Demonstration of 372 nm Micropillar Light Emitting Diodes Using Novel Ni/Au/Ni Dry Etch Mask and Ohmic Contact

Matthew Seitz[±], Matthew Hartensveld, Bryan Melanson, and Jing Zhang[‡]
[1]*Department of Electrical and Microelectronics Engineering, Rochester Institute of Technology, Rochester, NY 14623, USA*
[±]*Email: ms3897@rit.edu , [‡]Email: jzeme@rit.edu*

Abstract: Micropillar InGaN/AlGaN LEDs were fabricated using a novel Ni/Au/Ni etching mask. This Ni/Au/Ni structure effectively combines a good ohmic contact and etching mask into a single structure, allowing for demonstration of 372 nm micropillar LEDs.

The gallium nitride (GaN) materials system is of great research interest, due in part to its highly tunable peak emission wavelength when serving as active region for photonic/optoelectronic devices. By alloying GaN with aluminum or indium, the peak emission wavelength from those active regions can be tuned from deep ultraviolet (UV) to red. Most famously, GaN and InGaN enabled the fabrication of blue and violet light emitting diodes (LEDs) and laser diodes (LDs) [1]. GaN-based LEDs continue to find applications in sterilization, water purification, and in other biomedical devices [2]. These emitters have also enabled fabrication of full-color GaN-based displays [3]. As the resolution of these displays increases, LED emitters must shrink in size to serve as individual pixels. One solution to realize high-resolution display has been to move from planar LED device geometries to vertical micropillar LEDs. While these micropillar geometries dramatically reduce LED footprint, their small size introduces new challenges to device fabrication and realization.

From our previous works, a top-down approach has been developed to form micropillar/nanowire LEDs covering UV to visible wavelengths [4, 5]. Those III-Nitride high aspect ratio micropillar structures require long dry etch durations to form, necessitating highly durable etching masks. Metal masks are often used, typically formed from Ni or Cr, in place of the photoresists often used for more shallow etching. Our fabrication process typically involves lithographic patterning and deposition of a Ni metal mask, followed by dry etching with a Cl-Ar plasma. After removal of the etch mask, a different metal structure must be selectively deposited onto the tops of these pillars/wires to act as n-type contact. As devices shrink to the microscale and nanoscale, this deposition becomes increasingly challenging. To resolve this issue, one solution is to planarize the wafer with a polymer, covering all micropillars/nanowires. This coating can then be slowly and carefully etched back to reveal just the tips of the micropillars/nanowires. Once the tips are exposed, p-type metal contacts can be deposited as a universal contact, or a deposit and lift off process can be used to fabricate individual device contacts. Another approach is to use photolithography to pattern these p-type contacts. However, the alignment tolerance decreases quickly as device footprints shrink and any misalignment can lead to device failures and reduced yield.

In this work, we propose a new solution to these challenges and demonstrate the successful fabrication of UV micropillar LEDs at 372 nm. By embedding the device's ohmic contact within the dry etch mask, this novel single structure can serve two purposes – both as an effective, durable dry etching mask and also as a functional, p-type ohmic electrical contact. Specifically, here we proposed a novel Ni/Au/Ni contact structure, which was developed through a series of transmission line method (TLM) measurements. The first round of optimization utilized the same 20 nm bottom layer of Ni and 200 nm top layer for all test structures. Between these two Ni layers, a layer of Au was deposited, varying in thickness from 20 nm to 80 nm. After deposition, all structures were annealed at 500˚C for 5 minutes in an oxygen environment prior to testing. These different structures were compared to a 20 nm single Ni layer contact which served as our baseline. Our measurements show that 20 nm Ni/20 nm Au/200 nm Ni and 20 nm Ni/40 nm Au/200 nm Ni contacts show the lowest contact resistance – approximately 75% lower than the plain Ni contact. After observing this significant improvement, the 20 nm Ni/20 nm Au/200 nm Ni contact structure was selected for our micropillar LEDs. This structure and exact layer thicknesses can continue to be optimized to further reduce the contact resistance.

After completing our first round of optimization on the contact metal stack structure, we used this novel process to fabricate a set of micropillar UV LED devices. These LEDs were fabricated using a c-plane epitaxial stack similar to that used by Huang *et al* [6], consisting of a 20 nm AlN buffer layer, a 2 µm undoped GaN layer, a 2.5 µm n-AlGaN cladding layer, InGaN/AlGaN MQW, a 15 nm p-AlGaN cladding layer, and finally a 200 nm p-GaN contact layer, grown on a sapphire substrate via metal organic chemical vapor deposition (MOCVD). The MQW region consists of ten periods of 3 nm InGaN wells with 11 nm AlGaN barriers. As shown in Figure 1(a), below, the wafer was first coated in photoresist and patterned for deposition of the p-contact and etching mask. Based on our previous results, a 20 nm Ni layer was first deposited, followed by a 20 nm Au layer, and capped with a 200 nm Ni layer, each deposited via thermal evaporation. After lift-off, a Cl-Ar plasma (40 sccm Cl_2/10 sccm Ar, 500 W power, 225 W forward power, 3.2 minute etch duration) was used to etch these 2.5 µm diameter micropillar LEDs to a depth of 1.4 µm, as shown in Figure 1(b). After this dry etch, a second, wet etch was also performed to ensure that micropillar sidewalls are completely vertical and to remove any etch grass caused by micromasking. The wafer was immersed in a solution of 40% AZ400K (a photoresist developer containing KOH), heated to 80˚C for 15 minutes to perform this etch. Structures were examined via scanning electron microscope (SEM) following this wet etch and imaged (Figure 1(b)). Fabrication was finalized with the thermal deposition of 40 nm Ti and 200 nm Ni to serve as a self-aligned, universal n-contact.

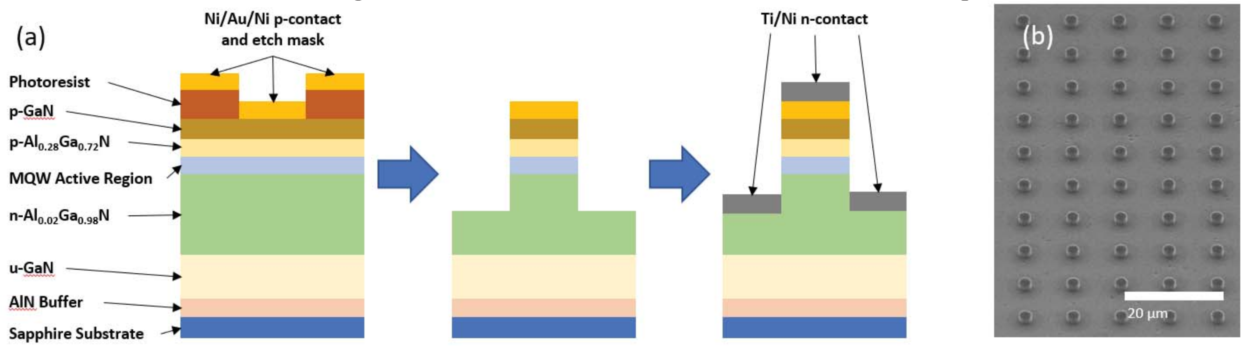

Figure 1(a): General process flow for micropillar LEDs using novel Ni/Au/Ni hard mask and electrical contact. 1(b): SEM image of micropillar LED array after dry and wet etching

After etching, a highly uniform array of 2.5 µm diameter micropillars with a 10 µm pitch was formed, as shown in the SEM image (Figure 1(b)). These encouraging results confirm that our novel Ni/Au/Ni structure can serve as an effective dry etch mask. Electrical measurements of one individual micropillar UV LED, shown in Figure 2(a), reveals a turn on voltage of approximately 5 V. This is a higher turn on voltage than has been reported by other groups and can be reduced with additional optimization of the Ni/Au/Ni layer structure. Electroluminescence (EL) results show a peak emission wavelength of 372 nm and a narrow linewidth of 11 nm from individual micropillar UV LED. The peak EL intensity varies with applied current, increasing by a factor of 25 when current is increased from 70 µA to 150 µA, as shown in Figure 2(b).

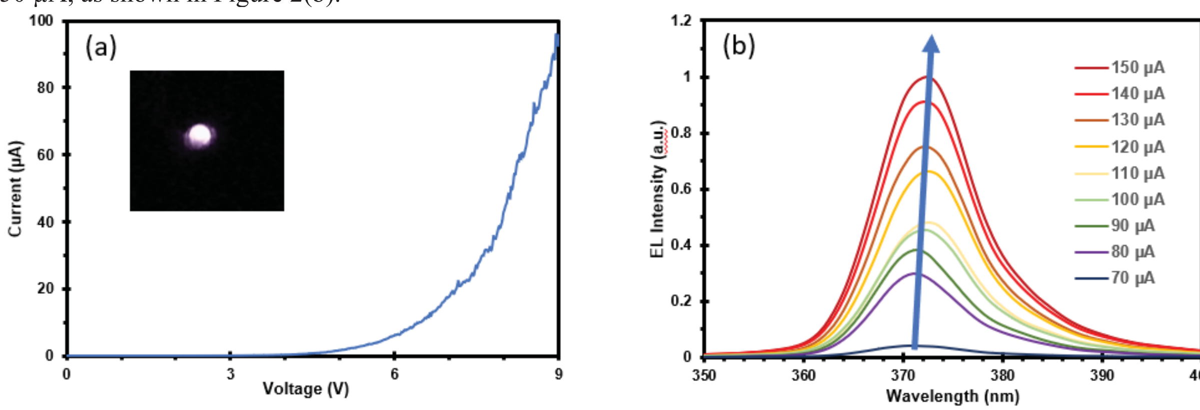

Figure 2(a): Electrical properties of individual micropillar UV LED, Inset – a single illuminated micropillar LED. 2(b): EL spectra of individual micropillar LED at a range of driving currents.

In conclusion, we have successfully demonstrated for the first time a Ni/Au/Ni structure which can be used as both an effective dry etching mask and as a p-type ohmic contact for electrically driven UV micropillar LEDs. This novel structure can be used to greatly simplify the fabrication of high aspect ratio devices by avoiding the need for the challenging post-etch deposition of p-type electrical contacts. This novel Ni/Au/Ni structure and fabrication process shows great promise for realization of high aspect ratio micropillar LEDs.

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