Building large scale photonic integrated circuits in suspended gallium arsenide: Passives

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ABSTRACT

The spectacular success of silicon-based photonic integrated circuits (PICs) in the past decade naturally begs the question of whether similar fabrication procedures can be applied to other material platforms with more desirable optical properties. In this work [1], we demonstrate the individual passive components (grating couplers, waveguides, multi-mode interferometers and ring resonators) necessary for building large scale integrated circuits in suspended gallium arsenide (GaAs). Implementing PICs in suspended GaAs is a viable route towards achieving optimal system performance in areas with stringent device constraints like energy efficient transceivers for exascale systems, integrated electro-optic comb lasers, integrated quantum photonics, cryogenic photonics and electromechanical guided wave acousto-optics.

Keywords: Photonic integrated circuits, grating couplers, rib waveguides, ring resonators, waveguide couplers, multimode interferometers

1 INTRODUCTION

The scale, complexity and performance of silicon photonic integrated circuits (PICs) has revolutionized optical communications in the past decade [2]. Perhaps the most surprising aspect of this revolution is the fact that silicon does not possess many desirable optical properties (apart from a high refractive index) and the silicon photonics revolution was primarily driven by the availability of a foundry fabrication infrastructure [4]. On the other hand, there are a number of application areas in which silicon's lack of desirable optical properties proves a severe limitation to achieving system performance. These limitations include the absence of a direct bandgap, lack of a $\chi^{(2)}$ nonlinearity to build fast electro-optic devices and zero piezoelectric response which makes it challenging to design acousto-optic devices. As a representative example, one of the key challenges facing transceivers for exascale systems is avoiding the ~ 3 dB penalty for coupling light from the III-V laser die to the silicon PIC. Other application areas where alternative material platforms are worth exploring are: cryogenic photonic circuits for interfacing superconducting digital circuits with the outside world and integrated acousto-optics, which requires a piezoelectric material for exciting acoustic waves [5].

Gallium arsenide (GaAs) presents a viable alternative to silicon for these applications as it possesses all the desirable optical properties that silicon lacks: a direct bandgap, a $\chi^{(2)}$ nonlinearity, and a (weak) piezoelectric coefficient [6]. More importantly, GaAs has a refractive index that is almost identical to silicon (λ = 1.55 μm), making it easy to port a variety of optimised photonic designs and fabrication process flows between the platforms. In contrast to other electro-optic platforms like lithium niobate, it has a higher refractive index allowing compact component design, which is key to monolithic systems integration. GaAs also provides a natural route towards incorporating active gain media like quantum dots and wells, which are promising for applications in both classical and quantum photonics. Traditionally integrated photonics in GaAs has suffered from the low index contrast achievable between GaAs and the AlGaAs buffers which serve as waveguide cladding layers. The low index contrast leads to large mode sizes and bend radii which make photonic integration challenging [6]. In addition, the reduced optical power density (due to larger mode area) makes it difficult to adequately exploit the nonlinear coefficients for frequency conversion and EO modulator applications [8]. In recent years, there has been tremendous progress in the development of thin films of GaAs on low index media (particularly silicon oxide and nitride) by wafer bonding and a wide variety of devices showing impressive nonlinear performance have been demonstrated. On the other hand, wafer bonding is well-known to be a notoriously fickle process and it is challenging to get high device yields (a prerequisite for building PICs) in an academic cleanroom environment.

In this work, we show that a multi-step fabrication process, derived from a standard passive silicon photonics platform [7], can be applied to build large scale photonic integrated circuits in suspended GaAs. The suspension of the GaAs layer, achieved by selective etching of the underlying AlGaAs film, is necessary to achieve high refractive index contrast [9].

2 FABRICATION PROCESS

Figure 1 shows a schematic illustration of the main process steps for a grating coupler fabricated using this process. The process starts by patterning the grating coupler teeth and defining the outline of the waveguides and

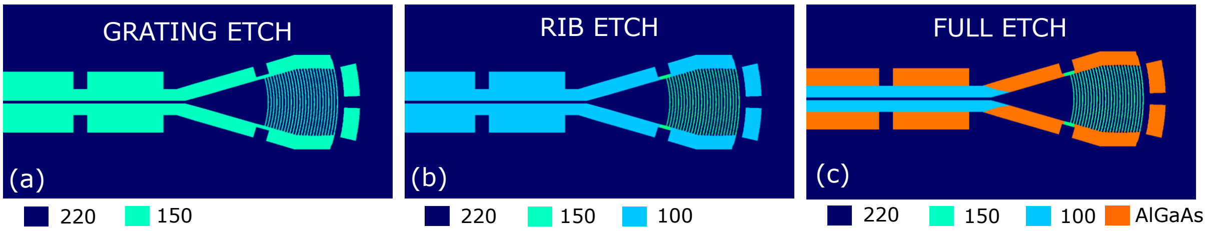

Figure 1. Illustrative schematic of the process flow for building a suspended waveguide platform in GaAs. The process follows the standard three step process used to fabricate passive silicon photonic devices. The GaAs thickness (in nm) in each region is indicated. (a) A 70 nm GRATING etch is used to define the grating coupler in GaAs. (b) The GaAs is etched a further 50 nm to define the rib waveguides (RIB etch). (c) Finally, a 100 nm FULL etch is carried out to reach the AlGaAs layer. The exposed AlGaAs layer is selectively etched away in weak HF acid and the sample is covered with $\sim 2\ \mu m$ SiO_2.

the tethers (GRATING etch) in GaAs (Fig. 1 (a)). The patterning is carried out using electron beam lithography with hydrogen silsesquioxane (HSQ) resist and the GaAs layer is etched using a standard Ar/Cl_2 chemistry with etch thickness monitored using an ellipsometer to ensure precise etch depths are achieved. This is followed by a RIB etch step (Fig. 1 (b)), where the GaAs layer is etched a further 50 nm to define the rib waveguides. The grating coupler region is protected with HSQ resist during this step. The two layers are registered with respect to each other using a set of alignment marks defined during the GRATING etch step. A FULL etch step is next carried out by etching the remaining 100 nm of the GaAs layer (+ 20 nm overetch) to access the AlGaAs buffer as shown in Fig.1(c). To suspend the GaAs layer, the AlGaAs buffer is selectively etched in dilute hydrofluoric acid (HF) solution. To remove any remnants of etch residue, the sample is cleaned in a dilute potassium hydroxide solution and flash dried using isopropanol [10]. After HF release, the suspended GaAs film is capped with $\sim 2\ \mu m$ of silicon oxide deposited using plasma enhanced chemical vapor deposition (PECVD). The oxide film is necessary for separating the metal electrodes (required for the electro-optic devices) from the GaAs layer. In addition, they provide mechanical rigidity to the suspended films by pinning them at the corners of the etch holes [1].

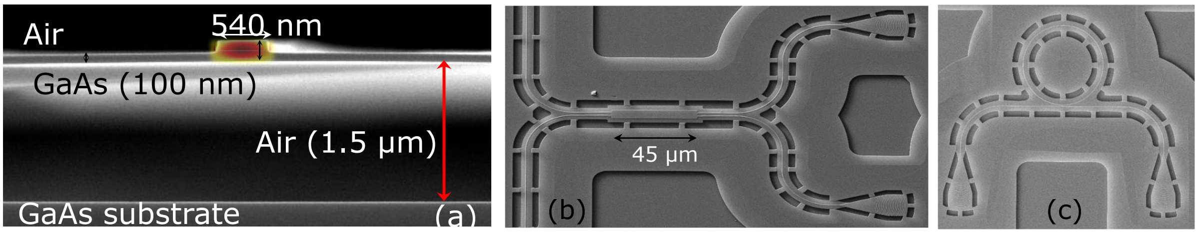

Figure 2. Representative devices fabricated in this platform: (a) Rib waveguides (b) 2x2 multimode interference (MMI) coupler and (c) Microring resonators (25 μm radius). The suspended grating couplers used to provide optical access can be seen in (b) and (c).

A representative set of passive devices fabricated using this suspended GaAs platform is shown in Fig.2. These include suspended rib waveguides (Fig.2(a)), grating couplers (Fig.2(b,c)), on-chip waveguide splitters (multimode interference couplers shown in Fig.2(b)) and microring resonators (Fig.2(c)). As silicon photonics and before it silicon microelectronics have shown, once a set of robust building blocks have been demonstrated, circuits of arbitrary complexity can be synthesized by connecting these building blocks together in the desired order. The passive devices demonstrated here serve as a key building block for the development of active devices, in particular, efficient integrated electro-optic and acousto-optic modulators, which are currently under development.

3 DEVICE CHARACTERISATION

Fig.3 shows the measured device performance for various components fabricated in this suspended GaAs platform. Fig.3(a) shows that a suspended 2x2 MMI coupler can achieve on-chip splitting ratios very close to 50:50, with very low excess loss. Grating couplers (shown by the blue curve in Fig.3(a) show coupling loss 4 dB/ coupler. In contrast to traditional III-V PICs which have relied on edge coupling, grating couplers open the door to in-situ device testing by avoiding the need for chip cleaving. This is especially useful to maximise device yield as the scale and component density of PICs increases. Fig.3(b,c) show the measured transmission spectra of microring resonators fabricated in this platform. The quality factor of our rings is $\sim$ 15000. Based on the measured resonator Q_{opt} and free spectral range (from Fig.3(b)), we estimate our current waveguide propagation loss to be $\sim$ 7 dB/cm. We believe the resonator is currently operating in the overcoupled regime, and hence the propagation loss estimate is an upper bound.

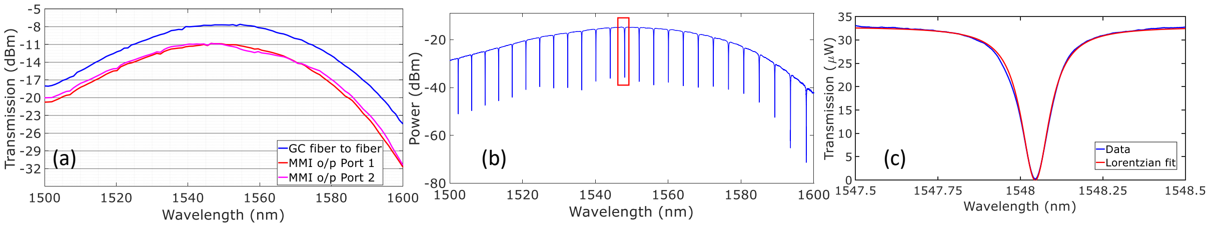

Figure 3. (a) Measured transmission spectrum through the two output ports (labelled 1 and 2 and indicated by the red and magenta curves) for a suspended MMI coupler. The reference fiber to fiber transmission spectrum, without the MMI, is shown in blue. (b) Measured transmission spectrum of the resonator showing a series of TE resonant modes (P_{in} = -6 dBm). The TE polarisation is determined by the grating coupler. (c) Zoomed-in scan of one of the resonances, fitted with a Lorentzian lineshape, giving a measured $Q_{opt} \sim$ 15000.

4 CONCLUSIONS AND FUTURE WORK

In this work, we have demonstrated that the complexity of the standard (passive) silicon photonics process can be readily transferred to more interesting optical materials, in particular GaAs. The similarity of the refractive indices of the two materials ensures that high device performance can be readily ensured without requiring extensive component re-design. Bringing the scale and complexity of silicon photonics to more interesting optical platforms will be revolutionary for device applications in wide-ranging areas from quantum photonics to cryogenic photonic circuits. Moving forward, we will extend this platform to demonstrate low-loss long spiral ($L_{wvg} \sim$ cm) waveguides, and active electro-optic and acousto-optic devices.

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