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2D NL model and design of SISCAP microring resonator with complex waveguide cross-section

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***Abstract*—We design silicon and polysilicon microring resonators with different cross-sections to minimise the nonlinear effects and self-heating in the SISCAP platform. We show that free carrier diffusion in rib waveguides reduces the impact of non-linearities resulting in high Q-factor and low free carriers lifetime.**

***Index Terms*—Microring resonators, nonlinear effects, SISCAP.**

I. INTRODUCTION

Microring resonators (MRRs) are passive optical devices used in many silicon photonic integrated circuits. Microring resonators find applications in various areas of photonics, for example in wavelength filtering, switching or light modulation. However the non linear response of silicon, even to moderate input powers, hinders the performance of high Q-factor MRR.

In this study, we show a rigorous method to simulate nonlinear and thermal effects in silicon MRRs with complex waveguide cross sections; we apply it to the design of MRRs in the SISCAP (semiconductor-insulator-semiconductor capacitor) platform [1].

II. MODEL

The main nonlinear effects in silicon are two photon absorption (TPA) and free carrier absorption (FCA). TPA occurs when two photons are absorbed generating an electron-hole pair; FCA occurs because the generated free carriers (FC) absorb other photons promoting electrons and holes to higher energies in conduction and valance band.

FCs change the refractive index, resulting in a blue shift of the resonant wavelength of the MRR transmission coefficient, whereas the FC loss degradates the Q-factor. Furthermore, the thermalization of FCs and recombination via Shockley Read Hall (SRH) recombination releases the energy in form of heat (self-heating), causing a red shift of transmission coefficient. For complex waveguide geometries (for example rib), the generated FCs diffuse in silicon and the heat is generated all over the Si region where carrier thermalization and recombination takes place. To calculate the non-linear effects and the self-heating in the MMRs, we employ 2D simulations considering FC generation via TPA, FC drift-diffusion transport, SRH recombination, heat generation and dissipation. In this paper we evaluate the impact of NL effects in MRRs as a function of any input power in the ring and for generic waveguide cross sections as those shown in Fig. 1 (a), where the waveguides are in silicon and poly-silicon according to the geometries available in the SISCAP platform.

In Fig.1 (b) we summarize the self-consistent model. We import in the Semiconductor Tool of COMSOL the optical field distribution of the fundamental guided mode ($\mathrm{E(x, y)}$ and $\mathrm{H(x, y)}$) in the ring waveguide and we solve self-consistently the drift-diffusion equations coupled with the thermal model. The solution gives the distribution of the free carriers FCs, $\mathrm{n(x, y)}$ and $\mathrm{p(x, y)}$, and the variation of temperature $\mathrm{T(x, y)}$ as a function of the circulating power in the cross section. Having then the local variation of FC loss and refractive index due to free carriers and temperature [2], we can compute the increase of modal loss ($\Delta\alpha$) and effective refractive index due to FCD or temperature ($\Delta \mathrm{neff_{FCD,T}}$) as shown in Fig.1 (b).

III. RESULTS

We consider four MMRs with $3.5\mu\mathrm{m}$ of radius, 0.0055 coupling coefficient ($\mathrm{k^2}$) and waveguide cross sections as in Fig. 1 a. The Si Rib has been neglected because this structure presents bend loss larger than $1\,\mathrm{dB/cm}$.

In Fig 1 (c). we report the simulated maximum temperature inside the waveguide as function of the circulating power. We can observe that Si/PolySi 3 wings Rib heats up less than the other two as will be explained in the following. From Fig. 1 (d). and Fig. 1 (e). we see that the Si/polySi 3 wings Rib presents the lowest nonlinear loss for the same circulating power as consequence of electrons and holes diffusion in the later wings of the rib waveguide and the faster SRH carrier recombination caused by an higher trap density in poly-Si with respect to Si. This reduces the density of FCs where the most of the optical field is confined giving smaller modal loss and variation of refractive index. Since heat is almost generated by the energy released by the relaxation of absorbed FCs, it results also in a smaller temperature increase. The resulting variation of the effective refractive index and the modal loss are fitted with third-degree polynomials as a function of the circulating power in the MRR and they are used as input parameters for the calculation of the MRR transmission coefficient [3] as shown in Fig. 1 (f). Here the Si/polySi 3 wings rib presents a

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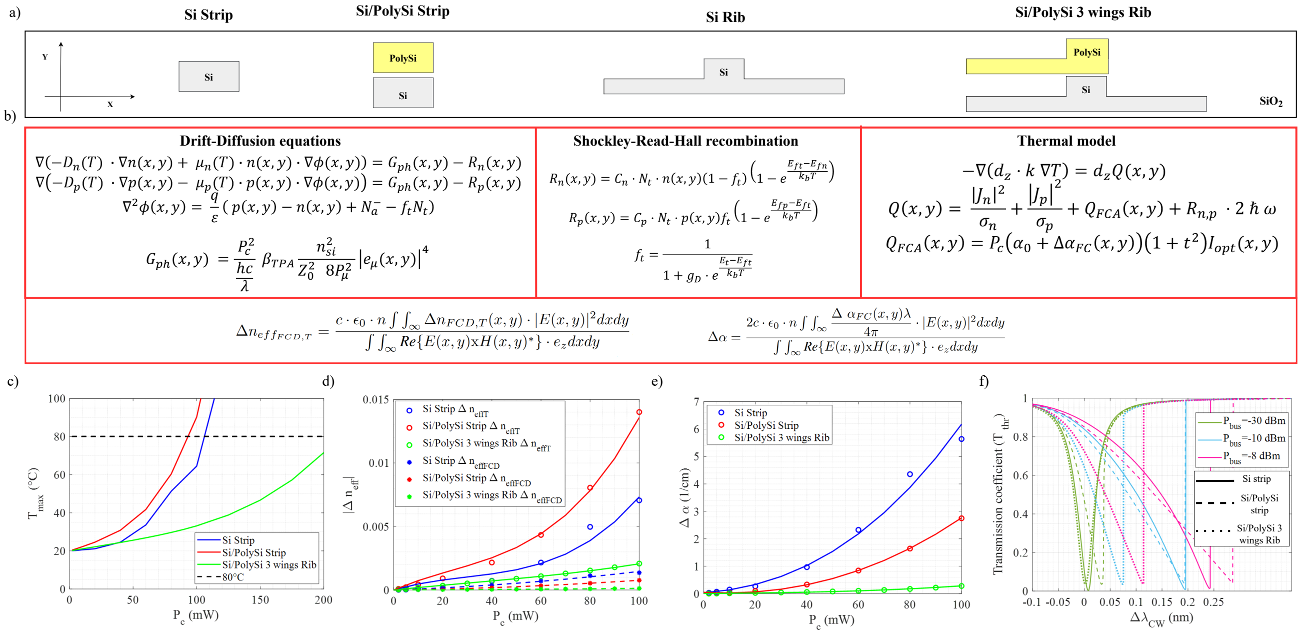

Drift-Diffusion equations

$$\nabla(-D_n(T)\ \cdot \nabla n(x,y) + \ \mu_n(T)\cdot n(x,y)\cdot \nabla\phi(x,y)) = G_{ph}(x,y) - R_n(x,y)$$

$$\nabla\big(-D_p(T)\ \cdot \nabla p(x,y) - \ \mu_p(T)\cdot p(x,y)\cdot \nabla\phi(x,y)\big) = G_{ph}(x,y) - R_p(x,y)$$

$$\nabla^2\phi(x,y) = \frac{q}{\varepsilon}(\,p(x,y) - n(x,y) + N_a^- - f_t N_t)$$

$$G_{ph}(x,y) \ = \frac{P_c^2}{\frac{hc}{\lambda}}\ \beta_{TPA}\frac{n_{si}^2}{Z_0^2\ \ 8P_\mu^2}\left|e_\mu(x,y)\right|^4$$

Shockley-Read-Hall recombination

$$R_n(x,y) = C_n\cdot N_t\cdot n(x,y)(1-f_t)\left(1-e^{\frac{E_{ft}-E_{fn}}{k_bT}}\right)$$

$$R_p(x,y) = C_p\cdot N_t\cdot p(x,y)f_t\left(1-e^{\frac{E_{fp}-E_{ft}}{k_bT}}\right)$$

$$f_t = \frac{1}{1+g_D\cdot e^{\frac{E_t-E_{ft}}{k_bT}}}$$

Thermal model

$$-\nabla(d_z\cdot k\,\nabla T) = d_z Q(x,y)$$

$$Q(x,y) = \frac{|J_n|^2}{\sigma_n} + \frac{\left|J_p\right|^2}{\sigma_p} + Q_{FCA}(x,y) + R_{n,p}\ \cdot 2\,\hbar\,\omega$$

$$Q_{FCA}(x,y) = P_c\big(\alpha_0 + \Delta\alpha_{FC}(x,y)\big)\big(1+t^2\big)I_{opt}(x,y)$$

$$\Delta n_{eff_{FCD,T}} = \frac{c\cdot\epsilon_0\cdot n\int\int_\infty \Delta n_{FCD,T}(x,y)\cdot|E(x,y)|^2dxdy}{\int\int_\infty Re\{E(x,y)\mathrm{x}H(x,y)^*\}\cdot e_z dxdy}$$

$$\Delta\alpha = \frac{2c\cdot\epsilon_0\cdot n\int\int_\infty \frac{\Delta\ \alpha_{FC}(x,y)\lambda}{4\pi}\cdot|E(x,y)|^2dxdy}{\int\int_\infty Re\{E(x,y)\mathrm{x}H(x,y)^*\}\cdot e_z dxdy}$$

Fig. 1: (a) Waveguide cross sections. (b) Model summary. (c) Maximum temperature in MRR as function of circulation power. (d) and (e) resulting variation of the effective refractive index and modal loss as function of the power ($\mathrm{P_c}$) . Solid lines are a polynomial fit of the numerical results reported with symbols.(f) Transmission coefficient of the 3 MRRs at different bus input power.

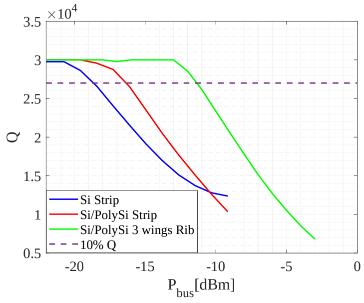

Fig. 2: Degradation of MRRs quality factor versus the input bus power.

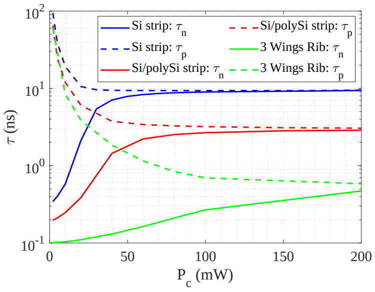

Fig. 3: Equivalent free carriers lifetime versus the circulation power.

smaller degradation of the transmission coefficient with respect to the other two MRRs Fig.2. This is also proven by comparing in Fig.2 the MRRs quality factor versus the input bus power; the 3 wings rib structure makes it possible to reach a maximum power (with 10% reduction of the Q) of about $-5\,\mathrm{dB}$.

To compare the impact of carrier diffusion in the the Si/PolySi 3 wings rib, we compute an equivalent free carrier lifetime that accounts for the rate carriers recombine but also diffuse out of the region where the optical field is confined. It is defined as:

$$\tau_{eq,n} = \frac{\int\int_{A_{eq}} n(x,y)dxdy}{\int\int_{A_{eq}} G_{ph}(x,y)dxdy} \tag{1}$$

Where A_{eq} is the equivalent area associated to the semiconductor region where optical power is higher than 10% its maximum value (located in the middle of the rib). Results are shown Fig 3. We can observe that the Si/polySi 3 wings Rib has a shorter FC lifetime which is the combination of free carrier diffusion and higher recombination rate in poly-Si. Such result demonstrates how the 3wings rib waveguide suffers less NL effects with respect to the other structures considered in this study.

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