GaN-based Mach-Zehnder Modulators for Highly Efficient Optical Modulation and Switching Applications

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The recent development of 8-in Gallium Nitride on Silicon (GaN-on-Si) wafers has facilitated cost effective, large-scale manufacturability of GaN-based electronics. Leveraging its wide band gap, capability to support a two-dimensional electron gas (2DEG) layer, and strong built-in polarization effects, GaN-based electronic devices have become a viable cost-effective successor to silicon-based devices for high-performance applications where the large bandgap and high breakdown field are required. The advantageous properties of GaN-on-Si material, however, have yet to be utilized for photonic integrated circuit applications. Therefore, the exploration of GaN for efficient on-chip optical modulation and switching applications is examined. In order to effectively characterize GaN's capabilities for optical modulation and switching, GaN-based Mach-Zehnder modulators are designed and fabricated. Through simulating the propagating optical modes supported in a GaN-based Mach-Zehnder structure, the geometry of the device is designed to optimize optical modal overlap with the 2DEG layer while maintaining single-mode performance. Through electrical and optical characterization, the effective electro-optic coefficient and V_π length are measured. These measurements provide a method of benchmarking GaN-based photonic devices for their optical modulation and switching efficiency.

***Index Terms*—Mach-Zehnder Modulator, Gallium Nitride, Optical Modulation, Optical Switching**

I. Introduction

As the rapid growth of data traffic continues to drive the demand for faster communication speeds at lower energy costs, the usage of traditional electrical interconnects to accommodate these requirements is becoming inadequate [1,2]. Photonic-based solutions have been shown not only to surpass electrical interconnects in performance but are projected to continuously support future generations of high-speed communications [1,2]. Photonic systems are widely available in the forms of optical transceiver modules and photonic integrated circuits (PICs) [1-3]. In both cases, the function of encoding an optical carrier wave with a high-frequency electronic data-transmission signal is required [4]. While it is possible to directly-modulate the laser with the high-frequency electrical data transmission, the modulation frequency is greatly limited due to the inability to overcome long relaxation times in addition to signal degradation effects such as non-linear distortions known as "frequency chirping" [4]. On the other hand, External modulation can provide significant advantages over directly-modulated lasers such as frequency chirp correction [5], phase modulation capability [4-6], and access to multilevel modulation formats that greatly increase the data transmission rate capacity without increasing the modulation frequency [6]. As a result, external modulation has been an established component in both optical transceivers and photonic integrated circuits [2,3].

With the increasing density of photonic integrated circuits on a chip level, a highly efficient optical modulator capable of operating on a low-power budget is needed. Several demonstrations of optical modulators fabricated from gallium arsenide [7], indium phosphide [8], and silicon [9] have been presented in the literature. However, these materials have been able to demonstrate modulation only over an interaction length of several millimeters or more. This is attributed to the centrosymmetric lattice structure of these materials that lead to low second-order nonlinear susceptibility (χ^2) and thus poor optical modulation and switching performance from these materials. For next-generation photonic integrated circuits that can require hundreds to thousands of optical modulators on a single chip [5], the interaction length of these devices becomes prohibitively large.

Conversely, gallium nitride (GaN) has been shown to possess higher first-order [10] and second-order nonlinear susceptibility [11] due to its non-centrosymmetric crystal. In addition to its wide band gap, ability to support a two-dimensional electron gas (2DEG) layer, and strong built-in polarization effects, GaN has advantageous material characteristics that can lead to a much smaller interaction length than other materials for highly efficient optical modulation and switching devices. In order to effectively characterize the optical modulation and switching efficiency of GaN, a Mach-Zehnder modulator structure is designed and fabricated to be electrically and optical characterized. These measurements can be used to extract the electro-optic coefficient and the V_π length in order to benchmark the performance of GaN-based devices for optical modulation and switching applications.

II. Design and Simulation

In order to fully utilize the unique advantages of GaN for optical modulation, a GaN/AlGaN interface grown on a silicon substrate is employed for this work and shown in Fig. 1. This wafer was obtained by a commercially available vendor. The GaN epitaxial structure grown by metal-organic chemical vapor deposition (MOCVD) consists of a silicon substrate that is 675 µm thick, a 700 nm AlGaN growth buffer layer, 380 nm of carbon doped GaN and 600 nm of unintentionally doped (UID) GaN. This epitaxial structure was chosen particularly since it supports a 2DEG layer in the AlGaN/GaN interface. The designed Mach-Zehnder modulating structure is optimized such that the supported propagating modes are impinged upon the 2DEG layer. Demonstrated in silicon-based modulating structures, the presence of excess charge carriers overlapping the optical mode can significantly increase free carrier absorption effects thereby modulating the optical signal [12]. Additionally, the presence or absence of a charge sheet creates an electric field which can be modulated by an applied voltage. The interaction of the electric field with the material controls its refractive index through the Pockels and Kerr effects [10, 11].

Utilizing multi-physics simulation software (COMSOL Multiphyiscs), the geometrical structure of the Mach-Zehnder waveguide arm is designed. Various parameters are considered during the design of the device such as single-mode operation, modal overlap with the 2DEG layer, and optical mode confinement. The waveguide arm structure and its supported propagating optical mode profile for a transmission wavelength of 980 nm is shown in Fig. 2. The mode index calculated for the fundamental mode is approximately 2.243 and the mode predominantly resides in the GaN region. In order to ensure single-mode operation, a design curve was mapped to determine the amount of modes supported for various geometrical waveguide structures. As shown in Fig. 3, through varying the ridge width and etch depth, for a given waveguide ridge width of 2 µm, the etch depth can vary between 100 to 300 nm while still maintaining single-mode performance. With further considerations for minimizing the optical mode loss in addition to maximal overlap between the optical mode and the 2DEG layer, a ridge width of 2 µm and 300 nm is selected as the optimal design.

The remainder of the Mach-Zehnder modulator is then designed based upon the optimized geometrical structure of the Mach-Zehnder waveguide arm. The designed Mach-Zehnder modulator and its key parameters are shown in Fig. 4. This structure consists of two parallel arms of varying lengths (500 µm, 1000 µm, and 2000 µm) in between two symmetrical 50/50 power Y-Branch splitters. The top arm is placed between two electrodes to apply a field through the propagating mode in order to induce an electro-optic phase shift for modulation. The arm separation is set at 10 µm to prevent coupling between the parallel arms. Consistent with the simulation results shown, the width of the waveguide arms

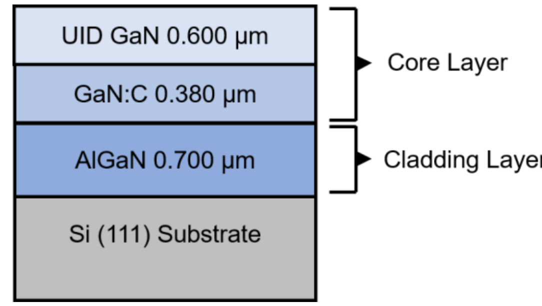

Fig. 1 Epitaxial layer structure of the GaN-on-Si material employed for fabrication in this work.

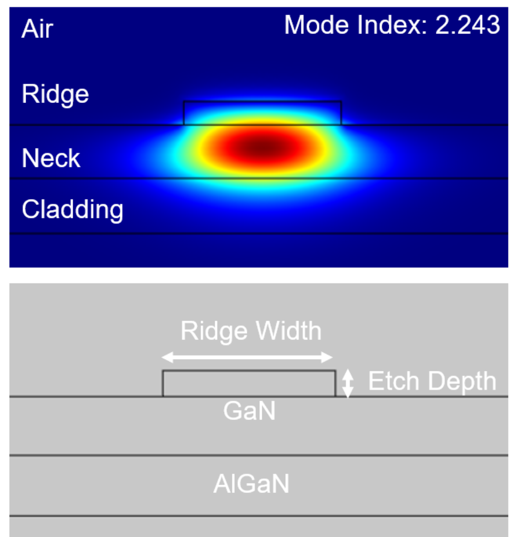

Fig. 2 Simulated electric-field mode profile for a 2 µm ridge width and 300 nm etch depth waveguide arm structure (top). Epitaxial structure of the simulated waveguide arm (bottom).

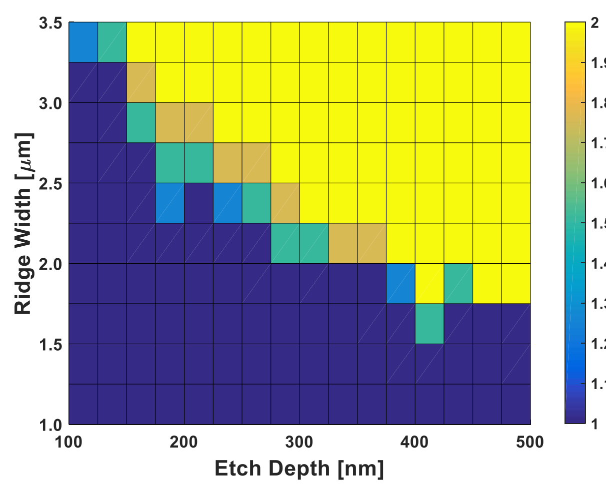

Fig. 3 Epitaxial layer structure of the GaN-on-Si material employed for fabrication in this work.

is designed to be 2 μm. It has been shown that y-branch splitters suffer from significant mode leakage when the branching angle is > 1° which result in a non-adiabatic mode evolution at the branching region [13,14]. Therefore, the branching angle is set to 0.65°.

III. Device Fabrication and measurement setup

The GaN-based Mach-Zehnder modulating structures are fabricated utilizing established semiconductor fabrication techniques. First, the GaN ridge waveguides are defined onto the surface of the sample. Silicon dioxide (SiO_2) is deposited as a dielectric hard mask and then lithographically patterned. The GaN is then dry-etched using an Oxford PlasmaLab 100 ICP-RIE system. A composition of BCl_3/Cl_2 gasses is used to obtain a smooth top-surface with anisotropic sidewalls. The device is then planarized with an electrically insulating polymer (BCB 3022-35) and fully cured via thermal baking under vacuum at 260°C for 5 hours. Using a PlasmaLab RIE system with a composition of CF_4/O_2 gasses, the insulating polymer is etched back until only approximately 300 nm remained above the top surface of the GaN ridge waveguide. Photoresist is then dispensed and patterned to provide an etch mask in order to selectively remove the insulating polymer from the surface of the interactive arm and a region for depositing a bottom electrode at the floor of the GaN ridge. Afterwards, metal electrodes are deposited via electron-beam evaporation. The metal deposited consists of Ti/Al (35/115 nm) layers [15] that were patterned via lithographic lift-off. The devices are annealed at 600°C for 5 minutes and a scanning electron microscope (SEM) is then used to capture the top view of the devices for inspection of quality and verification of device dimensions as shown in Fig. 5 and Fig. 6. The width of the GaN ridges arms fabricated are measured to be 1.64 μm. Utilizing a KLA Tencor Alpha-Step IQ profilometer, the height of the GaN ridge arm is measured to be 210 nm. Therefore, based on the design curve of Fig. 3, the device fabricated is suggested to be single-mode for a transmission wavelength of 980 nm.

Preliminary electrical measurements are being conducted at the time of writing. Further optical measurements in addition to iterative improvements on the fabrication and design of the device is expected to yield improved results.

IV. Conclusion

The wide band gap, ability to support a 2DEG layer, strong built-in polarization effects and non-centrosymmetric crystal of GaN present innate advantageous material properties for optical modulation and switching. However, GaN has yet to be utilized for optical networks and photonic integrated circuit applications. This work presents the exploration of GaN as a highly efficient optical modulation and switching material. Through the design and fabrication of a GaN-based Mach-Zehnder modulator, electrical and optical characterization of these device will provide a method of benchmarking GaN-based photonic devices for their optical modulation and switching efficiency.

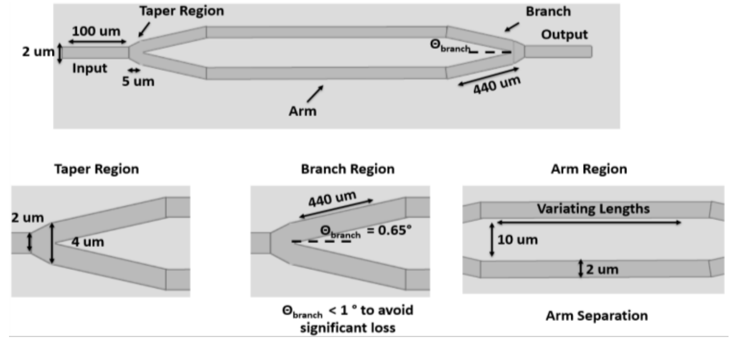

Fig. 4 Device schematic of the GaN-based Mach-Zehnder modulator with denoted key parameters.

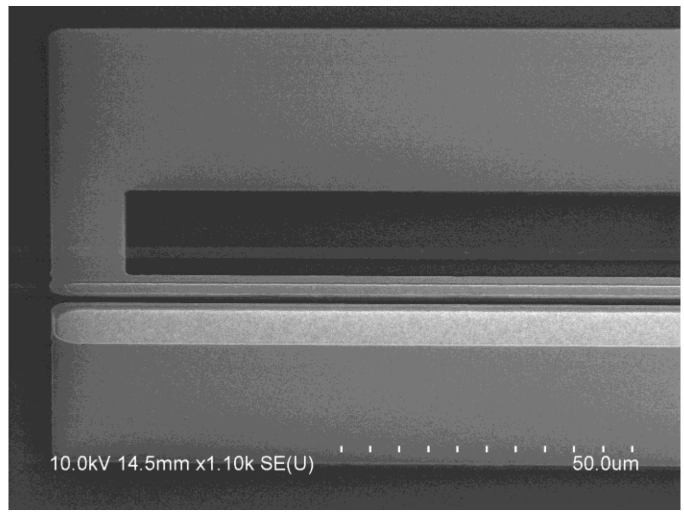

Fig. 5 SEM images showing a top-view of a fabricated GaN-based Mach-Zehnder modulator.

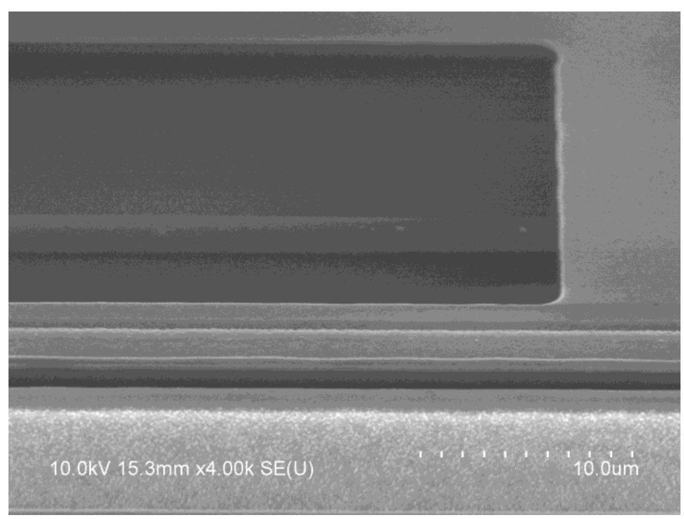

Fig. 6 SEM images showing an enlarged view that shows the ridge waveguide planarized under electrically insulating polymer.

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