Design of Si/polySi Microrings with Complex Waveguide Cross-Sections and Minimal non-Linearity

Original
Design of Si/polySi Microrings with Complex Waveguide Cross-Sections and Minimal non-Linearity / Cucco, Stefania; Novarese, Marco; Gioannini, Mariangela. - ELETTRONICO. - (2023). (Intervento presentato al convegno 2023 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD) tenutosi a Turin, Italy nel 18-21 September 2023) [10.1109/NUSOD59562.2023.10273460].

Publisher:
IEEE

Published
DOI:10.1109/NUSOD59562.2023.10273460

Design of Si/polySi microrings with complex waveguide cross-sections and minimal non-linearity

Stefania Cucco, Marco Novarese, Mariangela Gioannini
Department of Electronics and Telecommunications, Politecnico di Torino. Torino, Italy
stefania.cucco@polito.it marco.novarese@polito.it mariangela.gioannini@polito.it

***Abstract*—We model and simulate non-linear effects and self-heating in MRRs in silicon photonic platform and with generic waveguide cross sections. We demonstrate that free carrier diffusion in rib waveguides plays a fundamental role in reducing the non-linearties . Optimal waveguide cross sections and high Q microrings are designed for the SISCAP platform.**

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

I. INTRODUCTION

Microring resonators (MRRs) find applications in many silicon photonic integrated circuits and they are often employed in the mirror of III-V/Si tunable external cavity lasers [1]. The laser consists in the coupling between a III-V reflective semiconductor optical amplifier and an external photonic integrated circuit (PIC) in silicon. When the laser emits relatively high optical power ($> 20\,\mathrm{mW}$), the power entering in the MRRs can be high as well. In this case non-linear effects in silicon hinder the use of silicon MRRs making silicon nitride MRRs to be preferred instead. The drawback of silicon nitride is the small thermal tuning coefficient and the high bend loss when the ring radius is less than about $100\,\mu\mathrm{m}$. Hence compact (radius of less than $10\,\mu\mathrm{m}$) silicon MRRs are beneficial for improving the design. Here we present a method to model and simulate non-linear and thermal effects in silicon MRRs with any generic waveguide cross section; we apply it to the design of MRRs in the SISCAP (semiconductor-insulator-semiconductor capacitor) platform [2].

II. MODEL

Two processes cause nonlinear loss in silicon: two photon absorption (TPA), when two photons are absorbed generating an electron-hole pair, and free carrier absorption (FCA) when generated free carriers (FC) absorb other photons promoting the electrons and the holes to higher energy in their bands.

FCs cause also a change in the refractive index (free-carrier dispersion, FCD); FCs can thermally relax and recombine via Shockley Read Hall (SRH) recombination releasing the energy as heat (self-heating). Non-linearities and self-heating modify the MRR transmission coefficient as a blue shift of the resonant wavelength due to FCD or red shift caused by self-heating; the increased loss also reduces the Q of the ring. For rib or more complex waveguide geometries, FCs diffuse in the silicon and the heat is generated where carrier thermalization and recombination occur. In this case to evaluate the non-linear response and the self-heating of the ring, 2D simulations considering FC generation via TPA, FC transport, non-radiative recombination, heat generation and dissipation are required. In this paper we calculate the impact of NL effects in MRRs as a function of any input power in the ring and for any given geometry of the waveguide cross section as those shown in Fig. 1a.

We import in the Semiconductor Tool of COMSOL the optical field distribution of the fundamental guided mode ($\mathrm{E(x,y)}$ and $\mathrm{H(x,y)}$) of the ring waveguide. We then solve in COMSOL the 2D drift-diffusion equations (with generation due to TPA) coupled with the thermodynamic model (see Fig.1 b). We consider 4 MRRs with different waveguide cross-sections in Fig.1a. ; they are in silicon and poly-silicon according to the geometries available in the SISCAP platform.

The variation of the waveguide effective refractive index due to FCD or temperature ($\Delta \mathrm{neff}_{\mathrm{FCD,T}}(\mathrm{x,y})$) are calculated as:

$$\Delta n_{eff_{FCD,T}} = \frac{c \cdot \epsilon_0 \cdot n \int\int_{\infty} \Delta n_{FCD,T}(x,y) \cdot |E(x,y)|^2 dxdy}{\int\int_{\infty} Re\{E(x,y) \mathrm{x} H(x,y)^*\} \cdot e_z dxdy}, \tag{1}$$

with $\Delta \mathrm{n_T(x,y)} = \frac{\mathrm{dn}}{\mathrm{dT}} \cdot \Delta \mathrm{T(x,y)}$ and $\frac{\mathrm{dn}}{\mathrm{dT}} = 1.84 \cdot 10^{-4} \mathrm{K}^{-1}$ is the local variation of the refractive index due to self-heating for both silicon and poly-silicon. $\Delta \mathrm{n_{FCD}(x,y)}$ is the local variation of refractive index due to FCD. The optical modal loss due to FC is:

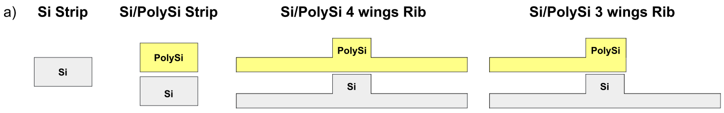
$$\Delta\alpha = \frac{2c \cdot \epsilon_0 \cdot n \int\int_{\infty} \frac{\Delta\ \alpha_{FC}(x,y)\lambda}{4\pi} \cdot |E(x,y)|^2 dxdy}{\int\int_{\infty} Re\{E(x,y) \mathrm{x} H(x,y)^*\} \cdot e_z dxdy} \tag{2}$$

In eq. (1)-(2) $\Delta \mathrm{n_{FC}(x,y)}$ and $\alpha_{\mathrm{FC}}(\mathrm{x,y})$ depends on the generated electrons $\mathrm{n(x,y)}$ and holes $\mathrm{p(x,y)}$ [3] found by solving the model in Fig.1b.

III. RESULTS

We consider three MMRs with different waveguide cross sections: Si strip, Si/poly-Si strip and Si/poly-Si 3 wings. All MRRs have radius $3.5\mu\mathrm{m}$ and coupling coefficient $\mathrm{k}^2 = 0.0055$ with a cold cavity quality factor $\mathrm{Q} \approx 30000$. The 4 wings rib has been neglected because the bend loss is larger

This work was partially supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on ”Telecommunications of the Future” (PE00000001 - program ”RESTART”).



b)

Drift-Diffusion equations

$$\nabla(-D_n \cdot \nabla n(x,y) + \mu_n \cdot n(x,y) \cdot \nabla\phi(x,y)) = G_{ph}(x,y) - R_n(x,y)$$
$$\nabla\left(-D_p \cdot \nabla p(x,y) - \mu_p \cdot p(x,y) \cdot \nabla\phi(x,y)\right) = G_{ph}(x,y) - R_p(x,y)$$
$$\nabla^2\phi(x,y) = \frac{q}{\varepsilon}\left(p(x,y) - n(x,y) + N_a^- - f_t N_t\right)$$
$$G_{ph}(x,y) = \frac{P_c^2}{\frac{hc}{\lambda}} \beta_{TPA} \frac{n^2}{Z_0^2 \quad 8P_\mu^2} \left|E_\mu(x,y)\right|^4$$

Shockley-Read-Hall recombination

$$R_n(x,y) = N_t \cdot n(x,y)(1-f_t)\left(1 - e^{\frac{E_{ft}-E_{fn}}{k_b T}}\right)$$
$$R_p(x,y) = N_t \cdot p(x,y) f_t\left(1 - e^{\frac{E_{fp}-E_{ft}}{k_b T}}\right)$$
$$f_t = \frac{1}{1 + g_D \cdot e^{\frac{E_t - E_{ft}}{k_b T}}}$$

Thermal model

$$d_z \cdot \rho \cdot C_p \cdot u \cdot \nabla T - \nabla(d_z \cdot k\, \nabla T) = d_z Q(x,y)$$
$$Q(x,y) = \frac{|J_n|^2}{\sigma_n} + \frac{\left|J_p\right|^2}{\sigma_p} + \Delta\alpha_{FCD} \cdot I_{opt} + R_{n,p} \cdot 2\,\hbar\,\omega$$

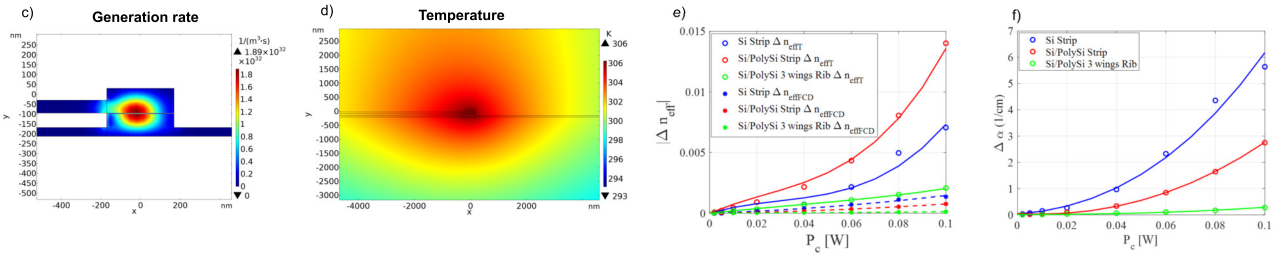


Fig. 1. (a) Waveguide cross sections. (b) Model summary. (c) Example FC generation rate due to TPA ($G_{ph}(x,y)$) in the case of the Si/polySi 3 wings Rib waveguide. d) Example of temperature variation due to self-heating; (e) and (f) resulting variation of the waveguide effective refractive index and modal loss as function of the power (P_c) circulating in the MRR. Solid lines are a polynomial fit of the numerical results reported with symbols.

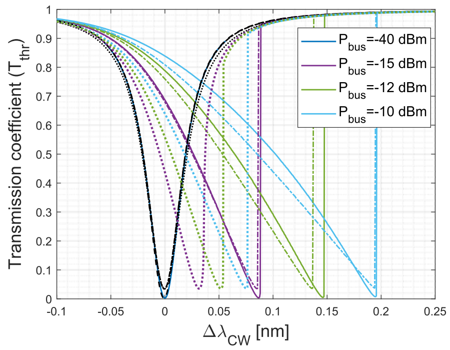


Fig. 2. Transmission spectra of the 3 MRRs at different bus input power: Si strip (continuos), Si/PolySi strip (dash-dotted), and Si/PolySi 3 wings Rib guide (dotted)

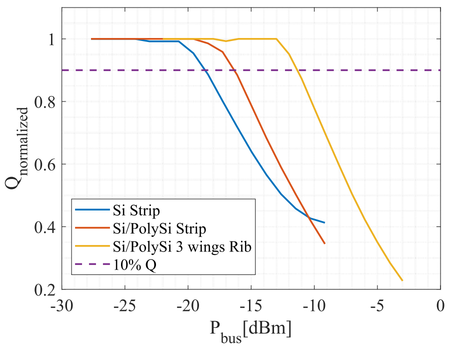


Fig. 3. Degradation of the quality factor versus the input bus power.

than $1\,\mathrm{dB/cm}$. From Fig. 1 e. and Fig. 1 f. it is observed that the Si/polySi 3 wings Rib presents the lowest nonlinear effects for the same circulating power when compared to the two other structures. The reason is that the rib waveguide has long lateral wings where electrons and holes diffuse; this reduces the density of FCs where the most of the optical field is confined (see Fig.1c.). The resulting variation of the effective refractive index and the modal loss were fitted with third-degree polynomials as a function of the circulating power of the MRR (Fig. 1 e and Fig. 1 f.). These polynomials are the input parameters for the model that calculates the MRR transmission coefficient [4]. Consequently, the MRR transmission spectrum of the Si/poly-Si 3 wings rib presents a smaller NL shift of the resonant wavelength and a smaller degradation of the Q with respect to the other two MRRs (Fig.2). This is also proven by comparing in (Fig.3) the MRR quality factor versus the input bus power; the 3 wings rib structure makes possible to reach a maximum power (with 10% reduction of the Q) about $12\mathrm{dB}$ higher than the standard Si strip waveguide.

In conclusion we report the development of a model and the numerical simulations of MRR in the SISCAP platform; the method is applied to design compact MRRs with minimal non-linear effect and self-heating. The results could be applied to the selection of the best MRRs for III-V/Si external cavity lasers.

REFERENCES

[1] A. Malik et al. Applied Physics Reviews 8, 031306 (2021).

[2] M. Webster et al. 11th International Conference on Group IV Photonics (GFP). 27-29 August 2014

[3] M. Novarese et al. EEE Photonics Technology Letters, vol. 35, no. 8, pp. 450-453, 15 April15, 2023

[4] M. Novarese et al. Vol. 30, No. 9, 25 Apr 2022. Optics Express 14341.