Directional Coupling Interface between Si-rich nitride and Si_3N_4 Waveguides Towards the Monolithic Co-integration of QD-InP and Si_3N_4 Photonic Components on Si

(Student paper)

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ABSTRACT

We demonstrate a directional coupler for light transition from a Si-rich nitride (SRN) with a refractive index of n=3.165 at λ =1550nm to a Silicon Nitride (Si_3N_4) waveguide, presenting both a theoretical analysis for the optimization of the coupling losses and experimental results corresponding to the fabricated device. Both the material and the design have been engineered specifically for monolithic co-integration strategies of InP-based Quantum-Dot (QD) active components on the Si_3N_4 passive photonic platform. Our numerical calculations estimated coupling losses lower than 0.5dB for the whole C-band, while our experimental measurements from a test structure revealed minimum losses of 1.34dB at 1620nm. The proposed design is compatible with Back end of the Line (BEOL) 248nm DUV lithographic techniques targeting maximum exploitation of low cost Si_3N_4 inherent advantage.

Keywords: Coupling, Waveguide, Si-rich Nitride, Silicon Nitride, Integrated Optics, Silicon Photonics

1. INTRODUCTION

Silicon nitride has emerged during the last years as a low cost, low loss solution for the fabrication of Photonic Integrated Circuits (PICs) [1]. However, the integration of III-V components on the Si_3N_4 waveguide platform has always been an arduous task owing to the large refractive index difference of the two materials. The co-integration of III-V lasers on the Si_3N_4 waveguide platform so far has been performed with flip chip bonding of the laser to the Si_3N_4 waveguide facet producing 3 dB losses, while this concept requires also precise alignment that produces low yield in mass production [2]. Relaxation of laser placement accuracy could be obtained with adiabatic coupling of the light from the III-V to the Si_3N_4, but this is quite challenging due to the existent refractive index difference. A solution to overcome this problem is the incorporation of an intermediate material layer with a suitable refractive index acting as an interposer. This approach was implemented in [3], where a hydrogenated amorphous silicon waveguide with n=3.37, was employed for adiabatic light transfer from a transfer printed InP/InAlGaAs based Semiconductor Optical Amplifiers to the Si_3N_4 layer with less than 2dB coupling loss. Targeting further cost and performance optimization, the next step would be to integrate both active and passive components on the same Si substrate in a monolithic way [4]. Towards this direction the interposer should provide a suitable refractive index for the accommodation of III-V materials, while the design for the directional coupling from the interposer to the Si_3N_4 passive platform should be adjusted in order to take into account the different refractive indices of the whole integration platform. Such a design was theoretically proposed in [5], where the numerical electromagnetic analysis proved that a SRN material with a high refractive index of n=3.18 outperforms a Si_3N_4 material for utilization as the interposing layer between an InP-QD emitter and a Si_3N_4 waveguide. Continuing our prior work, in this paper we present experimental results supported by detailed numerical calculations, of a fabricated SRN-to-Si_3N_4 directional coupling interface that is compatible with BEOL Process and 248nm DUV lithography.

2. DESIGN ANALYSIS

Figure 1(a) illustrates the design utilized for seamless light transfer from a QD-InP source to the Si_3N_4 passive platform, composed of the end-fire QD-to-SRN interface and the directional SRN-Si_3N_4 coupler, but herein we are focusing only on the second part of the complete interface. The refractive index of the SRN is set as n=3.18, while the thickness is set at 500nm, coming from simulation results, indicating low coupling losses and back reflections at the InP-SRN interface due to very good spatial mode and effective index matching. The other geometrical parameters of the SRN waveguide are based on the theoretical analysis presented in [5]. The cross section of the underlying Si_3N_4 platform is 800 x 800nm^2 mandated by the standard platform of Ligentec S.A. for IR wavelengths. The source is assumed to emit a field with 4μm x 500nm dimensions in agreement with the InP QD laser specifications in the monolithic integration scenario. The SRN waveguide, after a straight section of 20μm, is tapered down for high order mode suppression and the transformation of the fundamental mode. The taper length is 150μm and ends to a 210nm wide tip. The rationale behind the choice of both parameters is twofold; minimization of the SRN propagation length in order to tackle the high propagation-losses of the fabricated SRN waveguide [6] and maintenance of all critical dimensions of the coupler higher than 200nm for compatibility with low cost 248nm DUV lithography. Figure 1(b) depicts the xy-plane of the simulated taper geometry, while Fig. 1(c) shows the calculated |**E**| field at a plane at the middle of the SRN-waveguide.

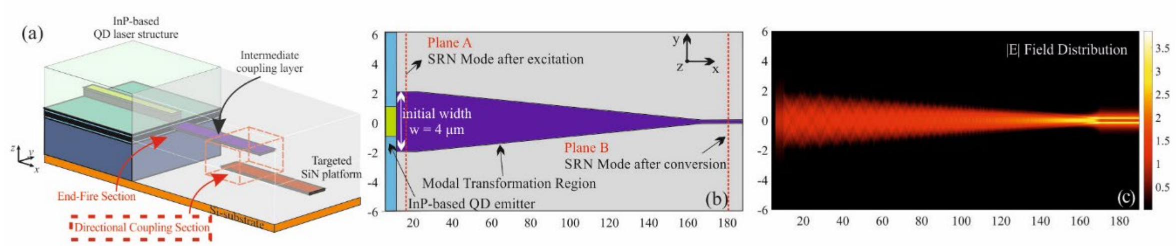

*Figure 1: (a) Coupling concept for the monolithic integration of InP-QD Sources and Si_3N_4 waveguides on Si-substrates that employs a SRN interposer waveguide, (b) Topview (xy) Plane of the InP-QD-to-SRN waveguide end-fire interface, (c) |**E**|-field depiction, derived from 3D-FDTD numerical calculations, indicating light propagation from the InP-QD-source to the SRN waveguide for the simulated geometry of (b).*

The directional coupling of the light to the Si_3N_4 is analysed via the 2D-eigenmode study of Fig. 2(a) that is presenting the cross-sectional plane of the hybrid waveguide system incorporating the SRN and the Si_3N_4 materials. The cladding of SRN is BCB with n=1.535, while the cladding of Si_3N_4 is SiO_2 with n=1.444. The gap between the two-waveguides is also filled with 100nm of SiO_2. The solution from the eigenvalue problem reveals that there are two supermodes; the quasi-even and quasi-odd presented in Fig. 2(b) and Fig. 2(c) respectively. Their beating leads to almost ideal light coupling from the SRN to Si_3N_4 for a coupling length L_C = 6.6μm at λ=1550nm. Numerical values for the coupling losses of the proposed directional coupling scheme were obtained via 3D-FDTD simulations revealing losses of 0.14dB during the transition from the 210nm x 500nm SRN cross-section to the 800nm x 800nm Si_3N_4 waveguide for a TE polarized mode source. Figure 2(d) illustrates the calculated side view (xz plane) of the |**E**| field distribution.

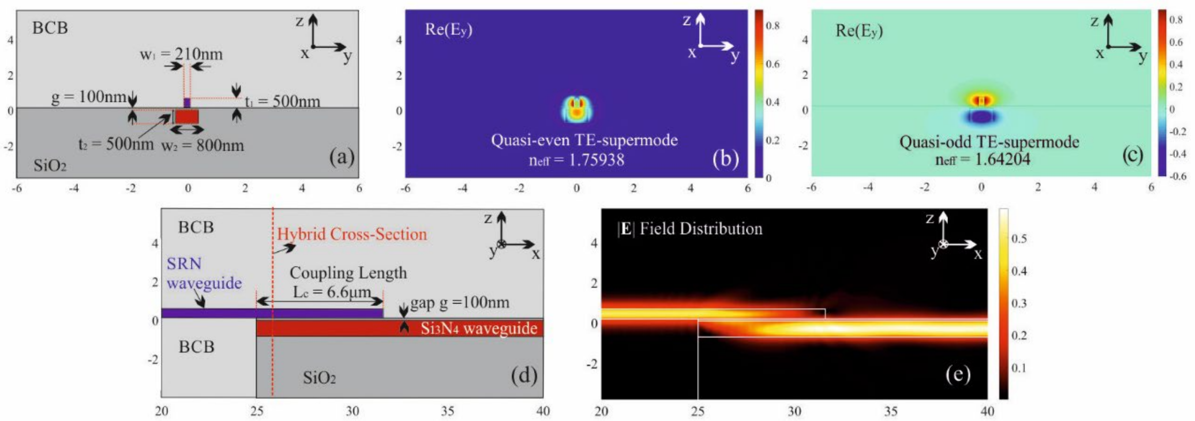

*Figure 2: (a) Cross-Sectional (yz) Plane of the Hybrid SRN-Si_3N_4 geometry, (b) Quasi-even TE supermode supported by the simulated hybrid geometry of (a), (c) Quasi-odd TE supermode supported by the simulated hybrid geometry of (a), (d) Sideview (xz) depiction of the SRN-to-Si_3N_4 directional coupler following the end of the SRN taper, (e) |**E**|-field depiction, derived from 3D-FDTD numerical calculations, indicating light propagation from the SRN to the Si_3N_4 waveguide for the simulated geometry of (d).*

3. FABRICATION AND EXPERIMENTAL CHARACTERIZATION

A detailed description of the SRN material fabrication and characterization is presented in [6]. The n-k measurements extracted from the fabricated SRN material indicated a high refractive index of n = 3.165 at the wavelength of λ =1550nm. This high value comes from the requirement to match the InP laser effective refractive index. After growth of the 500nm thick SRN films with a low stress recipe, waveguides of 500 x 500nm^2 cross section and length between 1 and 10 mm were formed via e-beam lithography, with the processing of the cutback measurements revealing a value of 15dB/cm propagation losses for these SRN waveguides at λ=1550nm. The next step was the deposition of the SRN material on top of the Si_3N_4 platform and the formation of the directional coupler according to the design of the previous section with e-beam lithography. Figure 3(a) illustrates a 3D schematic of the designed test structures fabricated for the characterization of the SRN- Si_3N_4 interface. The light goes from the 800 x 800nm^2 Si_3N_4 up to the 210 x 500nm^2 SRN, then follows the tapering to the 4μm x 500nm cross section and after this a straight section of 3mm length. The SRN waveguide is tapered then again to the 210 x 500nm^2 tip and from there the light goes down to the 800 x 800nm^2 Si_3N_4. Both fiber-to-PIC interfaces are grating couplers (GCs). Figure 3(b) shows a micrograph of the fabricated SRN-to-Si_3N_4 coupler, while Fig. 3(c) shows a SEM image of the sideview of the fabricated SRN taper tip.

The chip with the test structure was characterized by a tuneable laser source ranging from 1.5μm to 1.63μm. A polarization controller was employed to adjust the polarization of the light injected into the PIC. The corresponding characterization results for both TE and TM polarizations, after subtraction of the losses from a Si_3N_4 straight waveguide with two GCs, used a reference structure, are presented in Fig. 3(d). At 1620nm the ripple is absent for the TE polarization with a total loss value of 7.18dB. Assuming 4.5dB loss for the 3mm straight section also at λ=1620nm, the two SRN-Si_3N_4 interfaces produce in total 2.68dB losses, or 1.34dB/interface. Although this value is quite larger than the one expected from simulations, it is the first one reported for such an engineered material. However, work is ongoing towards the improvement of the SRN material quality and processing for the reduction of propagation and insertion losses in SRN waveguide structures. Additionally, the polarization selectivity is quite low with a maximum value of 6.318dB at 1620nm, while in simulations the obtained value was larger than 20dB. The origin of this deviation and the ripples at the lower wavelengths in the transfer function for the TE polarization are now under investigation through further calculations.

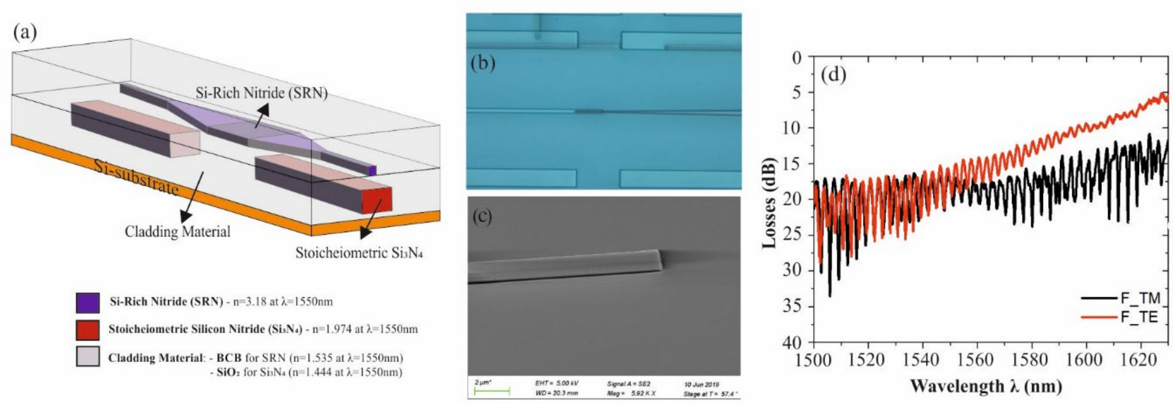

Figure 3: (a) 3D-Configuration utilized for the experimental study of the fabricated SRN-to-Si_3N_4 coupling interface, (b)Micrograph of the fabricated SRN-to-Si_3N_4 Coupler, (c) SEM sideview image of the fabricated SRN taper tip, (d) Experimental results for the total transition losses of Fig. 1(a) after normalization with the input/output structure

4. CONCLUSIONS

Herein, we have presented a SRN-Si_3N_4 directional coupler suitable for efficient light transfer from InP-based QD-sources on Si_3N_4 waveguides. The whole integration concept is compatible with BEOL monolithic integration strategies and low cost 248nm DUV lithographic techniques. The extracted losses from a test sample revealed losses of 1.34dB/interface at λ=1620nm.

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