Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp580-581

A-7-4

Infrared Absorption of N-type Tensile-Strained Ge-on-Si

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1. Introduction

Epitaxial Ge-on-Si is a particularly interesting candidate for monolithic lasers due to its compatibility with CMOS transistors and pseudo-direct gap behavior suitable for active photonic devices [1, 2]. Since the concept of band-engineered Ge lasers was proposed by using tensile strain and n-type doping to compensate the energy difference between direct (Γ) and indirect (L) valleys [3], great progress has been made towards monolithic Ge-on-Si lasers. Lasing from Ge-on-Si optical gain media have been successfully demonstrated under optical pumping [4], and very recently, under electrical pumping [5]. For the first electrically pumped Ge-on-Si laser, a net gain >500 cm^{-1} is achieved from the direct gap transition of Ge with n=4×10^{19} cm^{-3} and ~0.2% tensile strain. Remarkably, this doping level is much smaller than the theoretical value of 7.6×10^{19} cm^{-3} for a material gain of ~400 cm^{-1} [3] using free carrier absorption losses reported in literature. The discrepancy between theoretical modeling and experimental data needs to be investigated in order to gain more understanding to further optimize Ge-on-Si lasers.

In this letter, we report a strong L → Γ intervalley scattering and a low free carrier absorption in the near infrared regime from the infrared absorption spectra of Ge-on-Si gain media. The L → Γ intervalley absorption edge is in good agreement with theoretical value. On the other hand, the λ^2-dependent free carrier absorption is only presented at $\lambda \geq 15$ μm and it turns out to be negligible at the lasing wavelength range of 1.5-1.7 μm. The strong L → Γ intervalley scattering favors electronic occupation of the Γ valley for the direct gap transition of n^+ Ge-on-Si, while the low free carrier absorption leads to a larger net gain. These two factors explain the why a higher net gain is achieved at a lower doping level for the first electrically-pumped Ge-on-Si lasers compared to the theoretical estimation. These results also indicate that Ge-on-Si laser can potentially achieve a much better performance than our original theoretical prediction in Ref. [3].

2. Experimental Results

Ge epitaxial films with in-situ phosphorous doping were grown on Si by ultrahigh-vacuum chemical vapor deposition (UHVCVD) with two-step growth method [1, 2]. The thermally induced tensile strain in the Ge layer is 0.2~0.23% [4, 6]. Recently a delta-doping process is developed to increase the active phosphorus concentration to ~4×10^{19} cm^{-3}, as described in Ref. [5]. The P doping profile before and after activation anneal was measured by secondary ion mass spectrometry (SIMS). The activated P concentration was determined by Hall Effect measurements. Table 1 lists the tensile-strained n^+ Ge-on-Si samples with different thicknesses and doping levels in this study. To investigate the infrared absorption of n-Ge films, the transmittance spectra of these samples are measured with JASCO FTIR-4100 spectrometer in the wavelength range of 1.3~25 μm. With a combination of transfer matrix analysis and Kramers-Kronig relation, we were able to derive the real part of refractive index and the absorption coefficient of n^+ Ge deterministically from the transmittance data using an iterative self-consistent regression approach [6].

Table I List of n-Ge on Si samples

Sample	Ge thickness (nm)	Doping Concentration (/cm^3)
D1	360	7×10^{18} cm^{-3}, delta doping
D2	651	2.9×10^{19} cm^{-3}, delta doping
D3	651	3.9×10^{19} cm^{-3} delta doping
U1	740	1×10^{19} cm^{-3}, uniform doping

Fig. 1 shows the derived infrared absorption spectrum of Sample D1. The spectrum can be divided into 4 regimes. In Regime I the absorption drastically increases with wavelength at λ>9 μm, indicating free carrier absorption. For n-type bulk Ge, the characteristic λ^2-dependent free carrier absorption is widely observed at temperature ≥300 K in the wavelength range of 25~40 μm and n=1×10^{18}~5×10^{19} cm^{-3} [7-10]. As a comparison, the $A\lambda^2$ free carrier absorption model is shown with the dashed green line. While the observed free carrier absorption largely follows λ^2-dependence at λ>15 μm, it decreases much faster with wavelength than the λ^2 model at λ<11 μm. In fact, an extrapolation shows that the free carrier absorption is <20 cm^{-1} at the lasing wavelength range of 1.5-1.7 μm. This result holds true for all the tensile-strained n^+ Ge samples in this study with n-type doping up to 3.9×10^{19} cm^{-3}, although the free carrier absorption λat >9 μm does increases with doping level. Therefore, the free carrier absorption from tensile-strained n^+ Ge is drastically smaller than unstrained bulk n-Ge reported in literature, where explains why a higher net gain is achieved at a lower doping level for the electrically-pumped Ge-on-Si lasers compared to theoretical calculation using free carrier absorption data reported for bulk Ge.

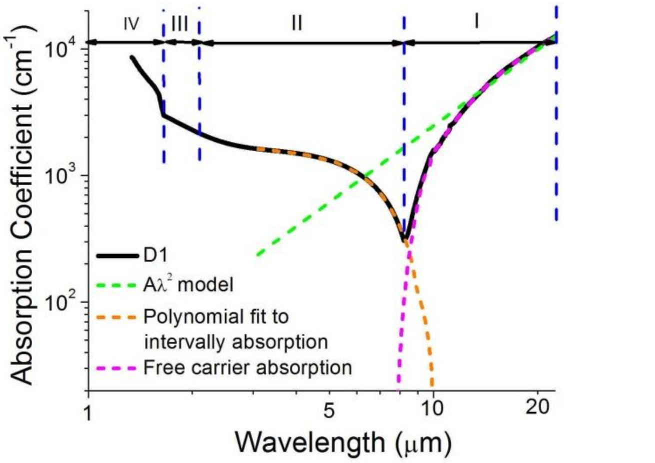

Fig. 1 Infrared absorption coefficient of smaple D1. Regimes I-IV are dominated by free carrier absorption, L → Γ intervalley scattering absorption, indirect gap+intervalley scattering absorption, and direct gap absorption, respectively.

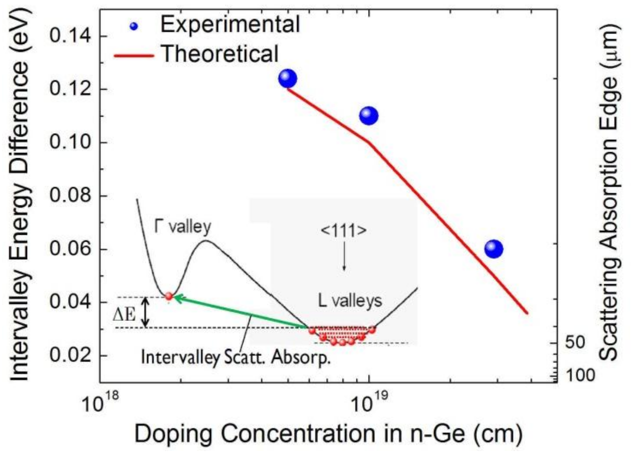

Fig. 2 Intervalley energy difference between L and Γ valleys as a function of doping concentration.

In Regime II, the absorption starts to increase significantly with the decrease of wavelength at λ<9 μm, indicating a change in dominant absorption mechanism. Since 9 μm is far from the band gaps of Ge, we found that the most reasonable explanation is the onset of L → Γ intervalley scattering absorption (IVSA). The increase in n-type doping concentration raises the Fermi level and reduces the energy difference ΔE between filled L conduction valley and Γ valley, leading to a redshift of the IVSA edge. A polynomial fit in Regime II reveals that the absorption edge of IVSA is at λ=10 μm for sample D1 and and 11 μm for sample U1. The IVSA edge for D2 is estimated to be ~20 μm, and the one for D3 is out of the measurement range (>25 μm). Fig. 2 summarizes the intervalley energy difference ΔE between L and Γ valleys as a function of doping concentration. The experimental result is in good agreement with theoretical calculaitons, confirming our interpretation of absorption in Regime II. The strong intervalley scattering from L to Γ valleys promotes electronic occupation of the direct conduction Γ valley. This process in turn enhances efficient light emission from the direct gap transition of Ge. Together with the low free carrier absorption in the wavelength range of 1.5-1.7 μm, these two factors reduce the n-type doping level and injected carrier density required for electrically pumped Ge-on-Si lasers.

Regime III in Fig. 1 shows a combined contribution of IVSA and possibly indirect gap absorption. The sharp absorption edge at ~1620 nm corresponds to the onset of direct gap absorption. We also found that with the increase of n-type doping level the boundary between direct and indirect transition becomes more and more blurry, which may be attributed to enhanced L → Γ intervalley scattering.

3. Conclusions

In conclusion, we report a strong L → Γ intervalley scattering and a low free carrier absorption in the near infrared regime from the infrared absorption spectra of Ge-on-Si gain media. The strong L → Γ intervalley scattering favors electronic occupation of the Γ valley for the direct gap transition of n^+ Ge-on-Si, while the low free carrier absorption leads to a larger net gain. These results are consistent with the resent report on electrically-pumped Ge-on-Si lasers, and indicate that Ge-on-Sis laser can potentially achieve a much better performance than our original theoretical prediction in Ref. [3].

Acknowledgements

This work was supported by the Si-based Laser Initiative of the Multidisciplinary University Research Initiative (MURI) sponsored by the Air Force Office of Scientific Research (AFOSR) and supervised by Dr. Gernot Pomrenke and by the Fully Laser Integrated Photonics (FLIP) program under APIC Corporation.

References

[1] D. H. Ahn, C. Y. Hong, J. F. Liu, M. Beals, W. Giziewicz, L. C. Kimerling and J. Michel, Opt. Express **15** (2007) 3916.

[2] J. F. Liu, M. Beals, A. Pomerene, S. Bernardis, R. Sun, J. Cheng, L. C. Kimerling and J. Michel, Nature Photonics **2** (2008) 433.

[3] J. Liu, X. Sun, D. Pan, X. X. Wang, L. C. Kimerling, T. L. Koch, and J. Michel, Opt. Express **15** (2007) 11272.

[4] J. F. Liu, X. Sun, R. Camacho-Aguilera, L. C. Kimerling and J. Michel, Opt. Lett. **35** (2010) 679.

[5] J. Michel, R. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bessette, M. Romagnoli, R. Dutt and L. Kimerling, *Optical Fiber Communication Conference, OSA Technical Digest* (2012) PDP5A.6.

[6] J. F. Liu, X. Sun, L. C. Kimerling and J. Michel, Opt. Lett. **34** (2009) 1738.

[7] H. Y. Fan, W. Spitzer, and R. J. Collin, Physical Review **101** 566 (1956).

[8] R. Rosenberg and M. Lax, Physical Review **112** (1958) 843.

[9] W.G. Spitzer, F. A. Trumbore, and R. A. Logan, J. Appl. Phys. **32** (1961) 1822.

[10] C. Haas, Phys. Rev. **125** (1962) 1965.