Extraction of Carrier Lifetime in Ge Waveguides using Pump Probe Spectroscopy

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Carrier lifetimes in Ge-on-Si waveguides are deduced using time-resolved infrared transmission pump-probe spectroscopy. Dynamics of pump-induced excess carriers generated in waveguides with varying Ge thickness and width are probed using a CW laser. The lifetimes of these excess carriers strongly depend on the thickness and width of the waveguide due to defect assisted surface recombination. Interface recombination velocities of 0.975×10^4 cm/s and 1.45×10^4 cm/s were extracted for the Ge/Si and the Ge/SiO_2 interfaces respectively.

Optical transceivers based on silicon photonics are being considered as an alternative to their electrical counterparts for short reach interconnects.[1] Silicon photonics benefits from CMOS infrastructure to fabricate optical circuits consisting of high-speed photodetectors[2], modulators[3] and filters[4]. Ge-on-Si waveguides (WG) with a p-i-n diode have shown to be a promising component in realizing high-speed and high-responsivity photodetectors[2] as well as low power consumption electro-absorption modulators[3]. Carrier injection based devices, such as variable optical attenuator (VOA) and Ge lasers, offer the possibility of having a complete set of Ge based active elements.[5] However, for these devices, carrier lifetimes in the WGs are important to determine the attenuation and power efficiency of the VOA as well as the threshold current density of the laser.[6,7] Therefore, we present a method based on pump-probe transmission-spectroscopy applicable to integrated WGs to study the impact of surface recombination on carrier lifetime in Ge-on-Si WGs.

A set of Ge-on-Si WGs with varying width (0.4 μm, 0.6 μm, 0.8 μm and 1.0 μm) and thickness (0.200 μm and 0.375 μm) is studied in this work. WGs of lengths 8 μm, 17.6 μm and 40 μm were used to model the carrier dynamics, but, only the 8 μm long WGs were used to extract the carrier lifetime as will be explained later in this work. The devices were fabricated using imec's 200 mm Si photonics platform using a 130 nm CMOS toolset on 200 mm SOI wafer with 220 nm of top Si layer and 2 μm buried oxide.[8] For the 0.200 μm and 0.375 μm thick WGs, Ge was selectively grown on 30 nm and 110 nm deep recessed Si respectively. The growth was performed using reduced pressure chemical vapour deposition (RPCVD).[8] The wafer was annealed to suppress the threading dislocation density and, using chemical-mechanical polishing, the Ge islands were planarized to their target thickness. The top surface was passivated with the deposition of PECVD SiO_2.[8] Poly-Si tapers were used for adiabatic optical coupling from the Ge-on-Si WG to the SOI WG. Coupling to and from the chip was performed by using TE-mode fiber grating couplers. Fig. 1 shows a cross-section scanning electron micrograph (SEM) and an optical micrograph of a 0.375 μm thick Ge-on-Si WG.

The pump-probe measurements were performed using a mode-locked femtosecond fiber laser (from Calmer laser) as the pump and a CW tunable laser source as the probe. The pump has a center wavelength of 1548.57 nm with a pulse width of <1 ps at the output of the fiber. In order to determine the appropriate probe wavelength, knowledge about the band-structure of Ge in the waveguide is necessary. This is estimated by using a Joint Density of States (JDOS) model to fit the absorption coefficient of Ge in the WG.[7] Transmission measurements were performed using a CW tunable laser source. Fig. 2 shows the extracted absorption coefficient for a 1 μm wide, 0.375 μm thick and 8 μm long Ge-on-Si WG after

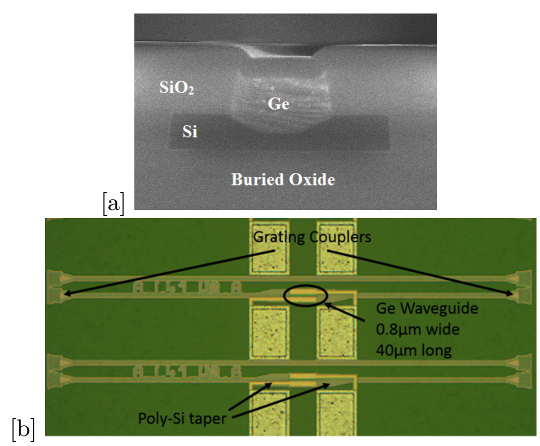

FIG. 1. a. Cross-section scanning electron micrograph of 0.8 μm wide and 0.375 μm thich Ge-on-Si WG. b. Microscope image of the Device under test (DUT).

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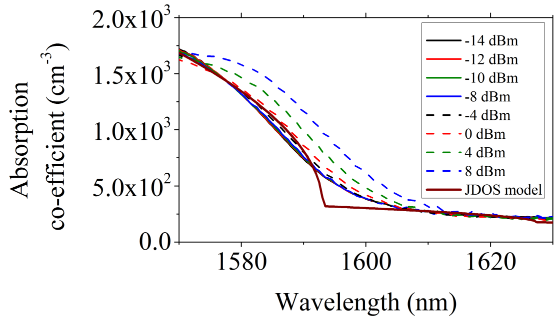

FIG. 2. Extracted absorption coefficient of Ge-on-Si WG for different laser input powers. At high laser input powers, the absorption coefficient is higher due FCA from probe-induced excess carriers. The absorption coefficient at low input power was used to fit a JDOS model to extract biaxial tensile strain and band-edge information of the Ge.

accounting for the coupling loss from a reference SOI WG and grating couplers. The coupling loss from the poly-Si tapers was estimated using the cut-back method. The impact of laser input power on extracting the absorption-coefficient evidences the presence of probe-induced excess carriers that interfere with the measurement due to free-carrier absorption (FCA) and optical bleaching effects (OBE). As a result, absorption coefficients extracted at low input laser power were used to fit the JDOS model.

For bulk Ge, *Jifeng Liu et. al* modeled the absorption due to Γ-lh and Γ-hh transitions using the JDOS model with $E_{g,\Gamma-lh}$ and $E_{g,\Gamma-hh}$ as the band-gaps for direct conduction band (Γ)-light hole (lh) and Γ-heavy hole (hh) valley respectively.[7] These band-gaps are influenced by the degree of bi-axial tensile strain in the layer and is modeled using model-solid theory developed by *C. Van De Walle et. al*[9]. Since TE grating couplers were used, the absorption corresponding to TE polarization will be dominant in the WG. The momentum matrix element reveals that the absorption due to Γ-hh transition is only TE polarization sensitive whereas the transition Γ-lh is predominantly TM polarization sensitive. Moreover, the sensitivity depends on the degree of bi-axial strain.[10] Taking this into account, TE based absorption can be simplified to Eq. 1 where $f_z(\varepsilon)$ is defined by *R. K. Schaevitz et. al*[10]. Indirect conduction valley mediated absorption is modelled using Macfarlane equations.[11]

$$\begin{aligned}\alpha_{TE}(h\nu,\varepsilon) =&\alpha_{E_{g,\Gamma-hh}}(h\nu,\varepsilon) + \\ &\alpha_{E_{g,\Gamma-lh}}(h\nu,\varepsilon)\frac{1-f_z(\varepsilon)}{1+f_z(\varepsilon)} + \\ &\alpha_{indirect}(h\nu,\varepsilon)\end{aligned} \tag{1}$$

For a 1 μm wide and 0.375 μm thick Ge-on-Si WG, the confinement factor for the fundamental TE mode is 73% as calculated from FemSIM^{TM} mode solver of RSOFT. Using Eq. 1 , the confinement factor and the JDOS absorption model, a biaxial tensile strain of 0.26% was estimated in the Ge-on-Si WG. This corresponds to $E_{g,\Gamma-lh} = 0.762$ eV (1627 nm) and $E_{g,\Gamma-hh} = 0.778$ eV (1593 nm). Since the absorption is dominated by the $E_{g,\Gamma-hh}$ transition for wavelengths below 1593 nm, the probe wavelength for the experiment was set to 1600 nm as shown in Fig. 3. The wavelength of peak coupling for the grating coupler was set to 1595 nm by adjusting the fiber-chip to 13^o from normal incidence to allow maximum coupling for the probe signal.

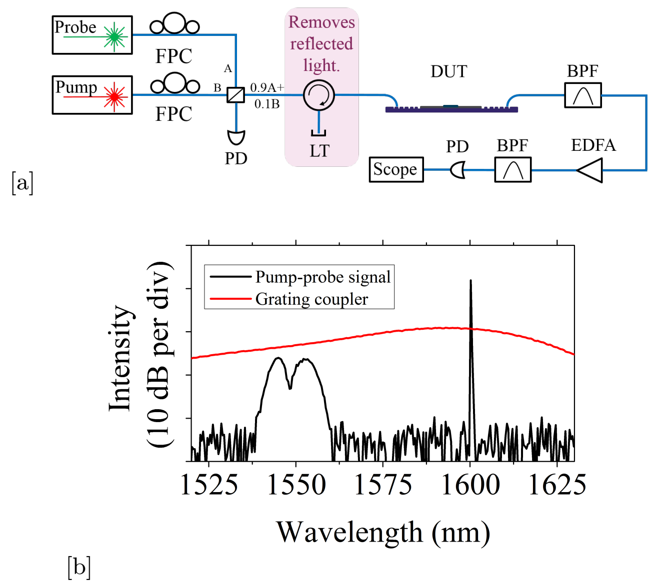

FIG. 3. a) Measurement schematic with band pass filters (BPF) centered at the probe wavelength to filter out the pump and noise from L-band EDFA with respect to the probe signal. b) The spectrum of probe signal (centered at 1600 nm), pump signal (centered at 1548.57 nm) and grating coupler efficiency.

The time-resolved pump-probe spectroscopy experiment is schematically shown in Fig. 3.[12] Here, the pump was operated at a repetition rate of 20 MHz with an average output power of 7.9 mW and has an energy of 400 pJ per pulse. The probe was set to an output power of 0 dBm at 1600 nm as shown in Fig. 3. The polarization of the pump and probe beam were independently controlled for maximum coupling through the grating couplers. They were both combined using a 90%:10% splitter-coupler leading to 0.5 dB attenuation in the probe signal and 10 dB attenuation in the pump signal. Such high attenuation of the pump signal reduces self-phase modulation along the optical path and is necessary to avoid two-photon absorption in the SOI WG that could generate photo-excited carriers and interfere with the measurement. Two band-pass filters (BPF) were used after the chip, to suppress the pump signal from the probe and the noise from the L-band EDFA used to amplify the probe signal. The band-pass filters were centered at the probe wavelength. An ultra-fast photodiode - UPD-15-IR2-FC from ALPHALAS and Tektronix CSA8000 Signal Analyzer (Oscilloscope) were used to extract the time-resolved transmission data. The

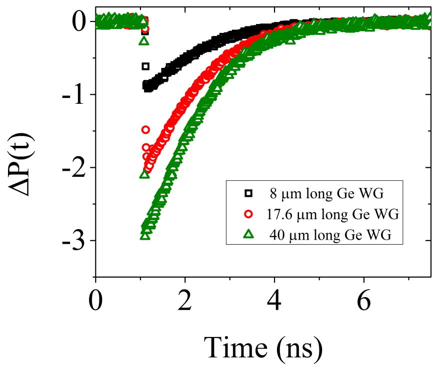

FIG. 4. Time-resolved transmission data of the probe signal from a 1 μm wide 0.375 μm thick Ge-on-Si WG of varying lengths. ΔP(t) is the excess loss experienced by the probe signal through the Ge-on-Si WG due to pump beam.

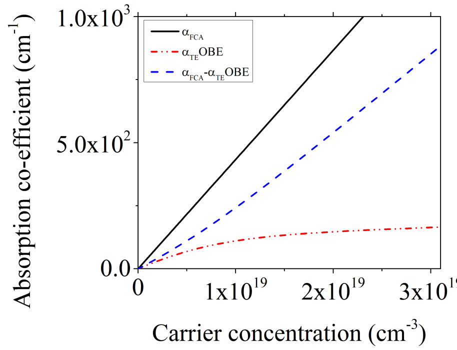

FIG. 5. Impact of photo-excited carrier on free-carrier absorption and optical bleaching effect for 1600 nm probe signal. $\alpha_{excarr} = \alpha_{FCA} - \alpha_{TE}OBE$ is almost linear with carrier concentration.

oscilloscope was triggered by the pump laser. The resolution of the experiment is <15 ps as the bandwidth of the photo-diode and the oscilloscope are >25 GHz.

The absorption of the pump pulses in the Ge-on-Si WG generates a high density of photo-excited electrons and holes that decay in time due to recombination. The decay of these pump-excited carriers is probed with the 1600 nm CW signal through monitoring the excess loss from pump-induced FCA and OBE. The temporal behaviour of the probe power is monitored using the ultra fast photo-diode and the oscilloscope. Typical results extracted for a 1 μm wide and 0.375 μm thick Ge-on-Si WG of 8 μm, 17.6 μm and 40 μm lengths are shown in Fig. 4. In order to quantitatively extract carrier lifetime in these Ge-on-Si WG, we correlate this transmission data to the carrier density. This correlation is done by modeling the FCA and OBE losses that the probe experiences in the presence and absence of the pump beam using the JDOS model according to the equations in 2a.

$$\begin{aligned}\Delta P_{out}(t)|_{dB} = & -(\alpha_{FCA}(t) + \alpha_{Ge}(t) - \alpha_{FCA}(t_0) \\ & - \alpha_{Ge}(t_0)) \times L_{WG} \times 10log_{10}e\end{aligned} \quad (2a)$$

where $\Delta P|_{dB}(t) = 10 \times log_{10}(P_{out}(t)/P_{out}(t_0))$, $P_{out}(t_0)$ and $P_{out}(t)$ are the output power level of the probe signal at time instant $t_0 = 0$ ns and $t > 0$ ns respectively. Time dependent absorption originates from FCA and intrinsic material absorption. The FCA that the 1600 nm probe signal endures due to pump/probe-induced free carriers N and P is expressed as $\alpha_{FCA}(t) = 3.1 \times 10^{-18}N(t) + 3.8 \times 10^{-17}P(t)$.[13] α_{Ge} is the intrinsic material absorption that takes into account optical bleaching effects due to pump/probe-induced carriers. It is mathematically expressed as

$$\begin{aligned}\alpha_{Ge}(t) &= \alpha_{TE} \times (f_v(N(t)) - f_c(N(t))) \\ &= \alpha_{TE} \times (1 - OBE(N(t)))\end{aligned} \quad (2b)$$

The modeling in Eq. 2b. includes the optical bleaching effect as $OBE = 1 - (f_v(N) - f_c(N))$, such that if we have no photo-excited carriers, $OBE = 0$ with $f_c = 0$ and $f_v = 1$.[7] This simplifies the Eq. 2a to

$$\begin{aligned}\Delta P_{out}(t)|_{dB} = & -(\alpha_{FCA}(N(t)) - \alpha_{TE}OBE(N(t)) \\ & - \alpha_{FCA}(N(t_0)) + \alpha_{TE}OBE(N(t_0))) \\ & \times L_{WG} \times 10log_{10}e\end{aligned} \quad (2c)$$

We express the increase in absorption coefficient for the WG due to photo-excited carriers as $\alpha_{excarr} = \alpha_{FCA} - \alpha_{TE}OBE$. The quasi-Fermi energy levels to estimate OBE were evaluated using a self-consistent algorithm for each assumed carrier concentration. The result of these calculations shows that α_{excarr} has a predominantly linear dependence with a slope K as seen in Fig. 5. We find that the time constant derived by fitting an exponential curve to $\Delta P_{out}(t)$ is the lifetime of excess carriers in the WG.

$$\begin{aligned}\Rightarrow \Delta P_{out}(t) = & (\alpha_{excarr}(N(t)) - \alpha_{excarr}(N(t_0))) \\ & \times L_{WG} \times 10log_{10}e \\ \Delta P_{out}(t) & \propto \Delta N(t) \\ \Delta P_{max}\ exp(-t/\tau) & \propto \Delta N_{max}\ exp(-t/\tau)\end{aligned} \quad (2d)$$

Note that in all of the above calculations, a uniform carrier concentration is assumed across the length of the waveguide. This assumption is valid at least for the 8 μm long Ge-on-Si WG as seen in Fig. 4, where ΔP_{out} for a 17.6 μm long Ge-on-Si WG is approximately 2.25 times larger than the one of 8 μm Ge-on-Si WG. As the pump signal is located close to the Γ-hh band-gap and has a high pump-energy, it undergoes OBE and FCA and the absorption profile deviates from the standard exponential decay. Therefore, all pump-probe experiments analysis presented in this work were performed on 8 μm long Ge-on-Si WGs.

Fig. 6 shows the extracted $\Delta P_{out}(t)$ data after normalization with their respective ΔP_{max}. The extracted lifetimes from these curves are summarized in Fig. 7. However, it is important to understand the dominant

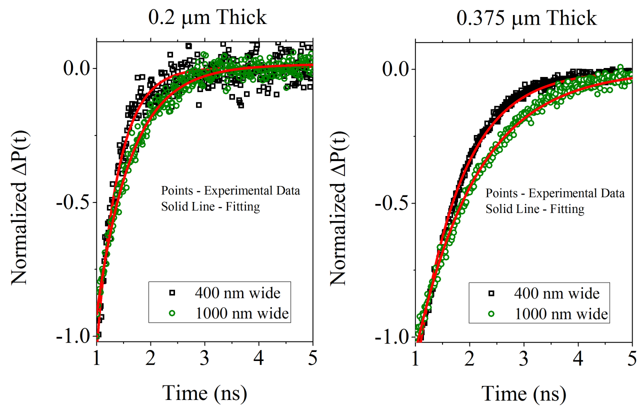

FIG. 6. Normalized ΔP_{out} decay as a function of time for 0.4 and 1.0 μm wide and 0.2-0.375 μm thick Ge-on-Si WGs. Each ΔP_{out} was normalized with their corresponding ΔP_{max} for extraction of carrier lifetime.

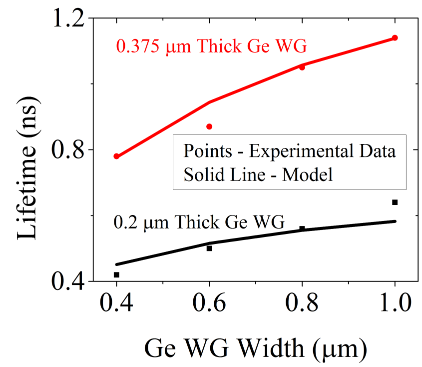

FIG. 7. Dependence of carrier lifetimes on width of the waveguide for 2 thickness extracted from Fig. 6 are shown in points. Using recombination model described by *S. Park et. al*[6], a surface recombination velocity of 0.975×10^4 cm/s and 1.45×10^4 cm/s were deduced for Ge/Si and Ge/SiO_2 respectively. Solid lines show the fitting of the model with the extracted lifetimes.

recombination phenomena limiting these lifetimes. For ΔP_{max}=1 dB in Fig. 4 , the peak carrier concentration in the waveguide is approximately 2×10^{19} cm^{-3}. Assuming a radiative recombination coefficient $B = 1\times10^{-10}$ cm^{3}s^{-1} and an Auger recombination coefficient $C = 1\times10^{-31}$cm^{6}s^{-1},[7,13] the radiative and Auger recombination limited lifetimes in the bulk are greater than 10 ns. Therefore, the extracted lifetimes of <1.2 ns, as shown in Fig. 6, suggest that they are defect-assisted recombination lifetimes and not radiative or Auger recombination limited. Due to high volume/surface area ratio, we assume that bulk defects assisted recombination effects are negligible. The extracted carrier lifetimes have a strong dependence on the side walls, top and bottom interfaces of the WG. This dependence can be quantitatively expressed by evaluating the surface recombination velocity (SRV) for Ge/Si and Ge/SiO_2.[6] In this study, the SRVs for the top and side Ge/SiO_2 interfaces were assumed to be similar for simplicity. On fitting the lifetime for each width and thickness, we extract a SRV of 0.975×10^4 cm/s and 1.45×10^4 cm/s for Ge/Si and Ge/SiO_2 respectively. The result for the Ge/Si interface is consistent with those reproduced in the literature[12,14,15] and is attributed to the lattice mismatch between the Ge and the Si. However, the SRV for the Ge/SiO_2 interface is found to be higher by a factor of 2-4 compared to those reported by *S. A. Srinivasan et. al*[12]. This may result from difference in process condition. It can be suppressed by exploring better passivation techniques for future devices. As a result, these experiments can be used to benchmark the performance of devices and aid in developing intuition for future designs. Waveguide coupled pump-probe spectroscopy techniques as presented in this paper allows the assessment of carrier lifetime in devices instead of blanket samples.[14,15] This technique can be used to determine the transit time of carriers in the waveguide, especially for devices such as photodetectors where the speed of the device is transit time limited and not RC limited.[2]

In summary, we present a time-resolved infrared transmission pump-probe spectroscopy of Ge-on-Si waveguides. Pump-induced excess carriers generated in the waveguides are probed using a CW laser beam. For a 1 μm wide and 0.375 μm thick Ge-on-Si WG, we extract a lifetime of 1.14 ns. These lifetimes are dependent on the width and thickness of Ge layers. Surface recombination velocities of 0.975×10^4 cm/s and 1.45×10^4 cm/s are extracted for Ge/Si and Ge/SiO_2 respectively. Recombination at the Ge/Si interface is caused by lattice mismatch associated defects. With improved passivation strategies, recombination at the top and side interfaces can be suppressed to increase the lifetime of carriers in the waveguides.

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