Deep-UV photonic devices enabled by distributed polarization doping

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ABSTRACT

Semiconductor light emitting devices that produce photons in the ultraviolet or deep-ultraviolet wavelengths by direct current injection have become possible due to advances in the physics and materials science of ultrawide bandgap semiconductors based on aluminum nitride. These unique photonic devices can produce photons up to the direct energy gap of aluminum nitride which is ~6.1 eV corresponding to ~203 nm. Here, we describe the key advances in physics and materials science that enabled these remarkable short wavelength photonic devices that stand to make a dramatic impact on future applications of photonics to biology, healthcare, and beyond.

Keywords: Semiconductor, LED, laser, quantum well, polarization, doping, ultraviolet

1. INTRODUCTION

There is no dearth of options for tabletop light sources that emit in the ultraviolet (UV) and deep-UV spectral window spanning wavelengths from 200 nm - 300 nm. For example, excimer lasers and high-harmonic YAG lasers generate 10s of milliwatts to 1 watt power levels and are widely used for applications ranging from lithography to disinfection and materials processing. But the story is different for semiconductor diode lasers and LEDs that offer unique opportunities owing to their microscopic size, high wall plug efficiency, ability of fast to ultrafast direct modulation, and a host of advantages of integration of multiple devices and massively parallel processing that come with the semiconductor eco-system. Semiconductor UV devices have struggled for a long time to harness the intrinsic advantages of this platform: the going gets increasingly difficult as the wavelengths get shorter and closer to 200 nm. This problem is intimately tied to the physics and materials science of the semiconductor structures used to make the photonic devices.

Semiconductors typically emit light when a filled electron in the conduction band falls into a hole or empty state in the valence band to emit a photon. This interband radiative transition is most efficient when the semiconductor is direct bandgap that possesses a strong interband optical dipole matrix element between the s-like orbitals of states at the bottom of the conduction band and p-like orbitals at the top of the valence band of the semiconductor bandstructure [1]. The ultrawide bandgap semiconductor aluminum nitride (AlN) and its alloys with gallium nitride (GaN), AlGaN, fit this bill, additionally providing the material combinations desired for boosting the matrix elements using quantum wells and quantum dots in heterostructures [2]. Blue LEDs and lasers use InGaN quantum wells embedded in GaN where the composition and thickness of wells and barriers determine the wavelength of emitted photons in the blue (or green and longer) spectral range. By analogy, for deep-UV light emitters it is necessary to use AlGaN quantum wells of the appropriate thickness (typically ~few nanometers) and compositions (ranging from 50-100% aluminum content) [3].

These Al(Ga)N/AlN heterostructures are now quite reliably realized, primarily by metalorganic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE) growth techniques. High optical emission efficiencies are achieved in chemically clean heterostructures by carefully controlling the epitaxial conditions on AlN-on-sapphire templates. Dramatic reduction of structural defects is enabled by using bulk AlN substrates (instead of templates); such bulk substrates now are available up to 100 mm diameter sizes. The research community struggled with controlling and reducing chemical and structural defects that introduce non-radiative processes that reduce IQE. Today this problem, though not eliminated, is at a stage that it does not limit the device performance. An interesting feature of the deep-UV light emission physics that differs from conventional blue emitters is that in beyond ~60% Al content AlGaN, the ordering of the valence band reverses, with the crystal-field hole (CH) band at the top, and the light hole (LH) and heavy hole (HH) bands below the CH. Because of the symmetry, the CB to CH transition produces photons whose momentum is in-plane, and the light preferentially moves laterally towards the edges of the wafer, instead of vertically towards the surfaces. This feature is useful for edge-emitting lasers but must be engineered for surface light extraction in UV LEDs.

Considering excellent optical properties of AlGaN quantum wells, what makes deep-UV semiconductor lasers difficult? An important characteristic of semiconductor laser diodes that makes them of such high practical value is that injection of a small amount of current (in 10s of mA) produces light output in milliwatts. The current flows by injection of electrons

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into the quantum well active region from a n-type side, and injection of holes into the same active region from the p-type side; the device is a pn junction diode. Nearly all the energy from the voltage supply is spent in creating the photon in an ideal pn junction emitter: the emitted photon is nearly of the same energy as the voltage times the charge on an electron. But for this to happen, it is necessary that the n-type semiconductor has an abundance of electrons in the conduction band and the p-type semiconductor has an abundance of holes in the valence band. To convert the spontaneous emission desired in LEDs at low injection currents to stimulated emission desired in lasers, it is necessary to simultaneously provide ample free carriers to the active region to cross the gain threshold and build an optical resonator cavity with sufficient feedback.

For blue laser diodes, the lack of mobile holes in GaN delayed successful laser oscillations for several decades till mid 1990s; the now well-known discovery of Mg doping of GaN was the key enabling breakthrough [4,5], which rapidly enabled solid state lighting. It was difficult to dope GaN with acceptors shallow enough that made it sufficiently p-type. The best acceptor, Mg, introduces an energy eigenvalue at ~180 meV above the valence band edge of GaN. This makes it not a very efficient dopant: at room temperature by Arrhenius relation only a few percent of the Mg acceptors are ionized to provide holes. The low hole density is compounded by the low hole mobility: the resulting p-type layers are of an order of magnitude or higher electrical resistivity than the n-type layers. Therefore, the device designer must play a balancing act in the design of blue laser diodes. The Mg-doped p-GaN layers must be close enough to the active region for electrical injection of holes, but far enough to prevent optical loss.

As deep an acceptor Mg is for GaN, the acceptor eigenvalue for Mg in AlN is so far from the valence band edge that thermal activation at room temperature produces nearly no mobile holes, making it unusable. Even the Si donor energy eigenvalue is ~250 meV below the conduction band edge of AlN, making it inefficient and unusable for n-type layers needed for electron injection in UV LEDs and lasers. While one can get around the n-type problem with the use of high Al composition AlGaN layers up to ~80% Al that show good n-type conductivity with Si doping, the situation is much more severe for p-type conductivity. The solution to this problem came from a different angle and new physics of semiconductors, which will be the major topic of discussion of this presentation.

AlN is central to UV photonics, but it needs to team with GaN and AlGaN to overcome its electrical resistivity. The physics of polarization discontinuity at heterojunctions dictates that when a thin layer of GaN is grown on the N-polar face of AlN, a mobile 2D electron gas should form at the GaN side without any donor doping due to the polarization discontinuity and the energy band offset. That this is indeed the case was discovered only recently [6]. By symmetry, when a thin layer of GaN is grown on the metal-polar face of AlN, a mobile 2D hole gas should form on the GaN side, *without any Mg acceptor dopants*! That this is indeed the case was observed for the first time in 2019 [7]. The duality of this is quite remarkable, because using polarization effects, highly n-type and p-type regions are created without any dopants at all, but only at the interfaces inside GaN. To make it useful for a LED or a laser diode, the holes and electrons must flow vertically from electrical contacts towards the optically active regions containing quantum wells (or dots). This requires the energy band offsets to be removed for efficient injection by grading, and the polarization to be *distributed* instead of being confined to a sharp interface. Distributed polarization doping (DPD) was realized for n-type layers for the first time in metal-polar graded AlGaN layers grown on GaN layers [8]. The first p-type DPD was realized in N-polar graded AlGaN layers grown on GaN [9]. It was the first photonic device (a visible LED) to implement this new technique of doping in polar semiconductors.

Using bulk AlN substrates, in 2019 the first electrically injected deep-UV laser diode using p-injection layers using DPD, and n-injection layers using Si-doped AlGaN, was finally realized after a long struggle [10]. Rapid progress is being made now with continuous wave lasing at room temperature and extending to various UV wavelengths [11]. While the shortest wavelength laser to be made with Mg doped hole injectors is >315 nm, DPD p-type doping has enabled semiconductor lasers to cross the "300 nm barrier" down to ~270 nm today. DPD p-type ultrawide bandgap layers have been characterized and found to host 3d hole gases as one would expect from the physics of polarization [12, 13, 14].

So, what are the challenges moving forward? While DPD does create mobile electrons and holes without acceptor or donor dopants, it is still necessary to form low-resistance ohmic contacts to these conductive layers for practical semiconductor devices. Because of the ultrawide bandgap nature of the AlGaN and AlN layers used in the UV LEDs and lasers, direct metal contacts to the valence band holes of UWBG regions are prohibitive because there are no metals with the appropriate work function. To make low-resistance metal/semiconductor contacts to connect to the DPD layers, Mg doping in a narrower bandgap GaN or InGaN region is used, and it is quite practically integrated with the contact metal scheme [15,16]. Nevertheless, the search should continue for shallow dopants for UWBG AlN [e.g. see 17], because it can assist in contact formation. It is likely going to remain preferable to use DPD close to the active regions to prevent optical losses due to incomplete ionization in the active regions. An added benefit of the DPD is it provides optical confinement because it has a graded refractive index, another freebie for the laser device designer.

Finally, deep-UV laser diodes, as well as far-UV C LEDs at even shorter wavelengths today suffer device degradation upon prolonged operation. A solution must be found to increase their practical usage. While DPD provides the photonic device designer a new tool in the delicate balancing act with a new 21st century discovery of doping without chemical dopants, its several ramifications in LED and laser design, operation, and reliability offer an exciting playground for unearthing new properties of the underlying semiconductor materials and device physics itself, and is expected to remain an active area of scientific research and high technological importance for the coming decades.

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