Analysis of Homogeneous Broadening in n-type doped Ge layers on Si for laser application

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***Abstract*— The homogeneous broadening in Phosphorus doped Ge layers is characterized using photoluminescence spectroscopy and absorption measurements. A broadening parameter Γ_{HOM}=45meV due to carrier scattering effects was extracted leading to an estimated increase in threshold current density for Ge lasers by a factor >4.**

***Index Terms*— Laser; Homogeneous broadening; Silicon photonics**

I. INTRODUCTION

Silicon photonics (SiPh) based optical interconnects are widely considered for short-reach interconnect applications where their electrical counterparts face the bandwidth-power density bottleneck [1]. An important component of every optical transceiver is the laser source and Germanium (Ge) is considered to be a promising material for realizing it in the scope of SiPh. Ge is intrinsically an indirect band gap material but can be made pseudo direct band gap by doping it with Phosphorus (P) [2,3]. However, doping Ge with $>2\times10^{19}$ cm^{-3} P atoms reduces the Shockley-Reed-Hall recombination lifetime of carriers and introduces additional carrier scattering effects due to phonons and impurities in the lattice [4]. These carrier scattering effects result in homogeneous broadening of the gain spectrum and increases the threshold current density of the laser. In this work, we extract the broadening parameter (Γ_{HOM}) of P doped Ge layers using photoluminescence spectroscopy (PL) and absorption measurements. A modified Joint Density of State (JDOS) model that considers many-body effects such as homogeneous broadening, the Urbach tail and dopant induced band-gap narrowing is used in this study.

II. MODELING HOMOGENEOUS BROADENING

The JDOS model is a commonly used technique to calculate the absorption, spontaneous emission and gain spectra of a semiconductor. However, one typically assumes an ideal quadratic JDOS together with recombination or carrier generation physics that obeys conservation of momentum and follows the k-selection rule. Deviations from this ideal behaviour are the result of many-body-effects due to phonons, carrier, impurities or defects. These deviations can be captured with the addition of an Urbach tail (an exponential tail below the band-edge), including homogeneous broadening effects (through convolution of the absorption and spontaneous emission spectra with a Lorentzian line shape function) and dopant induced band-gap narrowing effects (BGN) as proposed in [5,6]. Such a modified JDOS model is used here to model the measured photoluminescence and absorption spectra of P doped Ge samples. The full width at half maximum (FWHM) of the Lorentzian line shape function used to model the homogeneous broadening effects is represented here as the broadening parameter-Γ_{HOM}.

III. SAMPLE AND EXPERIMENT DETAILS

P-doped Ge layers of 0.2 µm were grown on 0.2 µm thick Ge buffer layers deposited on Si(001) substrates by a RPCVD process in a 300mm Intrepid^{TM} XP system from ASM [7], with Ge_2H_6 and PH_3 as the precursors. Rapid thermal annealing at 700^{O}C for 30 sec in N_2 allows diffusion of P-atoms into the underlying undoped Ge buffer, resulting in uniformly doped 0.4 µm Ge layers on Si, and also improves the crystallinity of the layer by reducing point defects. A summary of all samples investigated in this work is shown in Table 1. Their doping level is similar to that of the electrically pumped Ge laser demonstrated in [8,9]. An undoped layer of 0.6 µm Ge was used as a reference.

Table 1: Summary of sample details investigated in this paper.

Sample detail	Chem. P conc.	Active P conc.
0.6 µm Ge buffer (reference)	-	-
320^{O}C $ppPH_3/ppGe_2H_6$=0.006	2.8×10^{19} cm^{-3}	2.65×10^{19} cm^{-3}
320^{O}C $ppPH_3/ppGe_2H_6$=0.02	5.3×10^{19} cm^{-3}	4.5×10^{19} cm^{-3}
425^{O}C $ppPH_3/ppGe_2H_6$=0.02	5.2×10^{19} cm^{-3}	4.5×10^{19} cm^{-3}

Photoluminescence (PL) and absorption measurements were used to characterize the samples. The PL measurement was performed by exciting the sample with pump intensities in the range of 0.03-0.2 MW/cm^2 at a wavelength of 532 nm. The PL spectra were collected using an extended-InGaAs detector covering the range 1.3-2.2 µm. Absorption measurements were performed using a UV-VIS-IR Spectrophotometer.

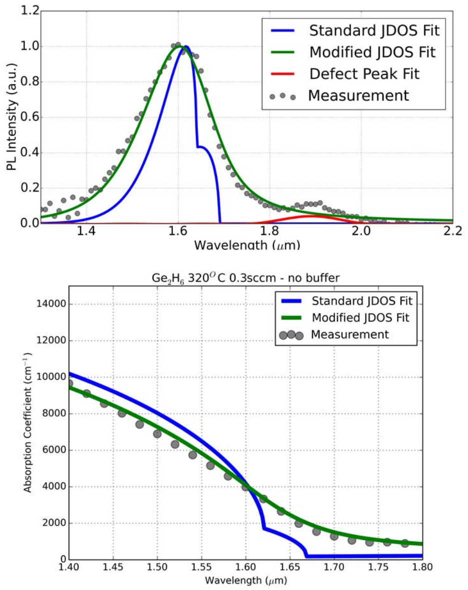

Fig. 1. PL and absorption spectra of the sample with growth condition - 320^{O}C $ppPH_3/ppGe_2H_6$=0.006. The PL spectra was obtained with a pump intensity of 0.08 MW/cm^2. The modified JDOS model was used to extract the broadening parameter (Γ_{HOM}), Urbach tail (E_O) and dopant induced band-gap narrowing (BGN).

Table 2: Summary of extracted broadening parameter (Γ_{HOM}), Urbach tail (E_O) and dopant induced band gap narrowing (BGN) using the modified JDOS model.

Sample detail	E_O (meV)	Γ_{HOM} (meV)	BGN (meV)
0.6 µm Ge buffer (reference)	8±1.5	3±2.5	0
320^{O}C $ppPH_3/ppGe_2H_6$=0.006	5±1.5	45±2.5	25
320^{O}C $ppPH_3/ppGe_2H_6$=0.02	5±1.5	45±2.5	37.5
425^{O}C $ppPH_3/ppGe_2H_6$=0.02	5±1.5	50±2.5	37.5

IV. RESULTS AND DISCUSSION

Fig. 1. shows the PL measurement and absorption co-efficient of the sample where the P-doped Ge layer was grown at 320^{O}C with $ppPH_3/ppGe_2H_6$=0.006. The PL spectrum shown in the figure was obtained for a pumping intensity of 0.08 MW/cm^2. The spontaneous emission associated with the direct Γ-valley results in a PL emission peak at 1.62 µm. The peak at 1.9 µm, which is not present in the PL spectrum from undoped Ge, is linked to defects present in the doped layers due to introduction of P dopants. In order to model the PL emission from the Γ valley, the carrier concentration in the layers was estimated by solving the carrier-continuity equation for each pump intensity assuming a cylindrical distribution of photo-excited carriers in the Ge layer. A Shockley-Reed-Hall recombination lifetime of 4 ns and 0.4 ns was considered for undoped and doped Ge respectively [10,11]. Taking these operating condition into account, we model an ideal PL spectra governed by the k-selection rule, without Urbach tail. However, this ideal spectrum does not well represent the measurements as is clear from Fig. 1. To overcome this problem, we included many-body effects and swept Γ_{HOM}, E_O and BGN to reproduce the PL and absorption spectra obtained experimentally. An example is shown in Fig. 1 where Γ_{HOM} =45 meV, E_O=5 meV and BGN=25 meV were used in the fit. For all doped Ge layers we found Γ_{HOM} ≥45 meV compared to Γ_{HOM}=3 meV for undoped Ge layers (see Table 2). We believe the high broadening parameter for doped Ge arises from carrier-carrier scattering, carrier-neutral impurity scattering, carrier-ionized impurity scattering, or carrier- acoustical/optical phonon scattering effects. These additional scattering effects generate broadening in the gain spectrum and lead to a substantial increase in the calculated threshold current density as shown in Fig 2 and in [5,6].

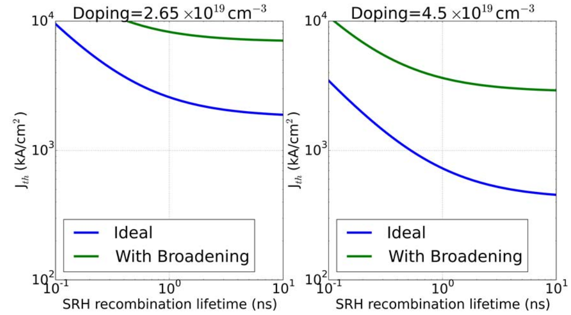

Fig. 2. Calculated threshold current density as a function of SRH recombination lifetime for n-type doped Ge layers. Simulation includes a target modal loss of 200 cm^{-1} and Γ_{HOM}=45 meV, E_O=5 meV for curves named "With Broadening".

V. CONCLUSION

In this work, we investigated homogeneous broadening due to carrier scattering effects in Phosphorus doped Ge layers grown on Si . By fitting results from photoluminescence and absorption spectroscopy with a modified JDOS model we could extract the broadening parameter (Γ_{HOM}). For uniformly doped Ge layers up to a doping level of 4.5×10^{19} cm^{-3}, Γ_{HOM}≥45 meV was extracted as compared to Γ_{HOM}=3 meV for undoped Ge layers. From these findings we estimate that the threshold current density of a Ge laser with active P doping is increased by a factor of 4 to 8 compared with a model where this broadening is not taken into account.

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