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Suspended Gallium Arsenide Electro-Optic Racetrack Ring Modulator

Student paper

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We present the design, fabrication and characterization of electro-optic racetrack ring modulator on suspended gallium-arsenide (GaAs) platform. This is the first demonstration of active devices fabricated on suspended thin-film GaAs with multi-layer metallization while exhibiting desirable electro-optic performances. This work opens up the route towards dense passive and active device monolithic integration achieving optimal system performance.

Keywords: *Racetrack ring resonator, electro-optic modulator, gallium arsenide optoelectronics*

INTRODUCTION

For the past decade, the silicon photonic integrated circuits (PICs) have revolutionized the scale, complexity and performance of photonic devices and optical communication. Nevertheless, due to the lack of desirable optical properties, silicon photonics proves a severe limitation to achieving system performance. These limitations include an absence of direct bandgap and $\chi^{(2)}$ nonlinearity to build fast optoelectronic devices, and the lack of zero piezoelectric response to build acousto-optic devices.[1] This forces silicon photonics to resort with other traditional optical material like III-V and ferroelectric materials, and will suffer coupling loss during the energy transfer between different material systems.

While efforts have been made on bringing III-V materials to silicon photonics by hybrid integration, there has been relatively little effort on improving the existing III-V PIC platform by applying ideas from silicon photonics manufacturing. In particular, gallium arsenide has always been the material of choice for high-speed devices for its high electron mobility and the availability of low-loss semi-insulating substrate.[2] GaAs possesses all the desirable optical properties that silicon lacks: a direct bandgap, a $\chi^{(2)}$ nonlinearity, and a piezoelectric coefficient which activates mutual links among microwave, acoustic and optical domain. The refractive index of GaAs is close to silicon at λ = 1.55µm, making it easy to transfer a variety of optimised photonic designs and fabrication process flows between the platforms. In contrast to other electro-optic materials like lithium niobate, it has a high refractive index allowing compact component design at small footprint to achieving system performance. GaAs also provides a natural route towards incorporating active gain media like quantum dots and wells in favour of monolithic integration in both classical and quantum photonics. Traditionally integrated photonics in GaAs suffers 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.[3]

In this work, we bring the idea from silicon photonics and silicon microelectromechanical systems (MEMS) foundry to build high-performance electrical-optic modulators (EOM) on the suspended GaAs platform. This platform, by releasing the thin-film GaAs on low-index media of air, generates a large index contrast to tightly confine optical mode in waveguides. The reduced optical mode size enables us to build compact structures without incurring extra scattering losses. Our suspended EOM demonstrates that active devices requiring multi-layer metallization can be built on suspended GaAs platform. Exhibiting desirable electro-optic performance, the racetrack ring EOM from high yield (>90%) cleanroom fabrication has shown as a strong proof of principle. The tight optical confinement also enables a reduced electrode separation and higher effective electric fields resulting in a lower half-wave (V_π) voltage (required for achieving π phase shifts). This work opens up route towards dense monolithic integration up to wafer scale, and underpins a variety of III-V experiments ranging from quantum photonics to cryogenic photonics for satellite communication.

RESULTS

The racetrack design for EOM is chosen mainly for the ease proof of principle, since the resonator is environment-sensitive, and is susceptible to change induced by EO modulation. The geometry of the suspended GaAs racetrack ring EOM is shown as Fig. 1(a) in an angled view (silicon dioxide cladding unshown). The modulator consists of a pair of surface grating couplers (blue) as optical input and output, a 385-um-long optical racetrack resonator with point coupling design to bus waveguide (pink), and microwave electrodes (gold) to deliver electrical signals. The device has three electrical connections for a ground-signal-ground (GSG) configuration, with two ground electrodes seated on the n-doped substrate and a signal electrode above the racetrack expect for coupler region. A not-to-scale view of waveguide cross section in Fig. 1(b) shows the relative position of electrodes to the waveguides. When a voltage is applied across the signal and ground electrodes, a vertical electric field (black arrow) is induced predominantly in the vertical direction overlapping with the TE polarized optical mode (color scale) due to the Pockels effect. When the ring is near resonance and the coupled portion of light oscillates inside the cavity, this overlap transforms the optical phase (frequency) of propagating light and change into intensity modulation that can be detected from the output.

The fabrication of the suspended EOM begins with a 340-nm (001)-oriented GaAs epitaxial layer. Fig. 1(c) shows the optical micrograph of a fabricated suspended racetrack EOM. The devices are fabricated first by structuring optical components and tethers by Electron-Beam Lithography. All structures are then suspended by surrounding tethers and a selective wet etch through etch holes to remove the underlying $Al_{0.65}Ga_{0.35}As$ layer. A 2.6-um-thick silicon dioxide (SiO_2) cladding is then deposited over the device to separate the electrode from the waveguide to reduce metal absorption losses. In addition, SiO_2 improves the rigidity of the suspended structures by pinning them at the corners of the etch holes. This has been proven to survive even in high-power ultrasonic bath, thus the suspended structure can bear the load of heavy electrodes. To make sure a sufficient delivery of electrical signal, we use wire-bonding to connect the devices with outer signal source, as shown in the camera view in Fig. 1(d).

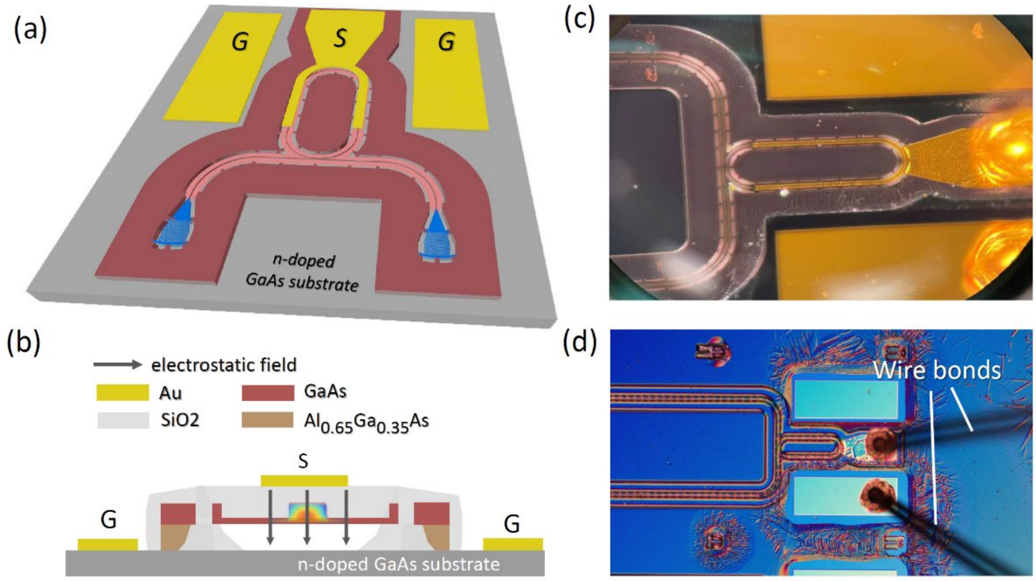

Fig. 1 Device geometry of suspended GaAs electro-optic modulator in (a) angled 3D view and (b) cross-sectional view. (c) The device dark-field images and (d) the top-camera view showing devices driven via wire bonds

Fig. 2(a) shows the optical spectrum and its Lorentzian fit of one resonant mode around 1550nm. The loaded quality factor (Q) of the resonator is 98,000 and the extinction ratio is 3dB. It is determined that the resonator works at the under-coupled regime (where intrinsic propagation attenuation is greater than coupling coefficient). The obtained intrinsic Q is 113,000 corresponding to a linear propagation loss of ~6dB/cm, which is still far from the optimal loss in thin-film GaAs waveguide (~1dB/cm), but can be further reduced by improving fabrication quality.

To determine the EO performance of the modulator, an RF signal with peak-to-peak voltage (V_{P-P}) of 5V is used to drive the modulator. The intensity-modulated output is detected by high-speed photodetector (PD) and then fed to the lock-in amplifier as measured modulation amplitude. The pump laser is scanned across the optical resonance and the EO modulation is measured as a function of wavelength, as shown in Fig. 2(a) (dark blue). We can extract the modulation index, β, the relative phase shift induced by EO modulation, which is defined as:

$$\beta = \frac{1}{2}\frac{\Delta\lambda}{FWHM} \tag{1}$$

where $\Delta\lambda$ is the full wavelength swing under the applied signal amplitude and FWHM is the linewidth of the optical resonance. The theoretical small-signal analysis model [5-6] gives us the fit of $\beta \approx 0.07$ at 2MHz. Backed out from β, a modulator V_π of ~ 70V is obtained, which indicates a relatively small modulation efficiency for our first EO devices. Nevertheless, V_π can be further improved by reducing the gap between the electrode and the waveguides. The large index contrast of waveguide provides the feasibility to make the devices on a more compact level while preserving a low optical loss. Besides, improving the SiO_2 deposition quality also a larger portion of effective electric field overlapping with optical waveguide. Besides, V_π can be reduced by pulling the design near to the critical coupling regime to achieve as high Q as possible. Taken all into account, the V_π can be optimized down to sub-10V at our current device dimension of sub-millimeter.

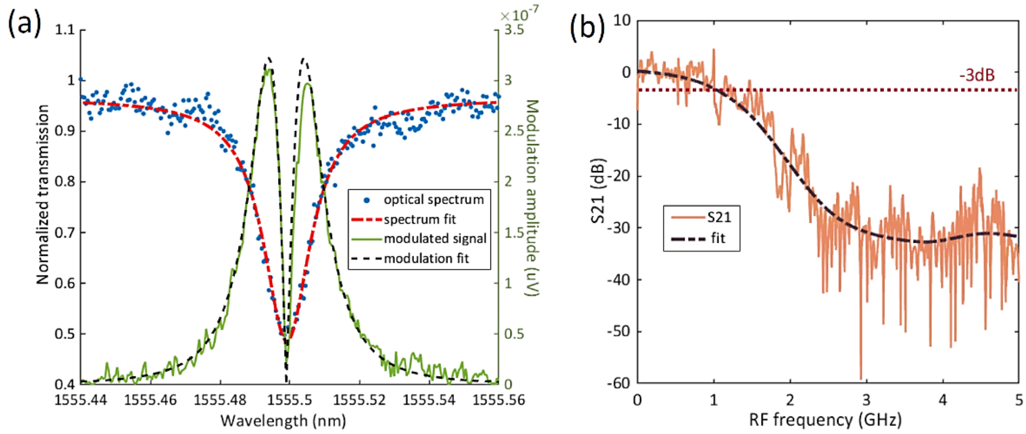

Fig. 2 (a) Experimental data and theoretical fit for optical spectrum, and EO modulation as a function of wavelength. (b) EO bandwidth of the modulator working at linear point (maximum EO modulation point)

The modulation bandwidth is measured by setting the pump wavelength at the maximum slope point, or linear point, of the optical resonance, where the maximum EO modulation is achieved. The modulator is driven at 0V DC bias with a small signal from vector network analyzer (VNA) swept from 1MHz to 6GHz, which shows a 3dB bandwidth of 1GHz. (Fig. 2(b)) One key limiting factor of the measured bandwidth is the wire bonds that used for source connection. The actual EO bandwidth can be out by de-embedding the peripherals. On the other hand, trade-off between optical quality factor and RF bandwidth exists. A low Q leads to a high bandwidth but a poor modulation efficiency.[7] The device design needs to be tailored to balance the typical trade-off relation between modulation efficiency and bandwidth and keep both at desirable levels for various application scenarios.

DISCUSSION

We've demonstrated the device geometry and fabrication process of suspended GaAs electro-optic racetrack ring modulators, which possesses high yield and desirable EO performances. The rigidity of the suspended platform provides feasibility for fabricating electro-optic devices with multi-layer metallization. In the recent future, the high index suspended platform enables a more compact device design and the V_π of the EOM will be significantly reduced to sub-10V with small footprints. Furthermore, we will extend this platform towards monolithic integration incorporating active gain media for making laser and photodetector. This will be revolutionary for device applications in wide-ranging areas from cryogenic photonics and quantum computing to satellite communication.

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