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Abstract: Gallium Nitride (GaN) based light-emitting diodes (LEDs) are being utilized in an ever expanding number of applications. The persistent issues, however, have been the use of alternating current (AC) to direct current (DC) converters and the inefficient p-type doping compared to n-type doping. Here, a novel hybrid AC InGaN quantum well (QW) LED without a p-GaN layer is demonstrated at 450 nm. A tunneling LED is fabricated through use of InGaN QWs, combined with a thin Al2O3 dielectric with NiO as the source of the holes. This hybrid InGaN LED utilizes Fowler-Nordheim tunneling and band bending in order to inject holes into the active region. Due to the symmetric nature of the tunneling, hole or electron injection through the top oxide layer leads to AC performance. Room temperature and cryogenic I-V measurements are performed to evaluate the tunneling mechanism. Tunneling of holes is found to lead to earlier device turn-on of ∼0.5 V compared with conventional blue LEDs at ∼2 V. The presented work can lead to a number of novel applications such as on-chip communication, monolithic integration with transistors, and LiFi.

Index Terms: LED, GaN, LiFi, Tunneling, MIS, AC.

1. Introduction

LEDs provide efficient solid-state lighting for homes, businesses, and display technology [1]–[4]. LEDs are also poised to be utilized in ever expanding applications such as visible light communication and LiFi [5], [6]. Conventional LEDs utilized for these applications are based on GaN, which is a wide bandgap semiconductor. The persistent issues for those LEDs, however, have been the requirement of AC to DC converters, and the inefficient p-type doping compared to n-type doping. Conventional LEDs conduct current in one direction, with corresponding light emission. Thus, AC to DC converters are often employed to prevent loss of half the signal from the LEDs. Though even with AC to DC conversion the high turn-on voltage of LEDs, ∼2 V for blue, can lead to a stroboscopic effect. On the aspect of p-type doping, Magnesium (Mg) is most commonly utilized for III-Nitrides, though it has a high activation energy - from 170 meV in GaN blue LEDs to >500 meV for AlGaN ultraviolet (UV) LEDs [7], [8]. At room temperature, this high activation energy equates to less than 1% acceptor ionization for p-GaN, in contrast to the silicon (Si) n-type dopant.
where vertically 100% of the donors are ionized. Furthermore, instead of p-GaN vertical growth, selective area p-type doping is also difficult due to the thermal degradation of the surface during the high temperature anneal necessary to incorporate Mg into the lattice [9]–[11]. The challenges of selective area doping for p-type GaN limit LED device integration. These limits often separate GaN transistors from LEDs, due to differences in growth structure. Therefore, it is important to pursue and explore alternative devices which can lead to integration between LEDs and transistors for emerging applications such as LiFi.

In order to address the lack of AC functionality and fundamental p-type issues, a novel approach is proposed and presented which removes the need for a p-GaN layer in the LED. Through this approach, AC functionality is demonstrated as a potential solution to eliminate the use of AC to DC converters [12]. However, to generate steady photon emission, both electrons and holes must be continuously supplied and radiatively recombine. Electrons can already be provided through impurity doping of Si, which has a low activation energy of 15 meV, allowing for complete ionization of donors at room temperature [13]. The intrinsic wide bandgap of 3.4 eV from GaN leads to a hole concentration of $10^{-10}$ cm$^{-3}$, which is worsened by vacancies which make the material slightly n-type [14]. Therefore, virtually no holes can be provided through thermal ionization or vacancies. To provide a steady source for holes, a material with excess holes must be utilized.

Here for our proposed tunneling GaN AC LED, holes are provided by a metal film stack and the formation of NiO, which together act as a source of both excess holes and electrons. The carriers tunnel through a dielectric film to be injected into the device. Use of NiO provides a better source of high density holes over other works with attempt to employ heavily doped GaN p-n junctions [15]. In this work, a Ti/Al/Ni/Ag metal film stack and a 50 nm Al$_2$O$_3$ dielectric film were used. Both the dielectric and metal stack were chosen due to the prevalence in GaN power devices to allow for potential integration. The epitaxial structure utilized is that of a conventional blue LED without the p-type layer, leaving the InGaN/GaN multiple quantum well (MQW) region on top. A schematic view of the hybrid device is shown in Fig. 1(a). The metal film stack is annealed which is thought to form NiO from the Al$_2$O$_3$ film. NiO is a p-type semiconductor with a bandgap of $\sim$3.6 eV and lowers the position of the valence band to promote hole tunneling. Uniform hole injection in the device provided by the NiO and metal can help overcome the current spreading and injection challenges without resorting to more complex designs [16]–[19]. The corresponding NiO band diagram under a forward bias is shown in Fig. 1(b). Application of a positive bias to the NiO reduces the effective barrier height and promotes Fowler-Nordheim (FN) tunneling [20], [21]. The band-offset on the conduction band is increased due to the positive bias, where electrons accumulate near the MQW surface and minimize tunneling.

Previous works have made use of metal-insulator-semiconductor (MIS) structures with NiO and MgO as the p-type and insulating layers respectively [20], [21]. Work by Wang, et. al. has previously showed use of 50 nm of MgO to be optimal for electron suppression, hole injection, and surface
passivation [21]. These works are expanded upon here, making use of Al₂O₃ which shows lower interface states with GaN and more advantageous band alignment for hole injection [22], [23]. For the first time, this work is also applied to InGaN/GaN MQWs to further optimize device performance, along with the use of an optimized metal stack. The holes provided through tunneling open up the possibility of device integration with existing GaN technologies such as high electron mobility transistors (HEMTs). Furthermore, a novel introduction of AC functionality is demonstrated from the tunneling GaN LED in this work.

2. Device Fabrication

An InGaN/GaN blue LED at 450 nm without the p-type GaN layer was utilized in this work. The growth was performed on a sapphire substrate with 2.5 µm of unintentionally doped GaN (~10¹⁶ cm⁻³ background doping), 2 µm of n-GaN (~7 × 10¹⁸ cm⁻³), and 6 pairs of InGaN/GaN MQWs on top. The MQWs were composed of 3 nm of In₀.₁₃Ga₀.₈₇N with 12.5 nm GaN barriers. To fabricate the devices, 50 nm of Al₂O₃ was first deposited using an Ultratech S200 thermal atomic layer deposition (ALD) system. Openings were patterned in the Al₂O₃ layer through a photoresist mask using a buffered oxide etch (BOE). Next, lift-off resist and photoresist were coated and patterned. A 14/140/30/100 nm of Ti/Al/Ni/Ag were deposited through thermal evaporation and lifted-off, forming the capacitor and substrate contact. The capacitor and substrate contact sizes were each 100 µm². A thermal annealing process was performed in a nitrogen ambient environment at 850 °C for 30 seconds to diffuse the metal to form a NiO layer, as well as forming an ohmic contact to the InGaN/GaN [20]. Use of the four metal layers was found to produce both increased photon emission and uniformity. Separate experiments were run with Ti/Al and Ni/Ag, finding no emission in the case of Ti/Al and weaker emission in the case of Ni/Ag. Annealing introduced roughness to the metal layer due to the diffusion of Al, with the common formation of Ni-Al clusters [24], [25].

3. Results and Discussion

Electrical and optical characterizations were performed on the fabricated hybrid AC LEDs. The I-V data collected for a single device are shown in Fig. 2(a). The measured I-V curve is comparable to reported measurements of previous NiO/MgO tunnel diodes, though with a lower turn-on voltage due to the reduced band offsets compared with MgO [20], [21]. Under forward bias, the valance band offset is lowered and holes are injected into the MQW to recombine with electrons. While under reverse bias, the offset for the conduction band is lowered, and electrons supplied by the metal can tunnel through the insulator. In order to better clarify the tunneling mechanism, both room temperature measurements and cryogenic measurements with liquid nitrogen were
performed for the p-type-less LED. At room temperature, significant noise was observed and can be attributed to interface states and traps states within the oxide film. Low temperature measurements with liquid nitrogen are used to study the impact of these interface states on the device. It can be seen that the I-V curve at low temperature is much smoother due to freeze-out of interface and trap states. Electroluminescence (EL) was still observed even when the sample was at cryogenic temperatures. Looking at both tested temperatures, rectifying behavior was still recorded. Due to the rectification and observed light emission at low temperature, the hole injection is attributed to FN tunneling instead of a trap-assisted tunneling mechanism which is more temperature dependent [26].

Hole injection through band bending and tunneling instead of impurity doping allows the device to turn-on when a low forward bias is applied of $\sim 0.5$ V, as seen in Fig. 2(b) from a log-scale of the I-V. A low forward bias bends the energy bands of the dielectric enough to promote FN tunneling. This contrasts with conventional LEDs that have a higher turn on voltage around the value of the bandgap of 2.75 eV. The tunneling mechanism can also allow for a faster response time in an LED when compared to conventional diffusion mechanisms. Excess forward voltages above 18 V are seen to induce breakdown of the capacitor dielectric. Once the capacitor has broken down, current flows in excess, however there was no longer observed light emission due the inability of the oxide to confine the opposite charge type at the surface.

Room temperature EL measurements were next performed, with results shown in Fig. 3. Significant photon emission begins at a forward bias of 6 V. Increasing the applied voltage from 6 V to 8 V leads to increased light emission by 4.25x, as more holes are injected through the oxide into the MQWs. The light emission is at 450 nm which corresponds to the bandgap of the InGaN QW. The linewidth was also narrower at $\sim 20$ nm compared to previously reported tunneling devices which had an extended tail, as the MQWs better confine carriers [21]. The In$_{0.13}$Ga$_{0.87}$N has a bandgap of $\sim 2.75$ eV, where the intrinsic carrier concentration is at a level of $10^{-9}$ cm$^{-3}$, meaning tunneling must be the sole source of holes. Light was seen to be emitted primarily around the edges of the capacitor, as the thick metal blocks the light. Light emission at lower voltages may be observed if collected from the backside of the device. In future iterations, a flip-chip design would be effective for enhancing light extraction efficiency.

EL measurements were also performed at different AC driving frequencies on a single device at room temperature, as shown by Fig. 4, driven with a voltage of 11 V. The frequencies tested were 10 Hz, 33 Hz, and 50 Hz. The peak emission wavelengths from the EL spectra at each frequency remained constant at 450 nm with almost constant bandwidth. Future works on testing at higher frequencies will be done, where it is suspected that the tunneling mechanism can react faster compared to the higher capacitance associated with p-n junctions.
Fig. 4. EL spectrum of the p-type-less LED under different frequencies.

Fig. 5. I-V curve of hybrid LED AC behavior, probing two capacitors. Insets show light emission in forward and reverse bias, along with the near field image of the device.

The AC aspect of the hybrid LED comes from utilization of the tunneling mechanism between two capacitors. Since the tunneling GaN LED can inject holes in forward bias, and electrons in reverse, the device acts symmetrically. The symmetry allows for more uniform performance, regardless of applied polarity of the voltage. Therefore, by probing two capacitors, EL can be produced in both forward and reverse bias. The capacitor that is in forward bias will supply holes and emit light, while the other capacitor is the source of injected electrons. An I-V curve showing the AC behavior is provided in Fig. 5, with insets showing the light emission on either ends and the equivalent circuit diagram. The equivalent circuit diagram is two diodes in parallel, but with opposite directions, where one LED is always on given an applied bias of either polarity. Both sides of the I-V curve are shown to be roughly symmetric, due to the symmetric electron/hole tunneling nature of the capacitors. An advantage of this two terminal LED device is that an AC waveform can be fed directly in, without need for an external AC to DC converter or loss of half the input power. Due to the continuum created by the tunneling current, the resulting AC signal will have minimal loss, as is the case with conventional GaN diodes with a high positive turn-on voltage of \( \sim 2 \) V. This novel hybrid AC LED can lead to a number of exciting applications such as on-chip communication, monolithic integration with transistors, and LiFi.

4. Conclusion
In summary, a novel tunneling GaN LED was presented. This device makes use of band bending and carrier tunneling in order to inject holes directly into the MQW region. Tunneling allows
earlier device turn-on of $\sim$0.5 V compared with conventional LEDs at $\sim$2 V, a reduction of 75%. Cryogenic testing was performed on the device which points towards FN tunneling, as opposed to trap-assisted tunneling. EL measurements showed emission wavelengths corresponding to the bandgap of the MQW, with no variation in wavelength or intensity at different driving frequencies. The symmetric tunneling of electrons and holes leads to AC performance, with a continuous I-V curve and minimal signal loss. These results could open the door to emerging applications such as on-chip communications, monolithic LED integration with transistors, and signal processing with LiFi.

### References


