Measurements and modelling of free carrier lifetimes in Si and Si/poly-Si microrings

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***Abstract: We* report pump-probe experiments for measuring free carrier lifetime in Si and Si/poly-Si microrings and compare results with trap-assisted Shockley-Read-Hall recombination model.**

Keywords: silicon micro-rings, two-photon absorption, free carrier, polysilicon, carrier lifetimes

I. INTRODUCTION

Silicon micro-rings are important components in photonics integrated circuits. Two-photon absorption (TPA), free carrier absorption (FCA), and dispersion (FCD) are detrimental when just a few milliwatts of power enters in high-Q rings. The lifetime of the free carriers is a key parameter regulating the effective loss for a given input power. It is determined by trap-assisted non-radiative recombination and thus by the density of bulk and surface traps. We present pump-probe experiments to measure carrier lifetime in micro-rings with Si or Si/poly-Si waveguides; in the latter case the lifetime is more than one order of magnitude faster than in Si waveguides. Experimental results are compared with ad-hoc simulations including trap-assisted recombination.

II. EXPERIMENTAL SETUP AND MODEL

Fig. 1 shows the set-up for CW or pump-probe characterization of micro-ring resonators. We inject a pump pulse of 100 ps with different pump energies and wavelength set at one of the resonant wavelengths of the microring in linear regime. The CW probe power in the bus is below -20dBm. The probe wavelength is varied around the resonant wavelength closest to the resonant wavelength of the pump injection (see inset of Fig. 1).

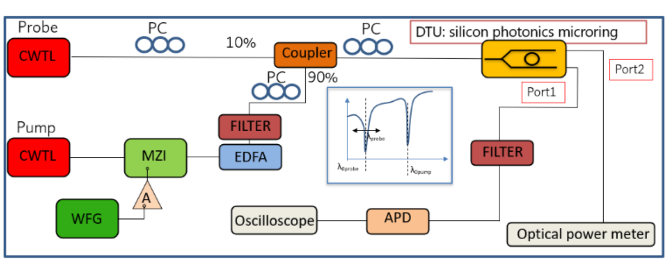

Fig.1. Setup implemented in steady state and pump-probe measurements.

Once the pump pulse has been absorbed due to TPA, the CW probe at different wavelengths monitors the non-linear response of the ring as a result of FC induced variation of the ring resonance and transmission.

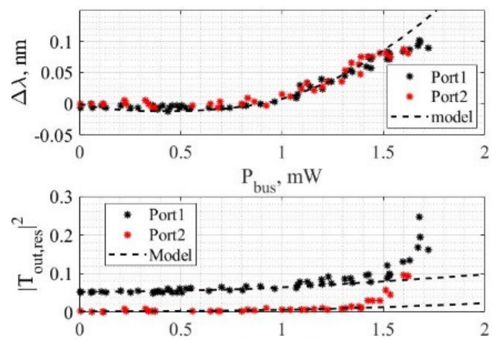

Fig.2. Measured and modelled variation of the resonant wavelength and trasmission coefficients for CW power injection. Ring with waveguide 580x107nm and radius R=5μm. From fitting we get $N_t = 8.5 \cdot 10^{16} cm^{-3}$.

Since the pump pulse is short (100ps) and repetition rate is 4kHz we avoid any thermal effects. To understand the experimental results, we employ the model we developed in [1] to simulate the CW non-linear response of silicon micro-rings. Here, the model is extended to the time domain [2] to simulate the non-linear response after the pump pulse. FC recombination is modelled by trap-assisted Shockley-Read-Hall (SRH) rate equations [1]. The density of traps N_t in the Si waveguide determines the SRH recombination rate of electrons and holes and it is the free parameter to fit the experiments.

III. RESULTS

Each ring was first characterized in steady state (CW forward wavelength sweep) to retrieve from modelling and fitting the trap density per unit of volume N_t and other linear parameters [1]. We report in Fig. 2 the measured and simulated response of a Si microring in which the power is injected into both up and low arms through a splitter; transmission is measured at the two output ports (through ports 1 and 2 in Fig. 1). The model [1] well reproduces the shift of resonant wavelength and transmission coefficient as function of the bus power.

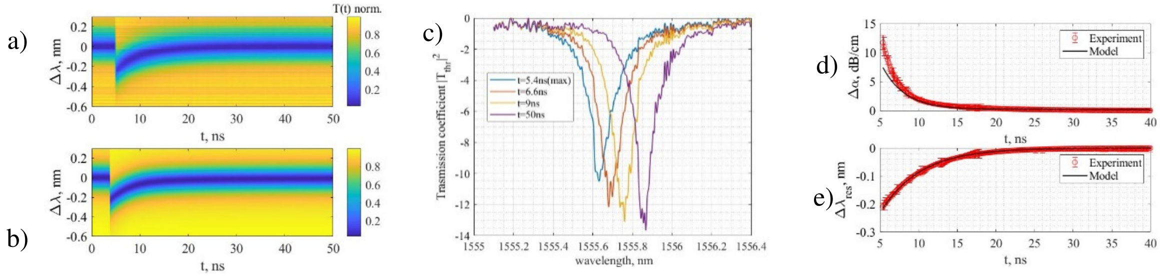

Fig.3. Measured (a) and simulated (b) probe traces at different wavelengths in the case of a pump pulse of 100ps injected at 5.1ns and peak power of 18dBm. Transmission spectrum of the ring reconstructed from Fig. 3a at different time instants after the pump. (c) Extracted variation of non-linear losses (d) and resonant wavelength(e) due to FCA and FCD. The ring is the same as in Fig.2.

Discrepancy at power higher than 1.6mW are due to the self-oscillations of the ring observed at this high power.

To retrieve the carrier lifetime and compare the FC lifetimes of rings with different structures and waveguides, we performed pump-probe measurements; results are in Fig. 3. Fig. 3(a) and (b) are respectively the maps of measured and simulated probe traces at different wavelengths with the pump pulse injected at 5.1 ns. From the map in Fig. 3(a) we recover in Fig. 3(c) the measured transmission coefficients of the ring at any time instant after the pump, displaying the recovery of the ring transmission from the maximum of the non-linear response (blue spectrum just after the pump) to the linear response (purple spectrum). By fitting the transmission at each time instant, we can extract the variation of the loss Δα(t) due to FCA (Fig. 3(d)) and the instantaneous shift of the resonant wavelength with respect to the linear case (Fig. 3(e)). The black solid lines in Fig. 3(d-e) are the model results in very good agreement with the experiments.

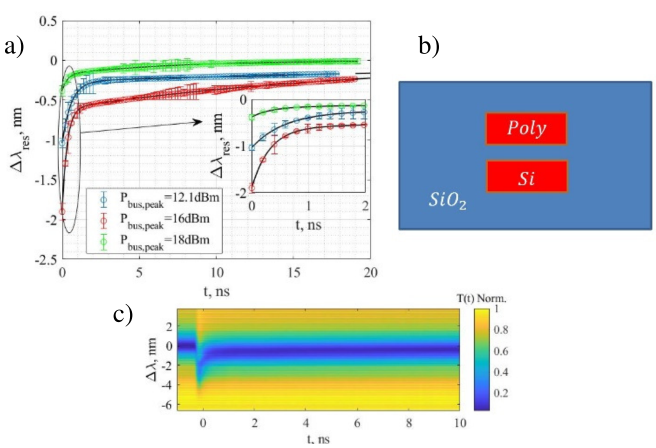

Fig. 4. Variation of resonant frequency extracted from the pump-probe experiments for a 100 ps pump pulse injected at t=0ns with different pump peak powers ($P_{bus,peak}$). The waveguide cross section is in Fig. 4(b), the ring radius is R=2µm. Fig.4 (c) Map of measured probe trace for $P_{bus,peak}$ =18dBm. Black solid lines in (a) is a fitting with two time constant exponentials.

Similar experimental results are reported in Fig. 4(a) for a ring resonantor with silicon and poly-silicon waveguide whose cross section is in Fig. 4(b). For the same values of pump energy, we observe a much stronger shift of the resonant wavelength that can be attributed to a higher variation of refractive index due to FC in poly-Si with respect to Si.

We also observed a recovery of the resonant wavelength characterized by two time constants: a fast one (τ_{fast}) attributed to SRH recombination in poly-Si with high trap density and a slower one (τ_{slow}) associated to SRH recombination in silicon. The lifetimes exctracted from the exponential fitting of the resonant wavelength recovery are summarized in Fig. 5 for different pump powers and for the Si and Si/poly-Si rings.

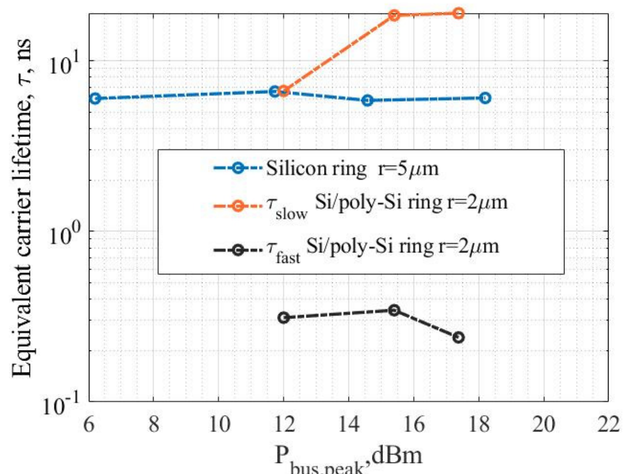

Fig. 5. Summary of equivalent carrier lifetimes extracted through an exponential fitting of the resonant wavelength shift with time for different ring resonators as a function of the pump peak power.

IV. Conclusion

We presented pump-probe experiments to retrieve the time resolved transmission spectra in non-linear regime of Si micro-ring resonators excited by strong pump pulses. Analysis of the measured spectra allows the extraction of the time variation of absorption and refractive index, and, in addition, the equivalent FC lifetimes in different types of resonators. Simulation results obtained with a time domain non-linear model of the rings including SRH trap-assisted recombination are in good agreement with the experiments.

V. (References)

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