Probing free-carrier recombination in silicon strip nano-waveguides

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Abstract: We analyze recombination dynamics of photo-generated free-carriers in strip silicon nanowaveguides, revealing a highly nonlinear decay dynamics with a time-dependent lifetime ranging from ∼800 ps at the beginning to ∼300 ns at the end of the decay.

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Free-carrier absorption and dispersion impact critically the performance of several silicon-based integrated devices [1]. For example they severely limit the effective gain of nonlinear amplifiers [2], are critical to understand instabilities in ring resonators [3], and can be exploited as a control mechanism [4]. An accurate characterization of free-carrier dynamics is therefore essential. In the particular case of silicon strip nano-waveguides, carrier generation is usually attributed to two-photon absorption (TPA), and the confined nature of the silicon core surrounded by oxide does not allow carrier diffusion outside the modal region, neither extraction using a p-i-n structure. In this structure, recombination is expected to be dominated by trap-assisted mechanism [5], either through bulk or surface defects or impurities. In this paper, we demonstrate a highly nonlinear recombination dynamics, with an instantaneous recombination lifetime varying throughout the decay, faster initially and slower at the end of the recombination process.

The sample under test was a silicon-on-insulator (SOI) strip waveguide fabricated at imec/Europractice using optical lithography. It has a cross-section of 220 nm×450 nm and a length of 5.9 mm. The waveguide has silica cladding and the light was coupled in and out through grating couplers. In order to observe the free-carrier decay dynamics, we conducted a pump-and-probe experiment with continuous wave probe and pulsed pump centered at 1549 nm and 1547 nm, respectively. The pump pulse train had a repetition rate of 500 kHz and a pulse duration of 130 ps or 20 ns. The launched optical power was controlled using a variable optical attenuator and, after blocking the the pump signal, the probe output was captured in a 20-GHz-bandwidth oscilloscope. It is worth noting that undesired carrier generation was avoided by setting the power of the probe at 60 μW and by gating the pump with a high-extinction ratio acousto-optic modulator.

Figure 1a shows the measured nonlinear loss for 130-ps pulses with pump peak powers of 0.07 W, 0.28 W and 1.1 W. Here, two different stages can be identified: an initial fast regime where the non-degenerate TPA is the main nonlinear loss mechanism and a slower regime dominated by free-carrier absorption (FCA). The time-resolved carrier density

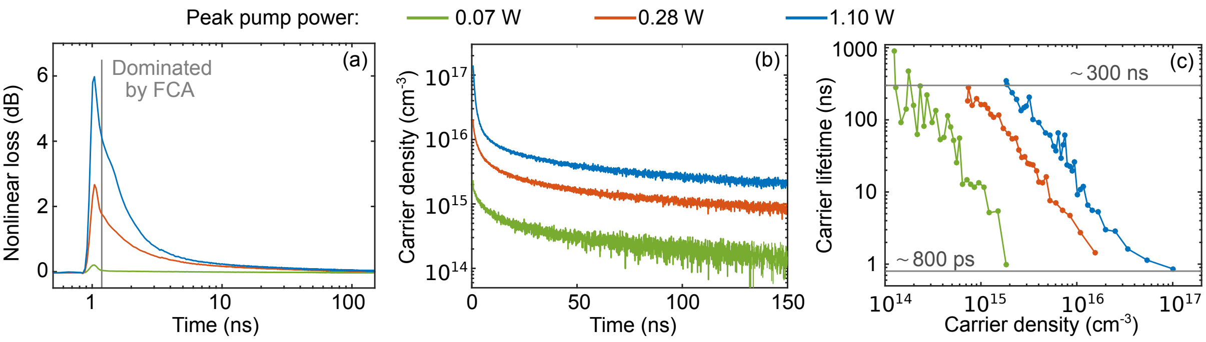

Fig. 1. (a) Measured nonlinear loss); (b) measured time-resolved carrier density and (c) extracted carrier lifetime in terms of carrier density.

can then be obtained from the nonlinear loss [6], and the results are shown in Fig. 1b. Note that the decay curves are plotted in logarithmic scale, and the inverse of the slope corresponds to the decay lifetime. Then, it is clear that carrier lifetime varies as recombination evolves, revealing an underlying nonlinear dynamics. The instantaneous decay lifetime is extracted from the results in Fig. 1b and shown in Fig. 1c. The lifetime is clearly faster (∼800 ps) at early stages of the recombination process and slows down as recombination progresses, reaching values as large as ∼300 ns. Another interesting observation is that the exact decay curve depends on the initial carrier densit, form of memory effect. This is quite clear also in Fig. 1b, in which different instantaneous lifetimes are observed at the same carrier density level. These observations are in fact closely related to a nonlinear decay dynamics when the density of traps is comparable or larger than the free-carrier density. In this scenario, significant trapping effect can cause an unbalance between the density of free-electrons and free-holes, leading to the aforementioned memory effect.

In order to envisage the effect of carrier dynamics on a system operating at longer duty cycle, we employed 20 ns pulses with peak powers between 5 mW and 191 mW. Figure 2a shows the nonlinear loss, where the TPA and FCA-dominated regimes can be clearly identified. The faster nature of the system at higher peak power is appreciated in the falling edge of the normalized nonlinear loss presented in Fig. 2. This faster behavior is explained by the faster decay of free carriers, shown in the inset, which is in accordance to the previous characterization. An additional interesting point is that the effect of faster carrier dynamics is not limited to the falling edge but it also affects the rising edge, as observed in Fig. 2c. In particular, we can see that the time required to pass from the 10% to the 90% decreases form ∼10 ns for a pump power of 5 mW to ∼1 ns for 191 mW.

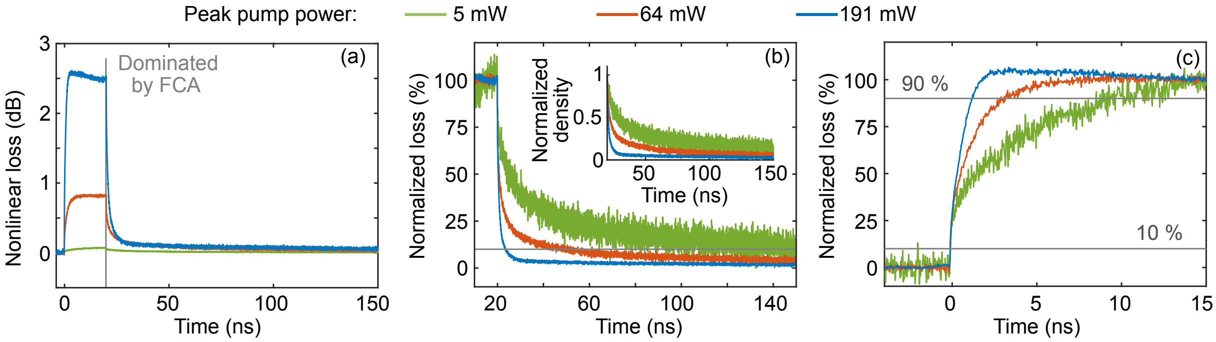

Fig. 2. (a) Measured nonlinear loss; (b) normalized nonlinear loss in the falling edge of the pulse (the inset represents the normalized carrier density after the pulse) and (c) normalized nonlinear loss in the rising edge of the pulse.

In summary, we used time-domain FCA measurements to characterize the recombination dynamics of free-carriers in silicon nano-waveguides. Experiments reveal a nonlinear dynamics characteristic of trap-assisted recombination in a large trap density regime. We show that this nonlinear dynamics has a deep impact on system performance, particularly exhibiting a memory effect in which the decay speed depends on the initial carrier density.

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