Blue InGaN/GaN-based
Quantum Electroabsorption Modulators

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***Abstract*—We introduce InGaN/GaN-based quantum electroabsorption modulator that incorporates ~5 nm thick $In_{0.35}Ga_{0.65}N$/GaN quantum structures for operation in the blue spectral range of 420-430 nm. This device exhibits an optical absorption coefficient change of ~6000 cm^{-1} below the band edge at highly transmissive, blue region (at λ_{peak}=424 nm) with a 6 V swing and emits blue light (at λ_{peak}=440 nm) with an optical output power of 0.35 mW at a 20 mA current injection level. Unlike infrared III-V quantum modulators, this blue modulator shows a blue shift in its electroabsorption (for $\lambda < 418$ nm) with increasing applied field accross it, due to high alternating polarization fields in its quantum structures; this electroabsorption behavior is opposite to the conventional quantum confined Stark effect that features common red shift. This device holds great promise for > 10 GHz optical clock injection directly into silicon CMOS chips in the blue because of its low parasitic in-series resistance (< 100 Ω) and the possibility to make smaller device mesas for low capacitance (1.2 fF for a 10μmx10μm mesa size). Considering high-speed operation and high responsivity of silicon-on-insulator (SOI) photodetectors in the blue range, unlike in the infrared, this approach eliminates the need for on-chip hybrid integration of Si CMOS with III-V photodetectors. Furthermore, the efficient electroluminescence of this device makes it feasible to consider on-chip blue laser-modulator integration for a compact optical clocking scheme.**

Keywords-modulator; electroabsorption; quantum structure; GaN, InGaN.

I. INTRODUCTION

Silicon is a good material for photodetection of the blue light due to its short absorption depth in the blue (~100 nm at λ=400 nm). Therefore, Si photodetectors fabricated in standard CMOS process favorably lack the diffusion tail problem when detecting the blue light, unlike the infrared. Thus, optical clock injection in this region of the optical spectrum enables high-speed optical interconnects and clock injection directly into Si CMOS (e.g. at >10 Gbps), without having to use a hybrid integrated compound semiconductor detector on CMOS [1]. The recent advances in GaN optoelectronics technology have produced high-brightness light emitting diodes and laser diodes [2] across the entire visible spectrum down to the ultraviolet.

To utilize the technological progress in GaN growth and processing and to address the demand for optical clock injection directly into CMOS, we develop blue InGaN/GaN-based quantum electroabsorption modulators; here we present their epitaxial growth, fabrication and experimental characterization.

II. GROWTH AND FABRICATION

The architecture of our modulators is based on a surface-normal *p-i-n* structure that houses InGaN/GaN quantum structures in its intrinsic region. Our epitaxial wafers are grown on c-plane double side polished sapphire substrates using AIXTRON RF200/4 RF-S metal organic chemical vapor deposition (MOCVD) system located at Bilkent University Nanotechnology Research Center. In our MOCVD, TEGa (for quantum structures), TMGa (for bulk layers), TMIn, TMAl and NH_3 are used as precursors.

The epitaxial growth is initiated with a 14 nm thick GaN nucleation layer and a 200 nm thick GaN buffer layer, and is followed by a 690 nm thick Si doped GaN layer (n-type contact layer) and subsequently five ~5 nm thick $In_{0.35}Ga_{0.65}N$ quantum well and ~5 nm thick GaN barrier structures grown at 682°C, and is finalized with Mg doped 50 nm thick $Al_{0.1}Ga_{0.9}N$ and 120 nm thick GaN layers–both p-type, the latter being the contact cap layer.

We start the fabrication with the dehydrogenation of Mg dopants by annealing our epitaxial wafers at 750°C for 15 minutes under N_2 purge. We use standart lithography for reactive ion etching of device mesas and subsequent metallization steps. We evaporate Ni:Au and Ti:Al for p- and n-contacts, respectively, both being 10/100 nm thick. We finally apply rapid thermal annealing at 650°C for 1 minute. Our fabricated devices have mesa sizes varying from 10μmx10μm (corresponding to 1.2 fF) to 300μmx300μm (corresponding to 1.5 pF), with open optical windows to increase incident light coupling into the device in operation.

III. CHARACTERIZATION

We perform photoluminescence (PL) characterization at room temperature using a He-Cd laser as the excitation source at an excitation wavelength of 325 nm. We observe the PL peak to be at 430 nm as shown in Fig. 1a. This spectrum verifies that the quantum wells are made of $In_{0.35}Ga_{0.65}N$. Figure 1b shows the electroluminescence spectrum (EL) of the device for a driving current of 10 mA. The total optical power is 0.35 mW at a 20 mA injection current level and the EL peak wavelength is 440 nm.

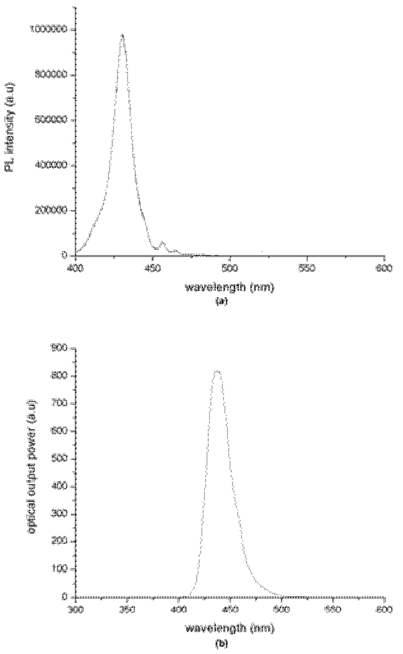

Figure 1. (a) Photoluminescense spectrum of the unprocessed epitaxial structure and (b) electroluminescense spectrum of the fabricated device.

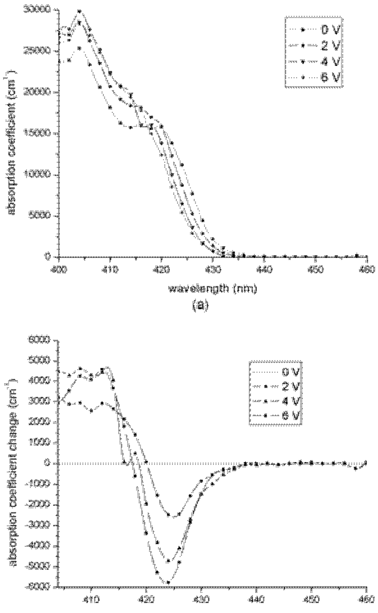

Figure 2. (a) Optical absorption spectra for various reverse bias voltages and (b) change in absorpton coefficient with respect to the absorption curve at 0 V.

We electrically characterize 300μmx300μm mesa devices using an HP4142 parameter analyzer. In forward bias, the in-series parasitic resistance is measured to be < 100 Ω. We also obtain the optical absorption spectra using photocurrent measurement setup that includes a Xenon lamp, a monochromator, a powermeter, a lock-in amplifier and a DC power supply for the application of various reverse bias voltages. Figure 2a shows the absorption spectra from 400 nm to 460 nm parameterized with respect to the reverse biases from 0 V to 6 V. We observe an inflection point on the absorption curves at 418 nm for our InGaN/GaN quantum structures, which is in agreement with the work of Friel *et al.* on AlGaN/GaN quantum structures [3]. This is an evidence of the polarization fields in GaN based quantum structures. Figure 2b shows that electroabsorption change is maximum at 424 nm with a change of ~6000 cm^{-1} with a 6 V swing (corresponding to 50 cm^{-1} absorption coefficient change for 1 V/μm field change). This is a good operating wavelength with low background absorption and large absorption change as shown in Figs. 2a and 2b.

We obtain the optical transmission spectra using an optical power meter and the same optical setup as in the photocurrent measurement. The transmission results agree with the photocurrent measurement including the same inflection point, although the stray light, not passing through the optical window of the modulator, renders a lower contrast (on/off) ratio in the transmission measurements.

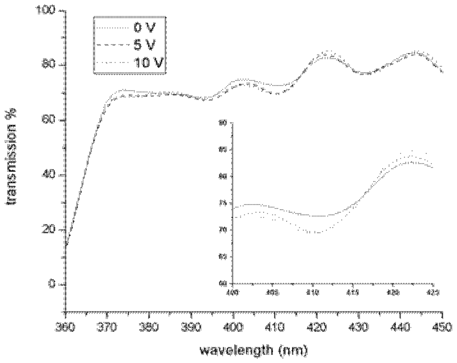

Figure 3. Transmission spectra for 0, 5 and 10 V reverse bias, with the inset zoomed in around the inflection point.

IV. CONCLUSIONS

We present blue InGaN/GaN-based quantum electroabsorption modulators for possible use in optical clock injection directly into Si CMOS in the blue. Unlike III-V modulators, these devices exhibit blue shift in their optical absorption with increasing external electric fields.

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