Characterisation and mitigation of surface related optical loss in suspended GaAs photonic integrated circuits

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Suspended GaAs photonic integrated circuits (PIC) offer a potential route towards monolithic integration of active and passive device functionality for improved efficiency and component density. Thus far, however, progress has been limited by excessive optical losses that occur at the surface of GaAs waveguides. In this work, we quantify the optical propagation loss due to surface absorption in a suspended GaAs PIC platform, probe its origins using X-ray photoemission spectroscopy (XPS), and show that it can be mitigated by surface passivation using an atomic layer deposition (ALD) of alumina. ***Keywords***: *Photonic integrated circuit, Gallium Arsenide, optical loss, surface state absorption, ring resonators, rib waveguides*

INTRODUCTION

No one PIC platform possesses all the optical, mechanical, and electronic properties that would enable arbitrary scale, complexity, and functionality of monolithically integrated devices. That said, of all the materials commonly used in integrated optics, III-Vs like gallium arsenide and indium phosphide, perhaps, come closest in this regard. III-V direct band gap materials enable efficient on-chip light emission and detection and with non-linear electro-optic and piezo-electric coefficients can enable other active functionalities; fast modulation; routing and signal processing. Of the available III-V materials, however, GaAs offers the key advantage of 8" fab, developed for electronics, but, with the potential for higher performance photonics. Nevertheless, when implemented within a GaAs/AlGaAs waveguide, poor optical confinement (due to the low index contrast between GaAs and AlGaAs) leads to large mode sizes, and bend radii, which make photonic integration challenging. A solution to the issue of mode confinement is to remove GaAs waveguides and other photonic structures from their underlying substrate to increase the index contrast between the GaAs waveguide core and the surrounding material [1]. In previous work [2], we reported a robust fabrication technique for a suspended GaAs PIC platform that enables strong mode confinement through the release of photonic structures by wet etch removal of an intermediate sacrificial layer of AlGaAs and demonstrated standard passive PIC components: grating couplers, waveguides, ring-resonators and waveguide splitters. Whilst overcoming the mode confinement issue, propagation losses in these 220 nm thick suspended GaAs waveguides were excessive, 10.7 dB/cm, when compared to equivalent 220 nm and 340 nm silicon on insulator (SOI) offerings (propagation loss ≈ 1dB/cm). We attribute this excessive loss to photon absorption by mid-band gap trap states at the surface of the GaAs waveguides. While there has been some recent work to address this issue of surface passivation of these trap states in III-Vs [3-5], building on work in GaAs electronics, a systematic exploration of the origin of surface loss, its quantification and mitigation by surface passivation techniques is critical to advancing research on III-V PICs.

In this work, we use micro-ring resonators (MRR), fabricated in our suspended GaAs platform, to quantify surface absorption and passivation. The MRR devices are fabricated from 370/1000 nm GaAs/$Al_{0.6}Ga_{0.4}As$ layers epitaxially grown on an undoped GaAs substrate. To differentiate losses occurring at the surface of the waveguides from those in their bulk, we compare the intrinsic quality factor, Q_i values (extracted from measurements of the loaded Q [6]) of devices measured with and without an (8 ± 2) nm thick conformal surface coating of alumina (deposited via ALD). By altering the chemistry of the GaAs surface reconstruction layer, the differential loss measured for treated and untreated devices is directly attributable to mechanisms that occur at the surface of the waveguides alone. The Q_i factors of the of the treated and untreated devices are calculated by numerically fitting a skewed Lorentzian function [7] to resonances recorded in the transmission spectra of the MRRs with the experimental set up illustrated in Figure 1. The wavelength response of the device is measured by sweeping the output wavelength of a tunable laser source in 0.5 pm increments (from short to long wavelength) and recording the transmitted power at each step. For both the ALD treated and untreated samples three different MRR devices were tested with between 2 - 4 resonances recorded for each device.

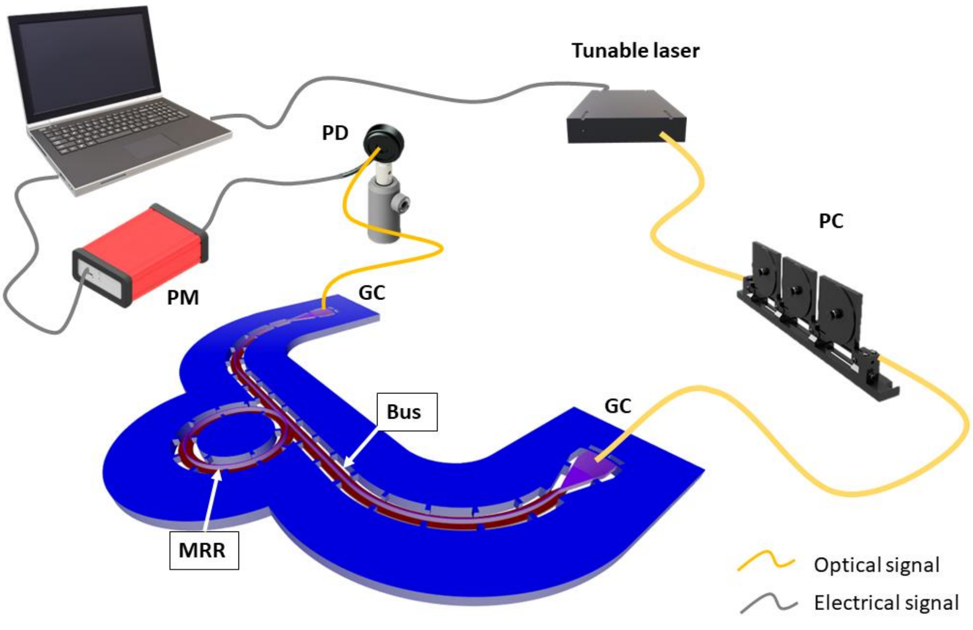
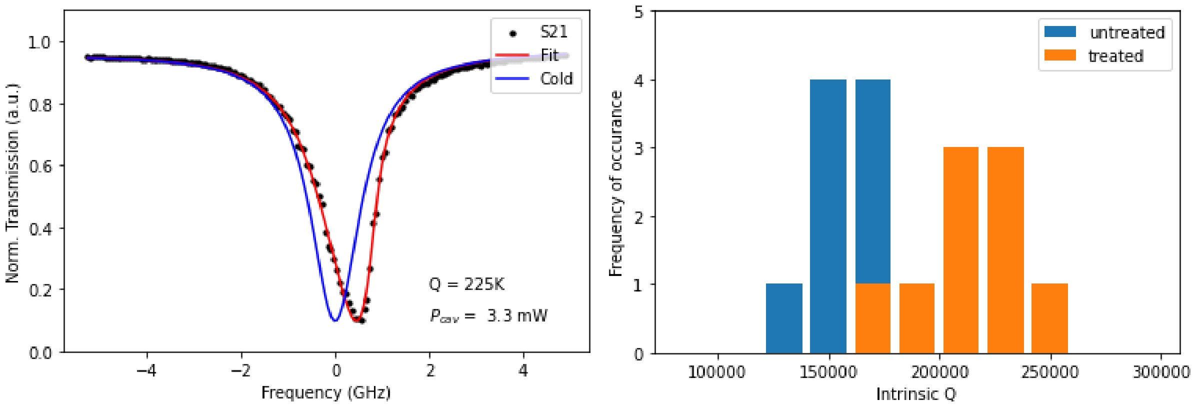


Fig. 1a. Illustration of the experimental set up for measuring MRR transmission spectra. light from a tunable laser passes through a polarization controller (PC), for TE polarized light only, and is inserted into the device via one a pair of tapered grating couplers (GC) situated at either end of the bus waveguide that couples at its mid-point to a 50 µm diameter MRR. The transmitted light from the second GC is fiber coupled to photodetector (PD) and the signal measured with a power meter (PM).

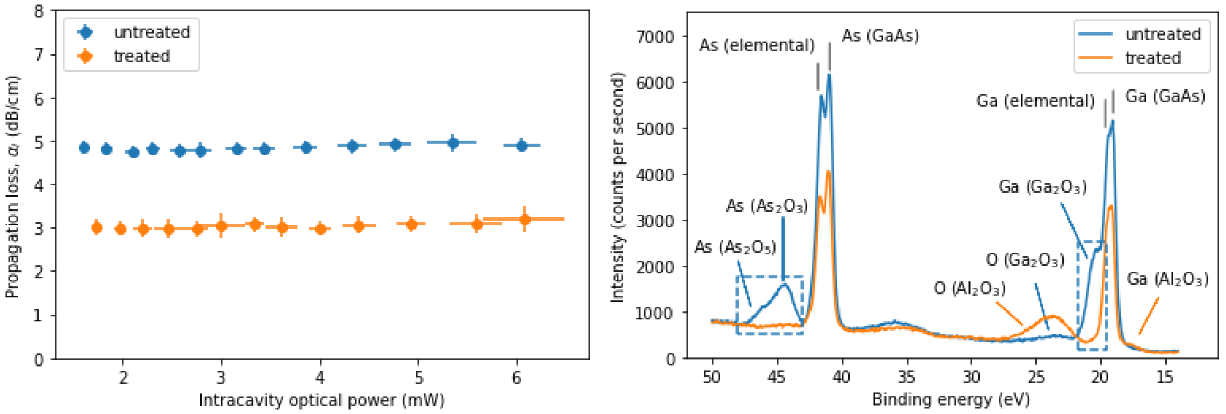
RESULTS/DISCUSSION

Figure 2a shows a typical normalized transmission spectrum recorded for of one of the alumina treated devices from which the Q_i values are extracted. The asymmetry of the resonance is evidence of optical absorption in the MRR cavity which causes it to heat up and induces a thermo-optic shift of the resonant frequency [7]. The Q_i comparison results are presented in the histogram in figure 2b. Taking the median Q_i values, 220k and 160k, to be representative of the treated and untreated sample groups respectively, we estimate that the alumina surface passivation treatment has improved the intrinsic Q of the MRRs by a factor of 1.4



(a) (b)

Fig. 2a. Transmission spectrum (plotted as resonant frequency detuning) measured for one of the ALD treated MRR resonances (black circles), numerically fitted Lorentzian function with thermo-optic 'skew' (red line) and 'cold cavity' Lorentzian fit (blue line) with the skew nullified. b. Histogram of the intrinsic Q values recorded for 10 resonances of both the ALD treated and untreated MRR devices.



(a) (b)

Fig. 3a Propagation loss, α_i, plotted as a function of MRR intracavity optical power for untreated (blue circles) and treated (orange circles). b. XPS surface chemistry analysis for ALD treated (orange lines) and untreated (blue lines) GaAs with native Ga and As oxides highlighted (dashed blue boxes).

In figure 3a the propagation loss, α_i, derived from the intrinsic Q values measured for the median treated and untreated devices, are plotted over a range intracavity optical power (power range over which non-linear absorption effects are not observed) showing that the differential loss remains consistent over a large power range. XPS measurements on treated and untreated GaAs samples, presented in figure 3b, elucidate the nature of the surface passivation. Spectral peaks corresponding to the oxides of Ga and As, observed in the untreated sample data (highlighted by dashed blue boxes,) are not evident in the spectrum of the treated sample, which instead, exhibits features corresponding to Ga bonded to Al_2O_3 and an oxygen signal from Al_2O_3, neither of which appear the spectrum of the untreated sample. This indicates that the alumina coating suppresses the formation of native oxides within the surface reconstruction layer of the GaAs that contribute to surface absorption.

CONCLUSIONS

The intrinsic quality factor and waveguide propagation loss of suspended GaAs MRR devices are improved by a factor of 1.4 through atomic layer deposition of a (8 ± 2) nm layer of alumina. XPS indicates that this is due to the passivation of the surface by suppression of native Ga and As oxides. The improvement in propagation loss afforded by the surface passivation method described here, brings the suspended GaAs photonic platform closer to the performance of Silicon photonics, to the point where the inherent advantages of a III-V material platform can become decisive.

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References

[1] J. H. Shin and N. Dagli, "Ultralow Drive Voltage Substrate Removed GaAs/AlGaAs Electro-Optic Modulators at 1550 nm," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 19, no. 6, pp. 150-157, Nov.-Dec. 2013

[2] P. Jiang and K. Balram, "Suspended gallium arsenide platform for building large scale photonic integrated circuits: passive devices," Opt. Express 28, 12262-12271 (2020).

[3] D. Parrain, C. Baker, G. Wang, B. Guha, E. Santos, A. Lemaitre, P. Senellart, G. Leo, S. Ducci, and I. Favero, "Origin of optical losses in gallium arsenide disk whispering gallery resonators," Opt. Express 23, 19656-19672 (2015).

[4] B. Guha, F. Marsault, F. Cadiz, L. Morgenroth, V. Ulin, V. Berkovitz, A. Lemaître, C. Gomez, A. Amo, S. Combrié, B. Gérard, G. Leo, and I. Favero, "Surface-enhanced gallium arsenide photonic resonator with quality factor of 6×10^{-6}," Optica 4, 218-221 (2017).

[5] B. Jacob, F. Camarneiro, J. Borme, O. Bondarchuk, J. B. Nieder and B. Romeira, "Surface Passivation of III–V GaAs Nanopillars by Low-Frequency Plasma Deposition of Silicon Nitride for Active Nanophotonic Devices," ACS Applied Electronic Materials 2022 Vol. 4 Issue 7 Pages 3399-3410.

[6] Bogaerts, W., De Heyn, P., Van Vaerenbergh, T., De Vos, K., Kumar Selvaraja, S., Claes, T., Dumon, P., Bienstman, P., Van Thourhout, D. and Baets, R. (2012), Silicon microring resonators. Laser & Photon. Rev., 6: 47-73.

[7] Gao, M., Yang, QF., Ji, QX. et al. Probing material absorption and optical nonlinearity of integrated photonic materials. Nat Commun 13, 3323 (2022).