. W. Liu, "The intermixing and strain effects on electroluminescence of SiGe dots," J. Appl. Phys. **102**, 053520 (2007).
6. R. A. Soref, and L. Friedman, "Direct-gap Ge/GeSn/Si and GeSn/Ge/Si Heterostructures," Superlattice Microst. **14**, 189-193 (1993).
7. X. Sunn, J. Liu, L. C. Kimerling and J. Michel, "Room temperature direct band gap electroluminescence from Ge-on-Si light emitting diode," Opt. Lett. **34**, 1198-1200 (2009).
8. M. H. Liao, C. Y. Yu, T. H. Guo, C. H. Lin, and C. W. Liu, "Electroluminescence from the Ge quantum dot MOS tunneling diodes," IEEE Electron Device Lett. **27**, 252-254 (2006).
9. C. O. Chui, K. Gopalakrishnan, P. G. Griffin, J. D. Plummer, and K. C. Saraswat, "Activation and diffusion studies of ion-implantated p and n dopants in germanium," Appl. Phys. Lett. **83**, 3275-3277 (2003).
10. H. Y. Yu, S. L. Cheng, P. B. Griffin, Y. Nishi, and K. C. Saraswat, "Germanium in-situ doped epitaxial growth on Si for high performance n+/p junction diode," (submitted to IEEE Electron Device Lett.).
11. Y. Ishikawa, K. Wada, D. D. Cannon, J. Liu, H. C. Luan, and L. C. Kimerling, "Strain-induced band gap shrinkage in Ge grown on Si substrate," Appl. Phys. Lett. **82**, 2044-2046 (2003).

1. Introduction

A silicon (Si) compatible laser for applications in telecommunication and optical interconnect systems [1] has been an interesting topic for several years now but has yet to be practically demonstrated. The main problem rests with the issue of having a material which is compatible with conventional CMOS process and has an emission wavelength around 1550 nm for coupling to the optical fiber network [2]. Germanium (Ge) is compatible with silicon and has a direct band gap of 0.8 eV, corresponding to the required telecommunication wavelength of 1550 nm. The small difference of 0.134 eV between the direct and indirect band gaps of Ge suggests the possibility of a direct band gap transition. There are three main approaches that researchers are taking to fulfill this goal, including quantum confinement (quantum wells and

#109859 - $15.00 USD Received 8 Apr 2009; revised 14 May 2009; accepted 17 May 2009; published 29 May 2009

quantum dots) [3-5], strain [6], and high concentration n-type doping [2]. However, until recently [7], room temperature electroluminescence (EL) reports at around 1550 nm have only been demonstrated in Ge/Si quantum dot p-i-n diode [3,4] and tunnel diodes [8]. By the quantum confinement effect between Ge and Si bands and the compressive strain applied to Ge from lattice mismatch, the indirect band gap of Ge is increased to match the required wavelength of 1550 nm. However, due to the type II junction between Ge and Si, only confinement of holes can be achieved. Without confining electrons, Ge/Si quantum dots still preserve the indirect band gap property of Ge and thus the light emitting efficiency of the dots are limited. Therefore, for higher efficiency devices, a direct band gap transition is necessary. Other methods of strain and high n-type doping have been proposed to have the potential of exhibiting a direct transition behavior. However, when the required 2% tensile strain is achieved to make Ge a direct band gap material, the corresponding emission wavelength shifts to 2500nm [2]. Therefore, only highly-doped n-type Ge can preserve the original direct band gap separation. Through large concentration n-type doping, the Fermi energy of Ge will be above the indirect conduction band (L valley) edge and the probability that electrons occupy the direct Γ valley will increase. This band filling effect can thus enhance the light emitting efficiency of Ge by raising the possibility of direct transitions. The higher the doping concentration, the more direct band-gap-like the material will become. From calculations, the required doping concentration is $7.6 \cdot 10^{19}$ cm^{-3} for Ge with 0.25 % tensile strain to become a direct band gap material [2]. Recently, the first room temperature direct band gap EL from a Ge/Si p-i-n diode has been successfully demonstrated [7]. In this work, we also demonstrate room temperature direct band gap EL at 1.6 µm from Ge n+/p light emitting diodes (LED) on a Si substrate with further discussions on the contribution of electron band filling effect to the device efficiency under different n-type doping concentrations and the temperature dependence of the device.

2. Experimental

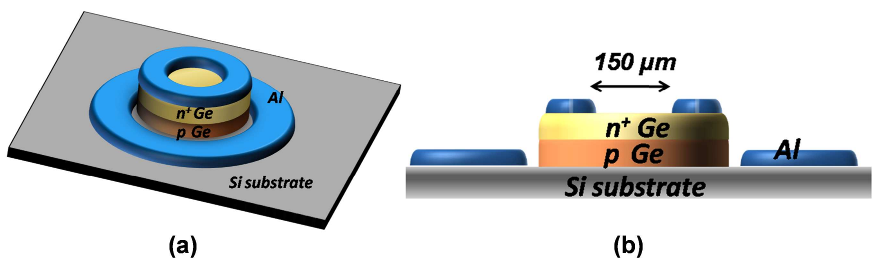

Fig. 1. Design of the Ge-based light emitting diode. (a) Isometric schematic of the device structure showing the Ge mesa on top of a p-type Si substrate with Al ring contacts. (b) Cross-section schematic of the device structure.

An n+/p Ge homojunction light emitting diode on a Si substrate was fabricated using an in-situ doping method. The isometric and cross-section schematics of the diode are shown in Fig. 1(a) and Fig. 1(b), respectively. A 500 nm thick silicon thermal oxide was first grown on a p-type (100) Si substrate. A 500 µm by 500µm window was defined by optical lithography and the oxide within this window was removed by an Applied Material plasma etcher. A 2.2 µm epi-Ge mesa was then grown selectively on the Si substrate by an Applied Materials reduced pressure chemical vapor deposition (CVD) system. The P and N regions of Ge were defined in-situ by flowing B_2H_6 and PH_3 during the deposition. The 0.8 µm p-type Ge layer was first grown at 400 °C and 8 Pa with GeH_4 for 24 min, followed by annealing at 825 °C in hydrogen ambient for 30 min. The mass flow ratio of B_2H_6 and GeH_4 for this p-layer is 10^{-3}. The growth temperature was then increased to 600 °C for 1.4 µm n-layer deposition at 8 Pa for 10 min. The mass flow ratio of PH_3 and GeH_4 for this n-layer is $5 \cdot 10^3$. A Ge mesa 300 µm in diameter was defined by dry etching and 100 nm thick Al ring contacts were then deposited on top and outside of the mesa.

#109859 - $15.00 USD Received 8 Apr 2009; revised 14 May 2009; accepted 17 May 2009; published 29 May 2009

In-situ doping was used because it can provide a better definition of the junction profile than traditional implantation techniques. This is especially important for Ge due to the much higher diffusion coefficient of the n-type dopants under post annealing and after ion implantation, which make the junction profile difficult to define [9]. The doping concentrations of phosphorous and boron are $7.5 \cdot 10^{18}$ cm^{-3} and $3.6 \cdot 10^{17}$ cm^{-3}, as measured by secondary ion mass spectrometry (SIMS). The activation level of the n+ Ge layer grown at 600 °C was confirmed to be 100% by the combined results of spreading resistance probe (SRP) measurement and SIMS in our recent submitted work [10].

Electroluminescence and photoluminescence measurements were collected with a 20x objective lens, directed towards a monochromator and detected with a liquid nitrogen-cooled linear InGaAs detector array. Either electrical probes or wire-bonding was used to electrically contact devices with Keithley 2635 sourcemeter. A pump laser at 633 nm, with 4 mW of incident power focused to an approximately 20 um spot was used to produce PL measurements. For low-temperature measurements, samples were placed in a liquid-He flow cryostat.

3. Ge LED characteristics

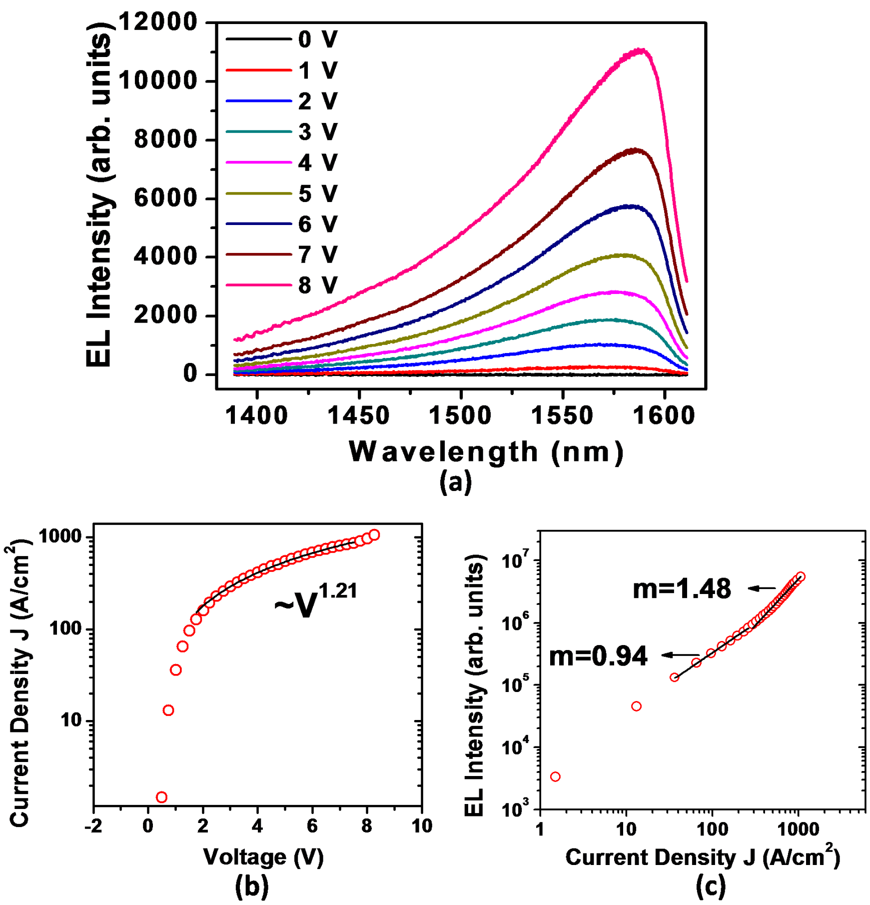

Fig. 2. (a). Electroluminescence spectra of the Ge LED under different applied biases. (b) Current density-to-voltage (J-V) characteristic of the device. The J-V curve exhibits a dependence of 1.21 for voltages greater than 2 V. (c) Integrated luminescence-to-current density L-J^m characteristics of the device. The factor m is 0.94 between 36-250 A/cm^2 and 1.48 for current densities greater than 300 A/cm^2.

#109859 - $15.00 USD Received 8 Apr 2009; revised 14 May 2009; accepted 17 May 2009; published 29 May 2009

Room temperature EL spectra of the Ge LED with different applied biases are shown in Fig. 2(a). The wavelength of the EL peak is located near 1.6 µm, which suggests emission from the direct band gap of Ge. The onset of the EL is at 0.75 V, closely matching the indirect band gap (0.66 eV) of Ge. The EL intensity is significantly enhanced for voltages greater than 2 V, which corresponds to a current density of 160 A/cm^2. Due to the spectrometer detection limit at 1600 nm, we cannot obtain a complete EL spectrum for this device. The actual peak position is expected at approximately 1610 nm due to the 0.2 % thermal-induced tensile strain from Ge on Si epitaxy [11].

The current density-to-voltage (J-V) curve of this device in Fig. 2(b) shows typical diode-like behavior. For applied voltages greater than 2 V, the J-V slope of 1.21 implies ohmic conduction from the series resistance of the device. The integrated EL intensity dependence on drive current is shown in Fig. 2(c). This dependence is also characterized empirically by the relation $L \propto J^m$, where L is the integrated EL intensity and J is the current density. The exponent m is an important factor used to understand the emission behavior. For current densities between 36 and 250 A/cm^2, the extracted exponent m is 0.94, indicating a linear relation. However, a superlinear L-J dependence with m of 1.48 is observed for currents greater than 300A/cm^2. This implies that the device is more effective when operating under high current. This phenomenon is contrary to typical LED behavior, which exhibits lower m values at higher currents due to lower radiative efficiency, caused by effects such as Auger recombination. We believe that this superlinear effect at high injection currents is caused by an increase in device temperature by Joule heating, which we examine further in section 5, as well as a shift of the position of the quasi Fermi-level E_{fn}, which is examined in Ref. [7]. In the future, we plan to include both temperature as well as quasi-fermi-level shifts in a simulation model of our device.

4. Electron band filling effect on light emitting efficiency

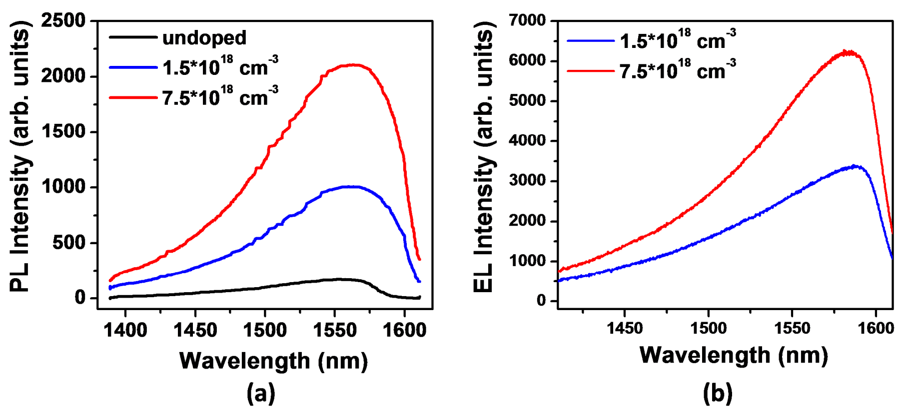

Fig. 3. (a). PL spectra of undoped, n-type $1.5{\cdot}10^{18}$ and $7.5{\cdot}10^{18}$ cm^{-3} concentrations of Ge. Better radiative efficiency is obtained with higher n-type doping concentration. (b) EL spectra of n-type $1.5{\cdot}10^{18}$ and $7.5{\cdot}10^{18}$ cm^{-3} concentration Ge devices under the same drive current of 700 A/cm^2. A similar emission trend is observed as that for the PL spectra. The evidence of similar spectra shapes suggests the same light emitting mechanism.

From previous reports, the band filling level of the electrons is essential to the radiative efficiency of Ge [2]. Here we compare two Ge LEDs with n type doping concentrations of $1.5{\cdot}10^{18}$ and $7.5{\cdot}10^{18}$ cm^{-3} to understand the importance of the electron band filling effect. The remainder of the fabrication conditions are the same for each device. Figure 3(a) shows the PL measurement results of these two devices and a reference sample of undoped epi-Ge on Si. As expected, the $7.5{\cdot}10^{18}$ cm^{-3} sample has the highest PL intensity, due to increased band-filling. The EL spectra for these two devices are shown in Fig. 3(b). In order to eliminate the factor of series resistance for these two devices, the spectra are taken under the same drive current density of 700 A/cm^2. This result shows a similar trend as that of the PL measurement; the

#109859 - $15.00 USD Received 8 Apr 2009; revised 14 May 2009; accepted 17 May 2009; published 29 May 2009

higher doping concentration sample is more radiatively efficient. The intensity ratio between the $7.5\cdot10^{18}$ and $1.5\cdot10^{18}$ cm^{-3} samples for PL and EL are 1.90 and 1.82, respectively. The similar spectral shapes and intensity ratios of PL and EL measurements suggest that the same luminescence mechanism takes place in both measurements. From a simple density of states calculation, the Fermi energy of the $7.5\cdot10^{18}$ cm^{-3} device is only at the edge of the indirect L valley. To have better radiative efficiency, increased gain, and lower series resistance, improving the electron band filling technique through increased doping is necessary.

5. Temperature dependence of electroluminescence

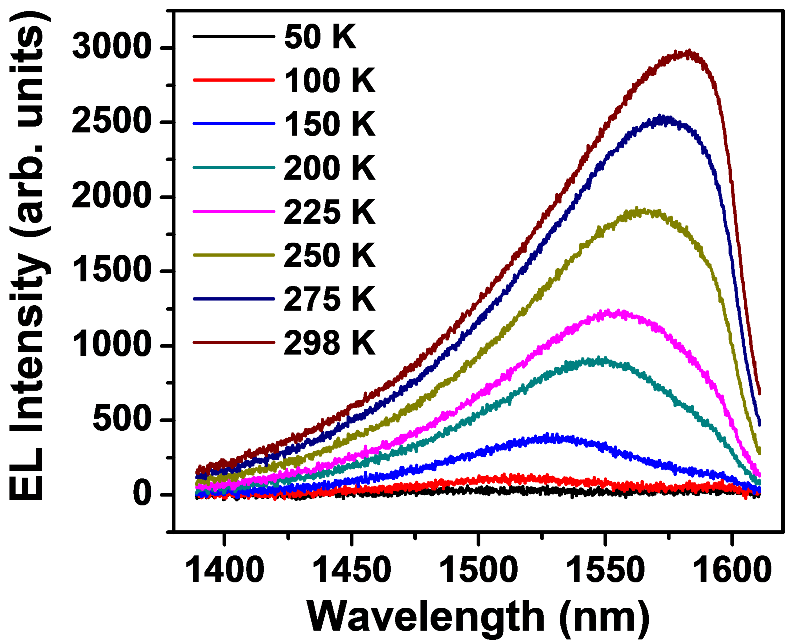

Fig. 4. EL spectra measured at various temperatures. Better radiative efficiencies are observed for higher temperatures. Redshifts of the EL peaks at higher temperature are also obtained due to the band gap shrinkage of Ge.

We conclude from the results shown in Fig. 2(c) that a cause of the EL enhancement effect at high current densities is likely due to the increase in electron density in the Γ valley caused by Joule heating. It is therefore important to further understand the dependence of EL with temperature. EL spectra from 50K to 300K, taken by placing the sample in a liquid-He cooled cryostat, are shown in Fig. 4. The spectra are obtained under the same drive current of 250 A/cm^2. Unlike the temperature dependence for a normal LED, EL intensity is enhanced as the temperature is increased. This effect is especially different from the temperature dependent EL reports of Ge quantum dot and SiGe quantum well devices [5, 8], which show EL quenching at high temperature. For an n-type doping concentration of $7.5\cdot10^{18}$ cm^{-3}, the Fermi energy is only at the edge of the in-direct L valley. Therefore, the electron density in the Γ valley, which contributes to the radiative transition, is highly dependent on the Fermi-Dirac distribution. At lower temperatures, the Fermi-Dirac distribution resembles a step function and the probability that electrons occupy Γ valley is decreased. Conversely, at higher temperatures the electron distribution is smeared out and the likelihood of electron occupation in the Γ valley increases. This is the reason why our temperature dependent EL measurements show a better radiative efficiency at higher temperatures. Part of the superlinear relation with m=1.48 from the L-J curve at higher current densities can be interpreted as being caused by Joule heating which increases the population of the Γ valley and thus the radiative efficiency of the device. An expected redshift is also observed in the temperature dependence data due to

#109859 - $15.00 USD Received 8 Apr 2009; revised 14 May 2009; accepted 17 May 2009; published 29 May 2009

the direct band gap shrinkage at higher temperature. Due to the detection limit of our system at 1600 nm, the exact peak position isn't available and a more precise study for this redshifting effect is underway.

6. Conclusion

We demonstrate a Si-compatible Ge-based LED at 1.6 μm. This is a significant step in achieving a Si-compatible laser, which have been studied for over two decades. The direct band gap transition characteristic of this device and the simple fabrication process make it attractive for telecommunication applications. The higher light emitting efficiency at higher temperatures shows the capability of this device to operate at room temperature, which is an important necessity from a practical point of view. To demonstrate a Ge-based Si-compatible laser using the band filling method, a higher n type doping concentration of Ge needs to be achieved in order to increase the radiative efficiency and achieve gain.

Acknowledgments

This work is supported by Toshiba, MARCO Interconnect Focus Center, AFOSR and SNF NNIN.

#109859 - $15.00 USD Received 8 Apr 2009; revised 14 May 2009; accepted 17 May 2009; published 29 May 2009