Lifetime Dependence on Carrier Density in Silicon Nanowires

I. Aldaya[1,*], A. Gil-Molina[1], J. L. Pita[1], H. L. Fragnito[1,2], and P. Dainese[1]

[1] *"Gleb Wataghin" Physics Institute, University of Campinas,13083-859 Campinas, SP, Brazil*
[2] *MackGraphe, Mackenzie Presbyterian University, São Paulo, SP, Brazil*
[*] *ivan.a.aldaya@ieee.org*

Free-carriers (FC) profoundly impact the performance of silicon nanophotonic devices including amplifiers, modulators, and ring microcavities [1]. Optimizing such devices relies on a good understanding of FC dynamics and how it depends on the FC density (N). This is particularly true in Si nanowaveguides, where surface recombination is important [2] and leads to an N-dependent lifetime [3]. Large density of surface-states enhances the N-dependence as compared to bulk, where recombination is impurity or defect dominated (as described by the Shockley-Read-Hall theory) while for very high N values, Auger process enters the picture [4]. The effect of carrier density on the recombination lifetime has been studied in silicon rib-waveguides [5], where surface effects are reduced somewhat relative to the case of nanowires considered in this paper, since carriers cannot diffuse away from the core region as in the rib. We used a pump-and-probe technique to investigate the recombination rate, and observe carrier lifetimes ranging over almost one order of magnitude for the range of N explored.

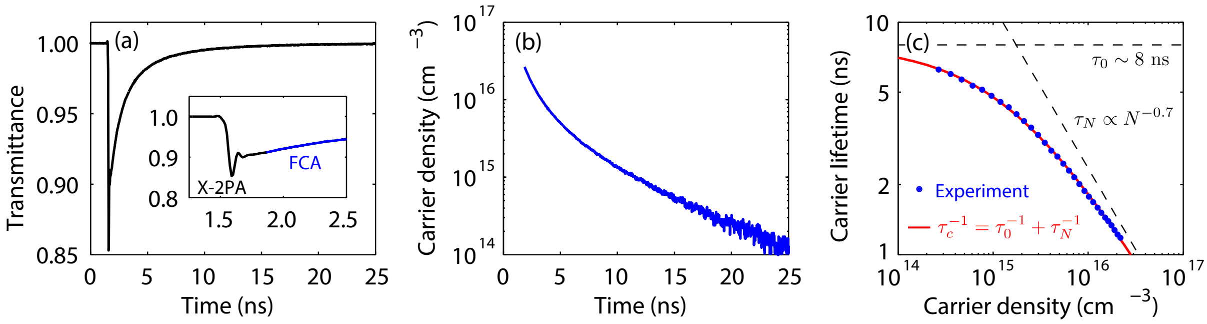

Fig. 1. (a) Normalized transmittance (inset: X-2PA and diffusion transient); (b) time-resolved carrier density; (c) lifetime as a function of carrier density;

A pulsed pump laser at 1547 nm (0.7 W peak power, 50 ps pulse-width, and 1 MHz repetition rate) is combined with a low-power continuous-wave probe (1557 nm) and coupled into a fully-etched silica-cladded waveguide with a cross section of 220 nm×450 nm. The pump generates carriers through two-photon absoprtion (2PA) and surface-state absorption, and the carrier dynamics is extracted from the probe transmission measured in an oscilloscope. Fig. 1a shows the measured transmittance T normalized to the linear loss. After an initial fast transient (inset) due to non-degenerate 2PA (X-2PA) and carrier diffusion, free-carrier absorption (FCA) dominates (highlighted in blue). The carrier density shown in Fig. 1b was then extracted using $N = -\ln[T]/\sigma_\alpha L$, where $\sigma_\alpha = 1.45 \cdot 10^{-21}\text{m}^2$ and $L = 2.4$ mm is the waveguide length. The nonlinear behavior clearly indicates that the recombination rate is faster in the high density region. The carrier lifetime was calculated as $\tau = -N \cdot (dN/dt)^{-1}$ using an adaptive sliding window fitting, and Fig. 1c shows the result. A fitting was performed using a constant term, $\tau_0 \sim 8$ ns, and a density-dependent term given by τ_N=$3.8 \cdot 10^{11}/N^{0.7}$ns ($N$ in cm^{-3}). The results reveal a significant reduction from ~ 8 ns to ~ 1 ns as carrier density increased from $\sim 10^{14}$ to $\sim 2 \cdot 10^{16}$ cm^{-3}, potentially impacting practical applications.

Acknowledgments: FAPESP (08/57857-2, 12/50259-8/15/11779-4, 13/20180-3, and 2015/04113-0) and CNPq.

References

1. Q. Lin, O. Painter, and G. Agrawal, "Nonlinear optical phenomena in silicon waveguides: Modeling and applications," Opt. Express **15**, 16604–16644 (2007).
2. D. Dimitropoulos *et al.*, "Lifetime of photogenerated carriers in silicon-on-insulator rib waveguides," App. Phys. Let. **86**, 071115 (2005).
3. A. W. Stephens, *et al.* , "Surface recombination velocity measurements at the silicon-silicon dioxide interface by microhave-detected photoconductance decay," J.App. Phys.**76**, 363–370 (1994).
4. J. Linnros, "Carrier lifetime measurements using free carrier absorption transients. I. Principle and injection dependence," J.App. Phys. **84**, 275–283 (1998).
5. S. Park *et al.*, "Influence of carrier lifetime on performance od silicon p-i-n variable optical attenuators fabricated on submicrometer rib waveguides," Opt. Express **18**, 11282–11291 (2010).