Carrier Lifetime Assessment in Integrated Ge Waveguide Devices

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***Abstract*— Carrier lifetimes in Ge waveguides on Si are deduced from time-resolved pump-probe spectroscopy. For a 1 µm wide Ge waveguide, a lifetime of 1.6 ns is estimated for a carrier density of around 2×10^{19} cm^{-3}.**

***Index Terms*— Waveguide modulator; Optical interconnects; Silicon photonics**

I. INTRODUCTION

Silicon photonics is widely considered as a potential solution in solving the bandwidth-power density bottleneck of electrical interconnects for future CMOS systems [1]. Ge waveguides (WG) with an embedded p-i-n diode integrated on a silicon photonics platform (Fig. 1) can be used as a building block for a number of devices such as Ge photodetectors [2], Ge electro-absorption modulators [3], as well as Ge variable optical attenuators (VOA) and Ge lasers (with high n-type doping and tensile strained active region [4]). In this work, we extract carrier lifetimes in Ge waveguides grown on Si, using time-resolved infrared transmission pump-probe spectroscopy. This experimental method and analysis enable benchmarking and subsequent optimization of carrier-injection based devices, such as VOAs and lasers. In this work, we study the impact of surface recombination on carrier lifetime in sub-micron Ge WGs.

II. DESIGN AND FABRICATION OF GE P-I-N WG

A set of Ge WGs with embedded p-i-n diode having a length of 8 µm and varying width (400 nm, 600 nm, 800 nm and 1 µm) are studied here. They were fabricated in imec's 200 mm Si photonics platform [5]. The Ge WG is adiabatically coupled to an SOI WG using poly-Si tapers. TE mode grating couplers with a peak wavelength of 1595 nm were used for coupling light to and from the chip. The p-i-n Ge WGs are 350 nm thick and grown on top of the recessed Si layer of the SOI wafer as shown in Fig. 1. Such a device was operated in reverse bias as an electro-absorption modulator in [3] but can in forward bias also be used as a VOA or Ge laser, provided with appropriate strain and high n-type doping [4].

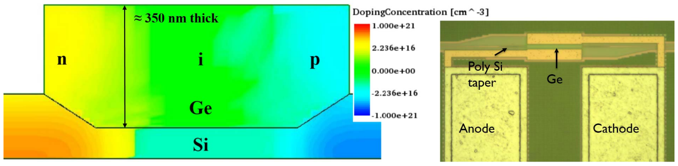

Fig. 1 Schematic of the Ge p-i-n diode used as a Ge electro-absorption modulator **(1 µm wide)** and a microscope image of the fabricated Ge p-i-n WG **[3]**.

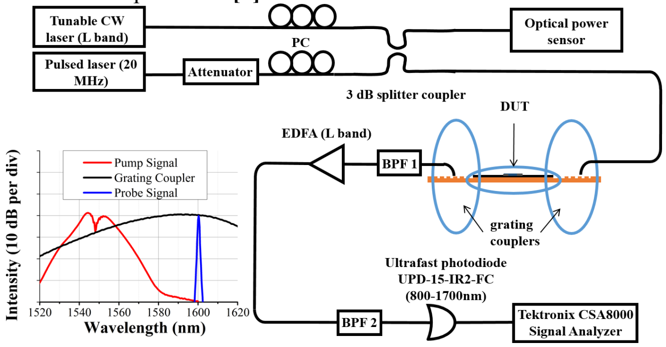

Fig. 2 Measurement schematic with band pass filters (BPF1 and BPF2) centered at probe wavelength to suppress the pump and noise from EDFA with respect to the probe signal. The spectrum of probe signal power, pump signal power and grating coupler efficiency are shown in the inset.

III. EXPERIMENT

We used a mode-locked femtosecond fiber laser from Calmer laser as the pump and a CW tunable laser source as the probe [6]. The pump signal has a center wavelength of 1548.57 nm with a pulse width of 0.235 ps while the probe signal has a center wavelength of 1600 nm. The light is coupled by the grating couplers into the TE-like waveguide mode and the absorption is dominated by the Γ-hh band gap (~1580 nm) [3]. The probe signal is set at 1600 nm so that it can be filtered out easily from the pump and is below the Γ-hh band-gap of Ge. The pump is operated at a repetition rate of 20 MHz with an average output power of around 7.9 mW and peak energy of 400 pJ. A 10 dB attenuator is placed after the pump source to avoid any self-phase modulation in the fiber as well as two-photon absorption in the SOI WG. Time-resolved transmission data is extracted from a Tektronix Signal Analyzer, which is triggered by the pulsed laser. The time resolution of the measurement is limited by the 15 ps rise time of the photodiode.

IV. DISCUSSION AND RESULTS

When pumping the device under test, the pump signal will be absorbed creating a high density of electrons and holes. These carriers will decay in time due to recombination. The dynamics of these carriers are probed using a CW signal at 1600 nm which suffers from the pump-induced excess free carrier absorption (FCA) and optical bleaching effect (OBE). The power of the probe signal is monitored using a high-speed oscilloscope as shown in the inset of Fig. 3. From the excess loss, and using the equations for FCA and OBE from [4], we can estimate the average carrier concentration in the Ge WG as function of time (Fig. 3) and the carrier lifetimes at these carrier densities. The latter are shown in Fig. 4, for a carrier concentration of approximately 2×10^{19} cm^{-3}, and for different Ge WG widths.

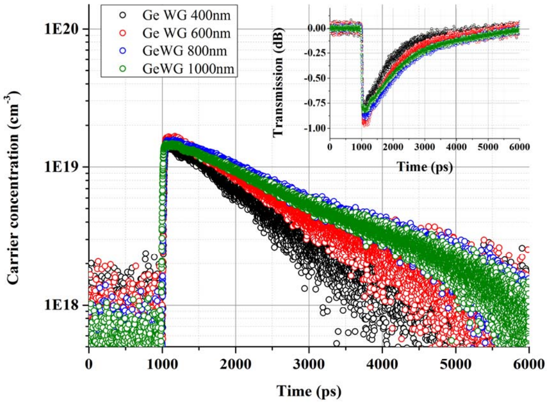

Fig. 3 Time resolved extracted carrier concentration in Ge WG from transmission measurements in 8 μm long device (inset) for different width.

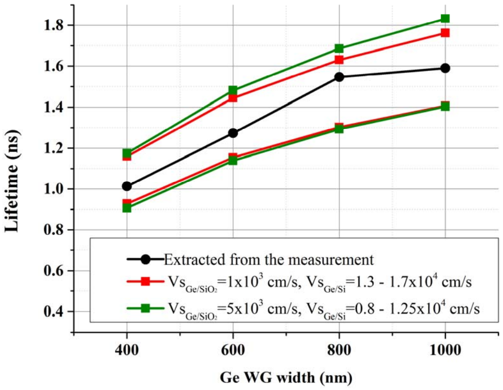

Fig. 4 Extracted carrier lifetimes for different Ge WG widths. The colored data points are the modeled carrier lifetimes assuming a fixed surface recombination velocity (V_s) for Ge/SiO_2 and Ge/Si. The data above the measurement correspond to under-estimation of V_s and those below the measurement correspond to over-estimation of V_s for Ge/Si interface for a fixed V_s for Ge/SiO_2 interface.

For such a carrier concentration, Auger recombination and radiative recombination from the direct and indirect band gap are expected to be small as compared to defect assisted SRH recombination and surface recombination at Ge/SiO_2 and Ge/Si interfaces [8]. In this paper, we assume that the carriers generated by the pump are distributed uniformly across the length of the WG and that carrier lifetimes are not affected by diffusion effects. The dependence of the carrier lifetime on the WG width suggests that the Ge/SiO_2 and Ge/Si interfaces in the side walls have a significant impact on the recombination rate. This impact is reduced as we increase the volume/surface-area ratio when using wider devices. Assuming that the lifetime is surface recombination limited, we extract the surface recombination velocity for each interface as shown in Fig. 4 using the related equation in [8]. In this extraction, we assume the top and side interfaces between Ge and SiO_2 and the bottom and sloped interfaces between Ge and Si to behave similarly and fit the recombination velocities (Fig. 4). From this fitting, we estimate the extracted recombination velocity for the Ge/Si interface to be less than 2×10^4 cm/s and the recombination velocity for the Ge/SiO_2 to be the range 1-5×10^3 cm/s. The recombination velocities for Ge/Si interface are in good agreement with those reported in [7, 9]. The contribution to carrier recombination at Ge/SiO_2 sidewall layers can be suppressed in future devices by using better passivation coatings.

V. CONCLUSION

We investigated carrier lifetimes of Ge p-i-n WG on Si with different widths using time-resolved infrared transmission pump-probe spectroscopy. The lifetime of free electrons and holes increases for wider devices, thus revealing the impact of side walls of the WG. For a 1 μm wide WG, we estimate the lifetime to be 1.6 ns. We also estimate the Ge/Si interface to have a recombination velocity of < 2×10^4 cm/s.

ACKNOWLEDGEMENTS

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