Limitations of active carrier removal in silicon Raman amplifiers and lasers

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The lifetime of two-photon generated carriers has been established as the critical parameter that determines the performance of silicon Raman lasers and amplifiers since it determines the optical loss. Here, we investigate the intensity dependence of the carrier lifetime in the case where the carriers are swept out by means of a *p-n* junction. Numerical simulations show that at sufficiently high pump intensities, the generated carriers screen the applied electric field and therefore result in a higher lifetime and hence a lower net Raman gain. We also quantify the electrical power dissipation necessary to maintain low optical losses. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2155071]

The recent demonstrations of Raman lasers have opened up new possibilities for silicon photonics.[1,2] These experiments, along with observations of large Raman gain[3–5] show promise for all-silicon photonic circuits. The main challenge in these devices is the nonlinear optical loss that competes with the Raman gain. This effect is the optical absorption loss due to free carriers that are created in the waveguide because of two-photon absorption (TPA) of the pump beam. Furthermore, because the rate of two-photon absorption scales as I_P^2, where I_P is the optical intensity of the pump beam, the rate at which signal photons are absorbed scales as $I_P^2 I_S$, where I_S is the intensity of the signal beam (the beam to be amplified in by the Raman scattering process). Since the rate of Raman amplification is proportional to $I_P I_S$, the above nonlinear loss can be detrimental.

The magnitude of this nonlinear optical loss is proportional to the carrier density that has been created in the waveguide, which in turn is proportional to the time it takes for carriers to disappear from the waveguide core. The carrier lifetime is therefore the critical parameter for continuous-wave operation, or for pulsed operation when the pulse repetition period is shorter than the carrier lifetime.

We previously calculated the carrier lifetime for rib waveguides[6] and also for carrier sweepout of waveguides with a reverse biased *p-n* junction. Our previous results have shown that lifetimes of less than 1 ns can be achieved in both bare waveguides, as well as in reverse biased *p-n* junction schemes. In a bare silicon-on-insulator waveguide, we found that the geometry of the waveguide plays a significant role in determining the carrier lifetime and that order of magnitude reduction can be achieved by varying the slab height and the rib to slab height ratio. We found that the lifetime is determined by the combination of diffusion and interface and surface recombination currents.

In this letter, we report the intensity dependence of the carrier lifetime in a rib waveguide for the case where a reverse biased *p-n* junction is used to sweep out the carriers. We find that the carrier lifetime depends on the generation rate in the waveguide and therefore on the intensity of the pump beam. We have used a commercial software (ATLAS, ATHENA v. 5.6.0.R Silvaco International) to find the carrier lifetime in a rib waveguide that is surrounded by a *p-n* junc-

tion as shown in Fig. 1. The carrier lifetime, τ, was determined as a function of the applied voltage V and the optical intensity. The lifetime of the carriers is found to increase with an increase in the intensity because of the screening of the applied electric field by the carriers. This renders the junction ineffective at high optical intensities. The dissipated electrical power necessary to keep the carrier density below a given level is also quantified.

We performed simulations for a rib waveguide with $w = 1.5$ μm, $h = 0.75$ μm, and $H = 1.55$ μm (Fig. 1). The distance of the p and n doped regions from the rib was $d = 2.25$ μm, and the corresponding doping concentration was 10^{19} cm^{-3} for both. This ensures negligible overlap between doped regions and the optical modes. The total number of carriers generated by TPA at a pump intensity I_P is $(\beta I_P^2 / 2E_P) A_{EFF}$, where $\beta = 0.7$ cm/GW is the TPA coefficient of silicon, E_P is the photon energy and A_{EFF} is effective area of the optical mode. The generation rate G in the simulation is assumed to be uniform over the rib cross section such that the total number of generated carriers is GwH. In this framework, the carrier lifetime is given by $\tau = \frac{1}{GwH} \int_0^H \int_{-w/2}^{w/2} N dx dy$, where N is the carrier concentration.

In Fig. 2, we show the effective lifetime $(\tau_e + \tau_h)/2$, for applied voltages of 2, 10, and 20 V, as a function of the intensity. The most important feature in this plot is that for a given voltage, when the intensity exceeds a critical value, the lifetime rapidly increases. As the intensity is further increased the lifetime growth saturates. Furthermore, an increase in the reverse bias voltage shifts the critical intensity that must be exceeded for the lifetime to vary to higher values.

We can understand the essential features by examining the case of a *p-n* junction, where there is a uniform generation rate in the depletion region. If the reverse bias applied voltage is V and the length of the depletion region is $w + 2d$,
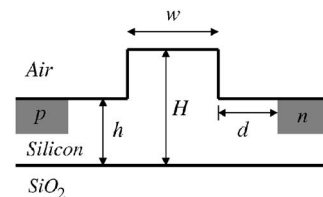

FIG. 1. Rib waveguide geometry with a *p-n* junction.

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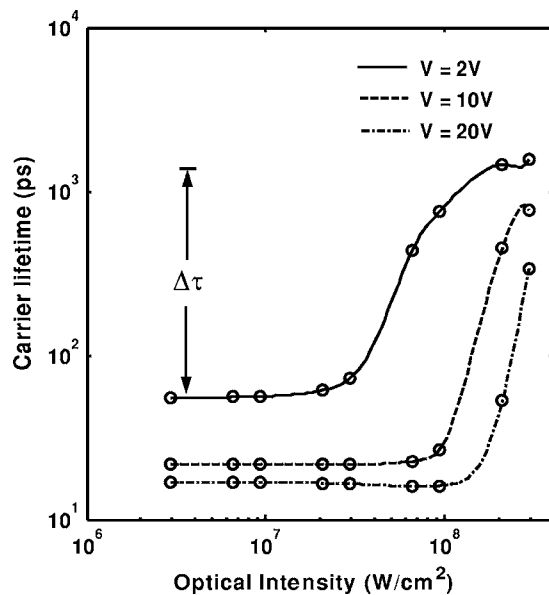
FIG. 2. Dependence of the effective carrier lifetime on the optical intensity for various values of the applied voltage.
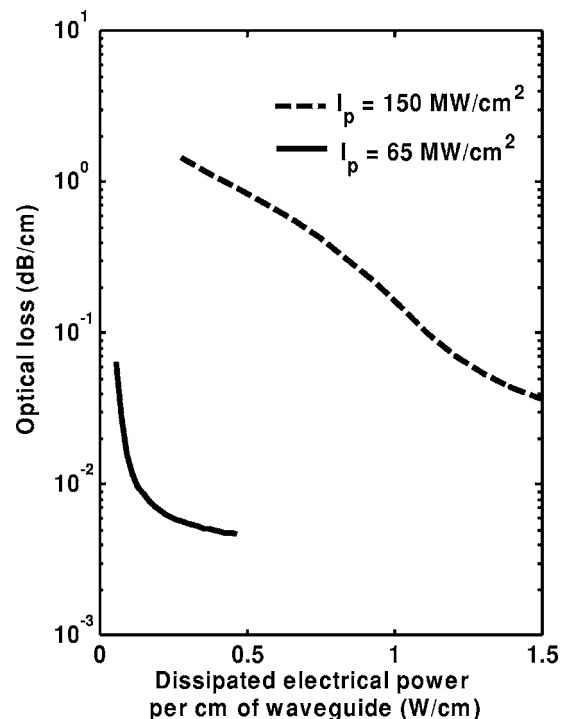

FIG. 3. Dependence of the FCA loss on the dissipated electrical power that is necessary to achieve that loss. Results are shown for optical intensities of 150 and 250 MW cm^2. Simulations were limited to a maximum applied voltage of 25 V.

then when no generation rate is taking place, the applied field is $E_o = V/(w+2d)$. Now, if an electron-hole pair is generated, the particles will drift under the action of the applied electric field. We note that the carrier drift velocity in silicon has a nonlinear dependence on the applied electric field due to velocity saturation. For electric fields smaller than $E_{SAT} \approx 2 \times 10^4$ V cm, the carrier velocities increase linearly with the applied field as $v_e = \mu_e E$, $v_h = \mu_h E$ ($\mu_e = 1500$ cm^2 s^{-1} V^{-1} and $\mu_h = 450$ cm$^2 \cdot$s$^{-1} \cdot$V^{-1}). For higher electric fields, the carrier velocity is saturated. For electrons, this saturation velocity is $v_{e,SAT} \approx 10^7$ cm s. The electric field can exceed E_{SAT} but it cannot exceed the material breakdown field $E_B \sim 3 \times 10^5$ V cm. When the generation rate is low enough, the generated carriers are swept out of waveguide core and the carrier lifetime is therefore the mean transit time through the rib region, i.e., $\tau_e = w/(2\mu_e E_o)$ when $E_o < E_{SAT}$ and $\tau_e = w/(2v_{e,SAT})$ when $E_o > E_{SAT}$. Similar expressions hold for the holes.

Since the electrons and holes drift in opposite directions, a secondary electric field will be set up in the depletion region with direction opposite to the applied field. The applied electric field will be screened by the secondary field leading to an increase of the carrier lifetime as observed in Fig. 2. The screening of the applied field by the carriers is the same effect that is responsible for the saturation of responsivity in high power photodetectors.[7]

In the regime in Fig. 2 where saturation has set in, drift is negligible and carrier transport is governed by diffusion and recombination. In this case, the lifetime should approach the lifetime of carriers in a waveguide with no junction. Therefore, the difference in lifetime at the low and high intensity regimes in Fig. 2, $\Delta\tau$, is the lifetime reduction enabled by the junction. We note that the generation rate along the waveguide varies slowly in comparison to that in the transverse direction. Therefore, in calculations of carrier lifetime, longitudinal carrier diffusion can be neglected.

The reduction in lifetime and the concomitant reduction in optical loss that is achieved with the *p-n* junction come at the expense of electrical power dissipation. Neglecting the recombination of carriers (this is permissible when the domi-

nant current is the drift current) the current (per unit length of the waveguide) is simply determined by the generation rate as $j = e(G \times w \times H)$. The power dissipation per unit length of the waveguide is $W_{DISS} = jV$ where V is the applied voltage. Figure 3 shows how the free carrier absorption (FCA) loss varies with the power dissipated to sweep out the carriers for intensities 65 and 150 MW/cm^2. Simulations were limited to a maximum applied voltage of 25 V. The FCA loss is determined from the average electron-hole density $N = G(\tau_e + \tau_h)/2$ as $a_{FCA} = \sigma N$, where $\sigma = 1.45 \times 10^{-17}$ cm^2 is the FCA loss cross section.[8] We note that the power dissipation per unit length is a strong function of pump intensity which varies along the waveguide length. Nonetheless, Fig. 3 indicates that the reduction in nonlinear absorption comes at the expense of significant on-chip electrical dissipation. The most direct path to power reduction is lateral scaling of device dimensions as indicated in the expression for the lifetime when the generation rate can be neglected.

In conclusion, we have presented numerical simulations for the lifetime of photogenerated carriers which are swept out by the electric field of a reverse biased junction formed along the waveguide. We determined the lifetime as a function of the optical intensity and the applied junction voltage. The dependence on the intensity is due to the screening of the applied field by the photogenerated carriers, and can result in an increase in the lifetime by more than an order of magnitude. Hence, this effect is expected to have significant implications for operation of silicon Raman lasers and amplifiers that employ carrier sweep out via a *p-n* junction.

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