Exploring Possibility of Replacing 248 nm KrF with AlGaN LED in DUV Photolithography

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I. Abstract:

With the increasing enhancements[1] on AlGaN LED's external quantum efficiency(EQE) and light output power and the trending popularity of UV (ultra-violet) LED photolithography, there is a glimpse that we may utilize AlGaN to replace 248 nm KrF in DUV (deep ultra-violet) lithography with a better power consumption efficiency and instantaneous on/off capability (ideal for high volume production) at lower fabrication cost. The key parameters for AlGaN LED to replace 248 nm KrF in DUV photolithography are peak wavelength of the spectrum (248 nm), optical power output around 10 - 30 W, size due to restraint of optical system and targeted expose image field (20*20 mm^2 wafer die), and considerations of power efficiency and fabrication cost. In this project, the aim is to simulate a 2D AlGaN LED with several state-of-art internal quantum efficiency(IQE) enhancement techniques to show how an AlGaN LED can meet the above requirement as a "free-form" light source.

II. Introduction

LED is an extended light source, meaning that increasing light density often correlates to increasing size. Thus, with size constraint, the significance of making DUV LED photolithography viable is the efficiency. The EQE of LED is defined as

$$\eta_{EQE} = \frac{photons_{emitted}}{electrons_{injected}} = \eta_{IQE} + \eta_{LEE}$$

where LEE is light extraction efficiency, defined by how much portion of generated photons can be emitted. Knowing these critical parameters, we can then highlight factors that limit these efficiency and state-of-art improvement to them. The IQE of AlGaN is mostly limited by the quality of the AlGaN crystal (threading dislocation density caused by epitaxial processes) and the low hole doping concentration (Mg's high activation energy[2]); LEE is limited by the GaN layer that provides more hole injections. Current IQE improvements that can be simulated on Crosslight are holes and current injections and electron blocking layer: the hole injection improvement is normally done by adding a p-GaN layer to provide extra holes; the electron injection[3] is done by implementing a depletion region to resist the polarization in the quantum well; and electron block layer[4] is to ensure most electrons recombine within quantum wells. We need to note that current improvements are mostly done for 280-300 nm AlGaN, so in the later simulation section, adjustments of those improvements will be discussed.

Most 248 nm KrF DUV photolithography steppers are scanning for 200mm wafer with 20*20 mm^2 die as the exposed image field with exposure dose of 30mJ/cm^2.[5] However, as we all know about the cons of using a laser, low power efficiency of 0.5% - 5% as wall-plug efficiency(WPE), expensive cost from \$11,000 to \$62950, high volume production limited by pulses, and comparably short lifetime due to contaminations in the gain medium,[6] we need to highlight those aspects pertaining to LEDs. Even for a low IQE LED like AlGaN, the WPE is normally around 10% to 35.3% varying due to different contact materials and injection current.[1] As for the cost of AlGaN, the high quality AlGaN may be expensive but not to the scale of $11000 (ignoring the sink cost of instruments used). Since LED is not a pulse/switch source but a broad bandwidth one, we do not need to modulate the pulse frequency for high volume production but use a filter for narrower band and scanning control. Yet, the stability and lifetime of the AlGaN (especially with high Al mol) is not optimistic: the EQE drops significantly to half of origin after 50 hours aging.[7]

This project is composed of three part, first I would specify the DUV requirements need to be met by the DUV AlGaN LED; then, tI will elaborate on the approach of my simulation, from tuning to 248 nm to updating improvement structures; lastly, I will be using the simulation result to visualize a theoretically feasible AlGaN 248 nm DUV Photolithography light source.

III. DUV Requirements and Pre-Simulation AlGaN Design Considerations

The hard requirements of the DUV photolithography are highly related to its optical system: NA of the annular ring, NA of the wafer, exposure dose/optical power output, and the peak wavelength at 248 nm. Despite the 248 nm hard requirement due to the properties of common photoresists (PR) used in DUV photolithography, the other parameters serve more as a reference and the project aims to add some degree of freedom to potentially fit different optical systems.

param.	Wavelength	Optical Power	$NA_{light\ source}$	NA_{wafer}	Exposed image field
spec.	248 nm	10 W	0.54	0.63 - 0.75	$(20\sqrt{2})^2$ mm^2

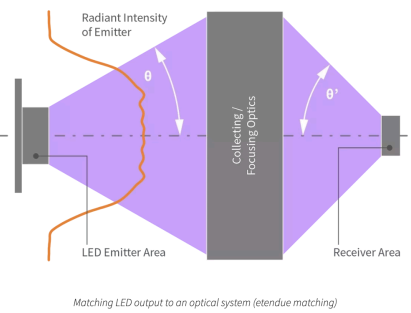


Table a and Figure 1, figure 1 cited from primelite website[11].

According to the specifications of DUV photolithography from several references[8][9][10] (table a.) , the minimum NA at wafer level is 0.63; at annular ring, NA=0.54; our target wafer exposure is 20*20 mm^2 die ($(20\sqrt{2})^2$ mm^2 as a circle to cover it). We can use estimation of Etendue[11] ($NA_1^2 * A_1 = NA_2^2 * A_2$, NA as numerical aperture and A as area, see figure 1) and use the information above to design our DUV LED light source.

$0.54^2 A_{light} = 0.63^2 (20\sqrt{2})^2; A_{light} \approx 1088.888889 mm^2$ $radius \approx 18.617 mm$

The expected power for the light source is 10~30 W due to uncalculated transmission loss in optical systems(reflections and absorptions of lens and PR)
and we can design the light source accordingly. The common light forms are conventional, annular, quadrupole, and dipole[9] . The project aims to set the size of AlGaN LED as micro-LED to have slightly lower IQE while fitting different forms by packing the wafer into a closed pack circle with $radius \approx 18.617 mm$ and the light form will be modulated by the polarization filter; the mesas of the LEDs are selected to light with required total optical output power for different forms the stepping is used. We do need to consider that the uniformity of the closed packed LED generated patterns will not be great since the mesas are in the form of rectangles

instead of circles, but we can increase the optical output power to higher than original for the polarization filter to better modulate both uniformity and shape (source mask optimization[12]).

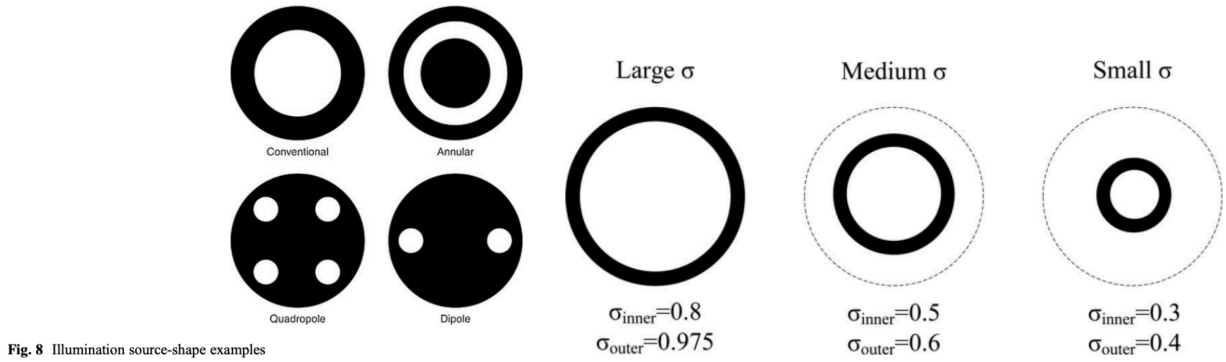


Figure 2 and 3; 2 cited from [9] and 3 cited from [11]

An order of 10^{-3} from 18.617 mm sought to be achieved, so the size of our LED shall be around the size of 1- 10 um; also, the lens of the optical systems to receive light from AlGaN LED is very limited due to the high refractive index of high Al mol AlGaN[13](n_{AlGaN}~2.19, see Figure 4)- arcsin(0.54/2.19) = 14.27°. Such a small angle indicates that that lens is constrained to be almost the same size as the light source's.

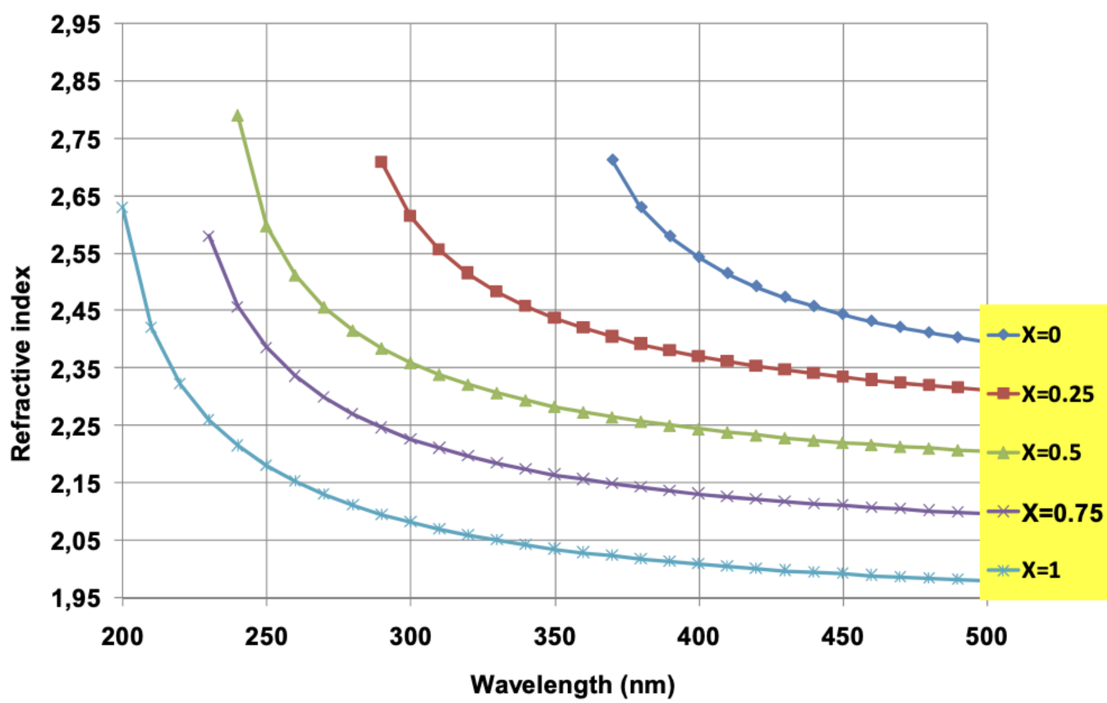
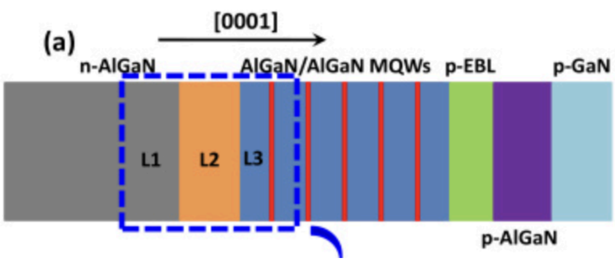


Figure 4; $Al_xGa_{1-x}N$ and the corresponding refractive index according to wavelength[13]

IV. Modeling of 248nm DUV AlGaN LED in Crosslight

I started with modeling the similar structure of reference [3] (without n-substrate stepping structure at first) and tuned the structure to have 248nm as its peak wavelength.



From the material library of Crosslight, we know that the bandgap of $Al_xGa_{1-x}N$ under 300k for 248 nm is x=0.661. However, when we simulated it with Crosslight, the spectrum is actually left shifted, so we slightly increase the x to 0.75, 0.78 and 0.8.

Figure 5,cited from [3], AlGaN LED structure.

Throughout the modification, the p-GaN hole injection layer was changed to p+AlGaN ($3*10^{18}$ cm^{-3} to not exceed Mg maximum doping in high Al mol AlGaN) due to the bandgap mismatch after increasing the composite; also, the bulk and electrons blocking layer (EBL) x are increased accordingly with the barrier. Then, we implement the n-substrate step (device 7 of reference [3]) to go against polarization of the quantum well. From the following two graphs, we can clearly see that qw=0.75 and with n-stepping substrates fit the goal more.

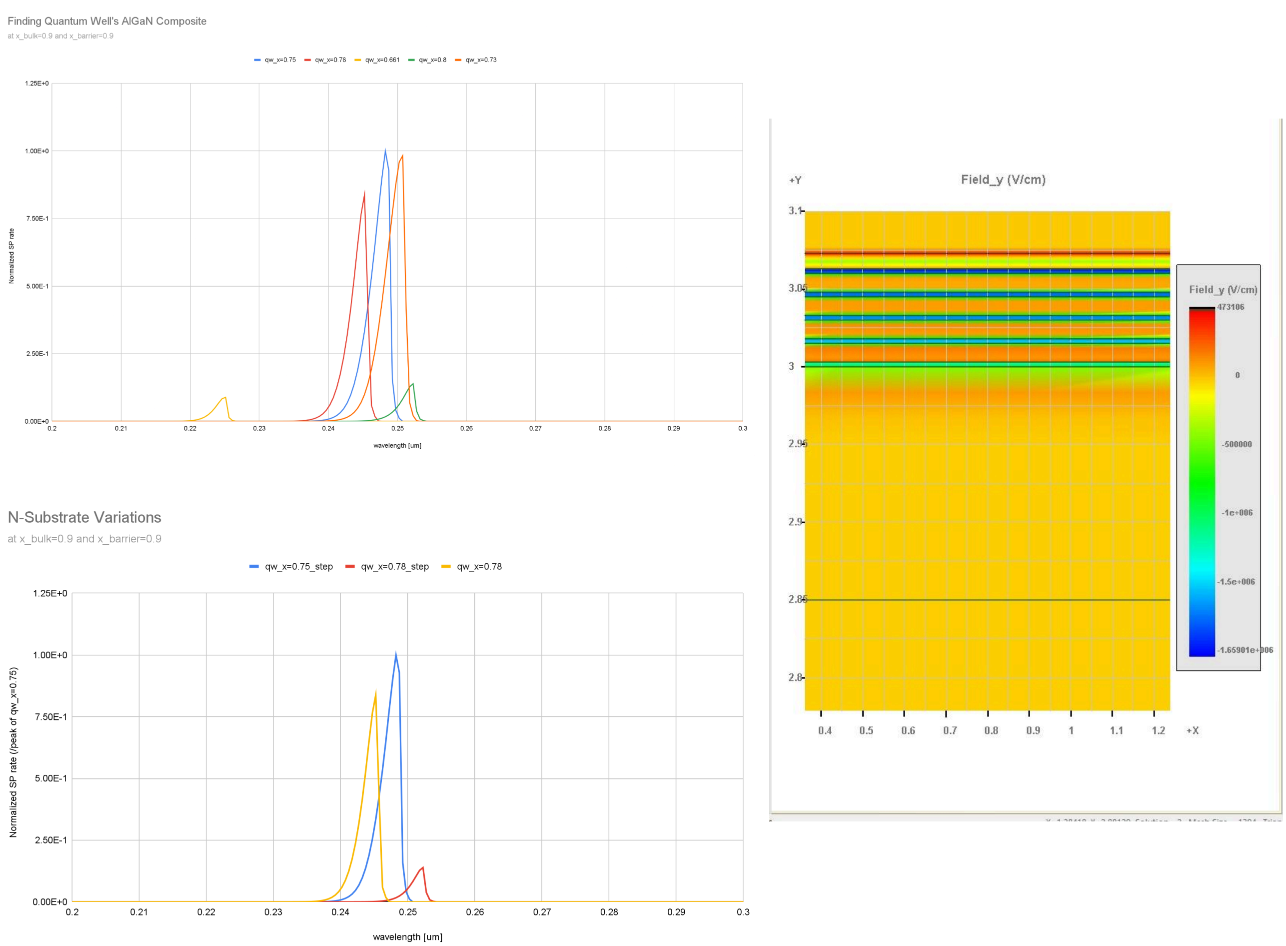


Figure 6,7,8. 4, spectrums of varying x to find peak wavelength; 5, spectra comparing including n-substrate stepping structure or not; 6, electric field y distribution

From figure 8, we can clearly see how the first quantum well's electric field along y direction is affected by the depletion form by transiting from n-AlGaN = $3*10^{18}$ cm^{-3} to n-AlGaN = $3*10^{17}$ cm^{-3}. After these, We derive the structure attached at the Structure section, noting that the contact covering the whole top of LED is for uniform injecting current to have better simulation; it can be changed in further/future design.

Then, we implement realistic ABC model constants(auger recombination constant for electron and hole and radiative recombination constant) and lifetime of electron and hole to Crosslight sol file as the table below[14]:

	Auger_n	Auger_p	lifetime_n	lifetime_p	Rad. Recomb.
material	3.4e-30 m^6/s	3.4e-30 m^6/s	1E-6 sec^{-1}	1E-6 sec^{-1}	default
Active region	3.4e-30 m^6	3.4e-30 m^6/s	1E-6 sec^{-1}	1E-6 sec^{-1}	2e-10 m^2/s

Table b, generation recombination parameters set up in Crosslight for AlGaN

We also turned on set_polarization, independent_mqw, self_consistent, and q_transport_mqw_bundle for a more authenticated multi-quantum-wells (mqw) simulation.

After these adjustments, we discovered that x_qw = 0.75(x variance of $Al_xGa_{1-x}N$ for a quantum well) has a slightly larger wavelength than 248 nm, so we run simulations for x_qw = 0.78 under barrier = 0.9 to see if the wavelength left shift while magnitude of the spontaneous rate(sp_rate) and the IQE are about the same. Unfortunately, the maximum magnitude of the spontaneous rate was half of x_qw=0.78's; after reinvestigating from the radiative recombination vs device position (see figure 7), the problem was exposed- the radiative recombination did not happen in the quantum well, so while the x_barrier of the mqw is increased to 0.93 and increase the EBL to 0.95 with p-doping of $5*10^{18}$ cm^{-3} to achieve better confinements of EHP in quantum wells.

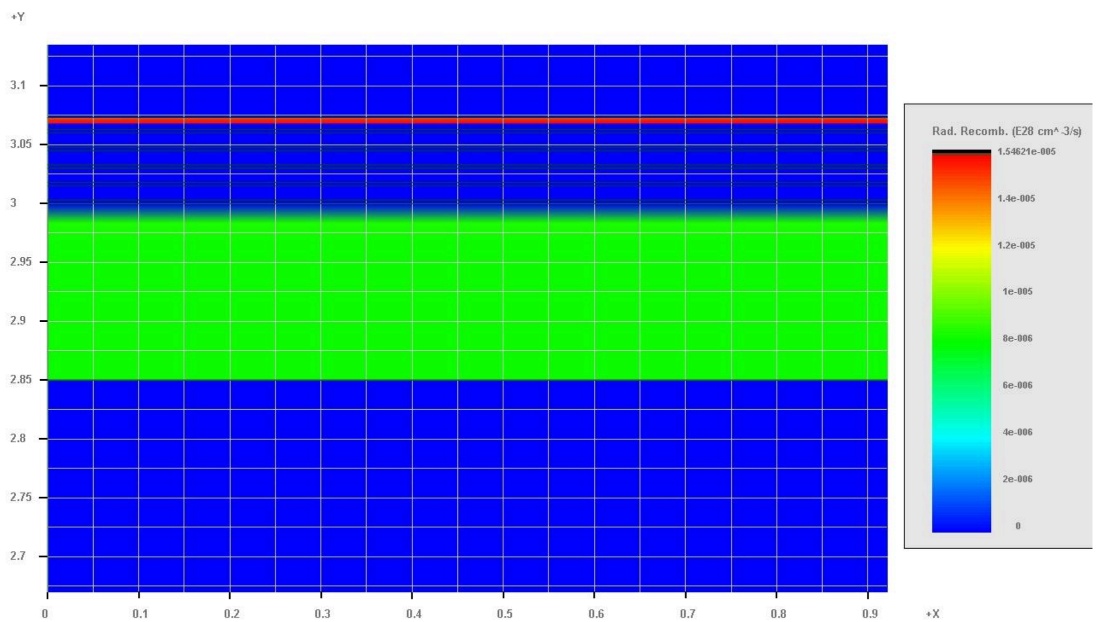
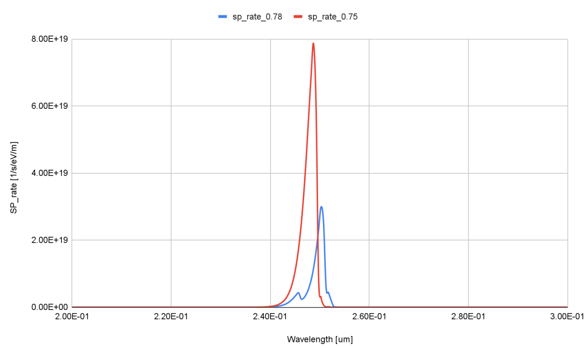


Figure 9, Radiative Recombination diagram of x_qw = 0.75 and x_barrier=0.9

With above conditions, simulations are run for both x_qw = 0.75 and x_qw = 0.78 where the performances (sp_rate and IQE) of x_qw = 0.75 are slightly better. (See Figure 8 and 9)



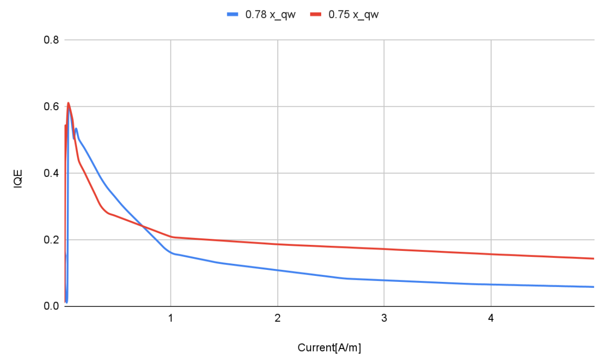
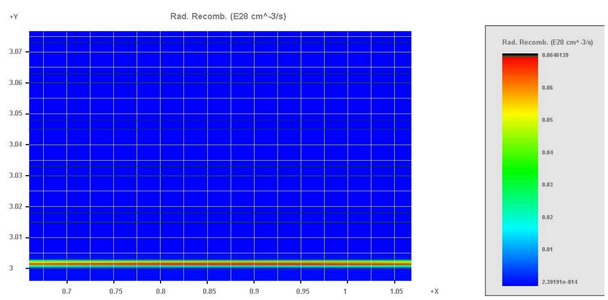


Figure 10 and 11; 10 is the sp_rate comparison and 11 is IQE comparison for 0.75 & 0.78 x_qw. However, I do need to acknowledge that our LED design does not reach its optimization since the radiative recombination does not happen evenly in the quantum wells (see figure 10 and 11); I suspected that a more step-wise electron depletion layer as well as a EBL with superlattice may help; potentially changing p+AlGaN to p+AlN could help as well but may cause more problem on LEE; the contact of the device itself can be improved as well[13].



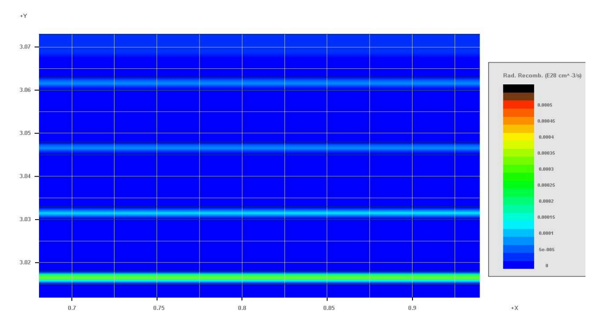
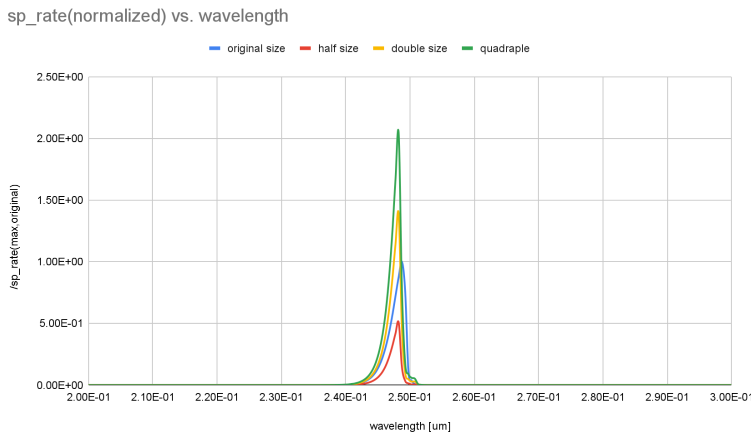


Figure 12 and 13. 12, most radiative recombination happens in lowest qw; 13, other qw still have decent radiative recombination (noticing that the scale is E28).

V. Post-Simulation AlGaN Design Considerations

After deciding on the structure of our 248 nm AlGaN, we need to reconsider the size as we want a decent DUV photolithography light source. Simulations on quadruple the size (20um width) double the size (10um width) and half of the size (2.5um) are compared as figure 12.



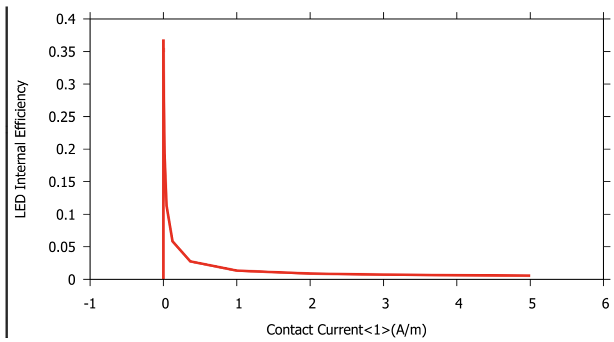


Figure 14 and Figure 15. 14 is comparing sp_rate of different size LED; 15, IQE vs I for half size

We can clearly see that increasing the size does not linearly reflect on the sp_rate, and a smaller size LED is actually better for the uniformity as a DUV photolithography light source. As for half of the size, although the sp_rate is more than 0.5 of the original maximum. Sp_rate, implying this may be a better choice than the original, its IQE decreases to 0.45 and drops abruptly right after; that is potentially bad for not only WPE but also the ability of being a “free-form” light source. Thus, we will stay with the original 4um width AlGaN LED.

In order to redesign the “free-form” DUV light source for source mask optimization, we need to first explore IQE versus I versus P_{optics} towards the power and corresponding IQE/WPE that we can manipulate.

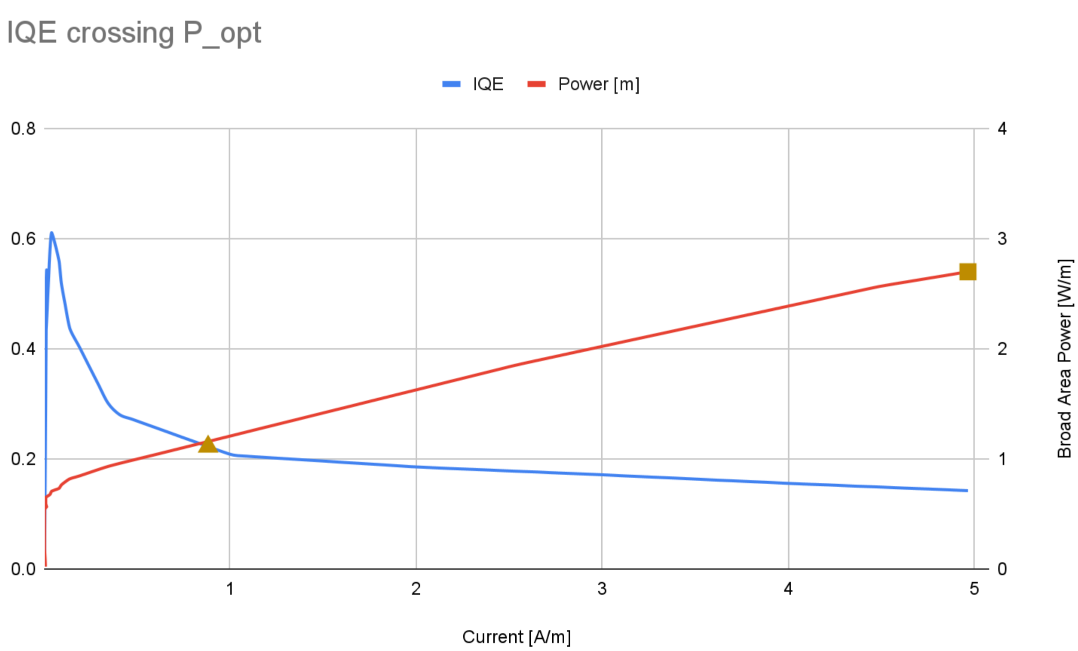


Figure 16, IQE versus I versus P_{opt} diagram

From the figure above and for the data collected from simulation, we can have the table with crucial points (optimal point started with triangular point and maximum power with the rectangular point) below:

Current [A/m]	IQE	WPE	P_elec [W/m]	P_opt [W/m]
0.815	0.231	0.221	4.075	0.905
4.9656	0.143	0.112	31.62	3.538

Table c. crucial datasets to explore AlGaN DUV Photolithography light source feasibility

With the table above we will be exploring to what extent how "free" our DUV LED light source can be. Recalling $radius \approx 18.617mm$, we can induce that the outermost LEDs (assuming cubic) are $number = \frac{2\pi * r}{5 * 10{-3}} = 23395$ and $P_{tot} = n * 3.538 * 10^{-6} = 0.0828W$. The first estimation sounds frustrated, but given 18.617mm >> $5*10^{-3}$ mm, we can quickly estimate how much more "radius" we need to know about the σ of the ring. (15W is set instead of threshold 10W) 15W/0.0828W=181.159, meaning that we need at least 182 arrays more of LED within this circular closed pack. That assume 190 arrays to be conservative, $190*5*10^{-3}$=0.95mm. The minimum σ is thus clear: 0.95/18.617 = 0.051. We do need to note that since this is only estimation, when using more inner circles as annular light sources, the minimum σ should be larger. For precision, we take a closer look with the help of calculus:

$$\int_a^b 2\pi * r\,dr \div d^2 \geq \frac{15W}{3.538 * 10^{-6}W};d = 5 * 10^{-3}mm; r \in [0, 18.617]mm$$

(left side, number of LEDs covered, right side, number of LED required)
where (a-b)/radius = σ ; a/radius = σ_{inner} , b/radius = σ_{outer}.

After these estimations, it is clear enough that LEDs can be versatile to change according to the mask (SMO). This is more advantageous than KrF since KrF uses constant pulses but filters to perform SMO while LED can adjust where to light for a better WPE, and if want precision/quicker exposure, larger power.

VI. Conclusion

In summary, the exploration into employing AlGaN LEDs for DUV photolithography presents a promising future for advancing semiconductor manufacturing processes. Through careful simulation and analysis, we have elaborated the potential of AlGaN LEDs to replace traditional 248 nm KrF lasers, offering superior efficiency and power output.

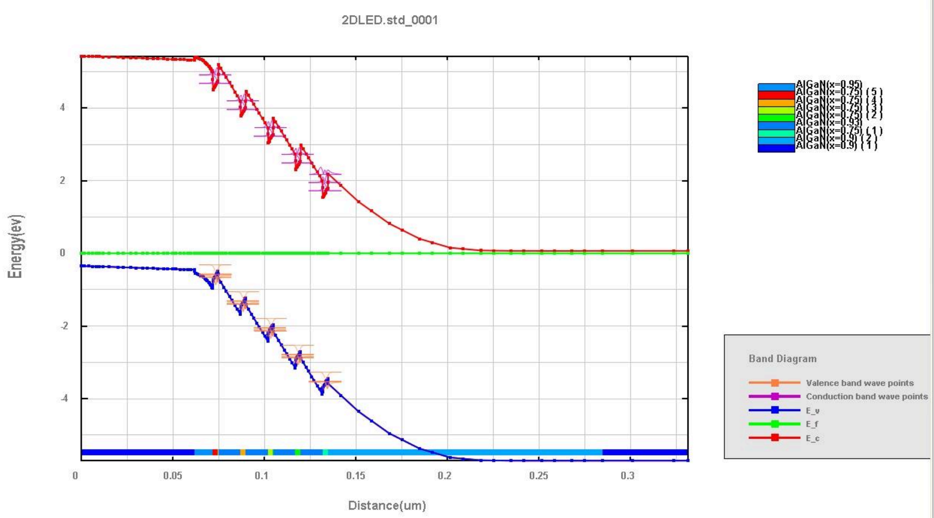
While our investigation demonstrates encouraging results, it is essential to acknowledge the constraints inherent in our study. The simulation does not encompass factors such as heat dissipation, trap effects, and surface recombination, which could influence real-world performance. Additionally, the modeling of polarization effects and the optimization of contact materials remain areas for future refinement.

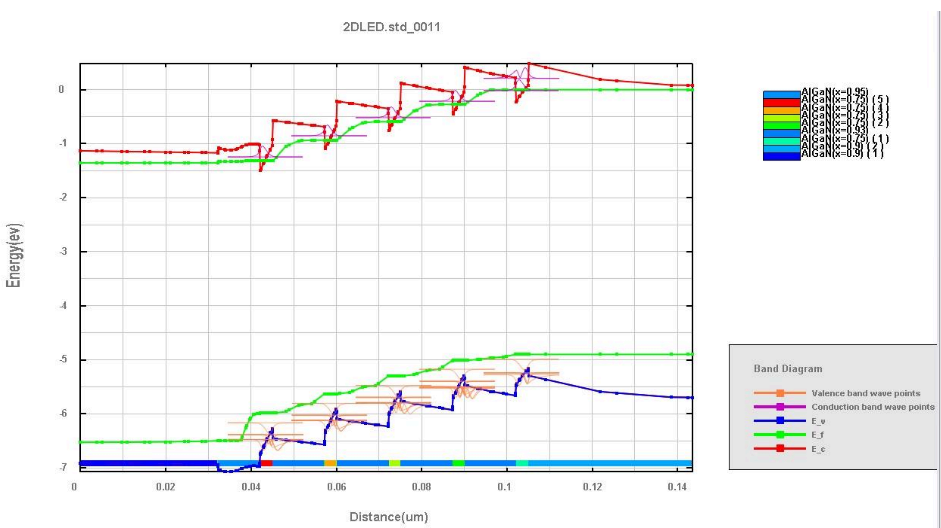
Despite these limitations, the project result suggests a strong case for the adoption of AlGaN LEDs in DUV lithography. AlGaN's broader band/easy-to-tune power and source mask optimization not only meet 248 nm wavelength requirements, but also outscore KrF laser in efficiency and power output, not to mention the aforementioned benefits in high volume production.

Further research should focus on refining simulation models, optimizing contact materials, addressing challenges related to light confinement and absorption, and improving the lifetime and stability of high Al mol AlGaN. Moreover, collaboration with industry to access relevant optical system details will be crucial for advancing the practical implementation of AlGaN LEDs in semiconductor manufacturing environments.

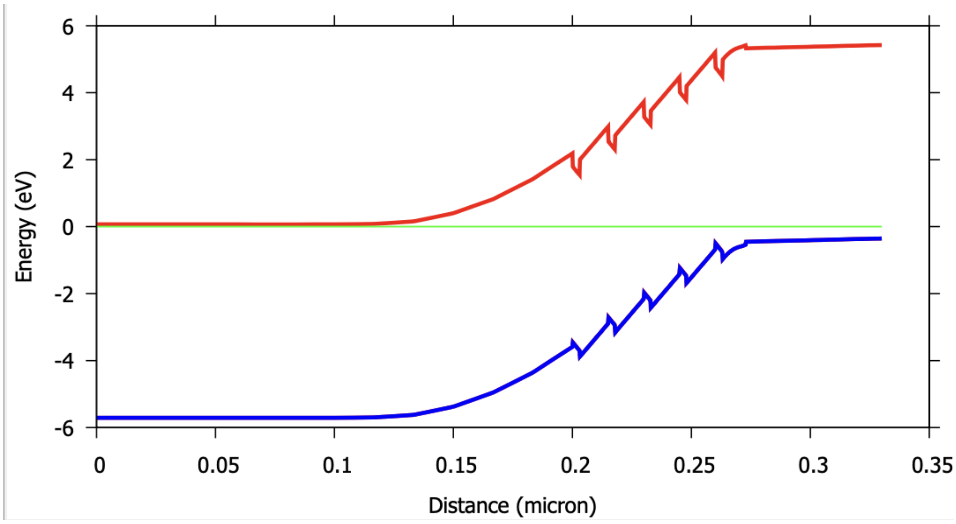
VII. Crucial Figures of the LED

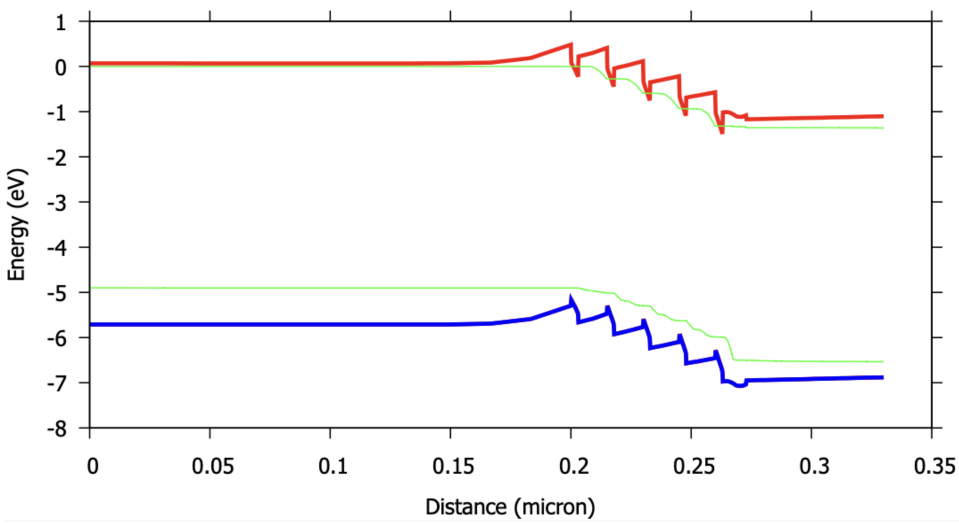
Closed look Equilibrium and Forward Bias Band Diagrams (from y~3.3 to y ~3):



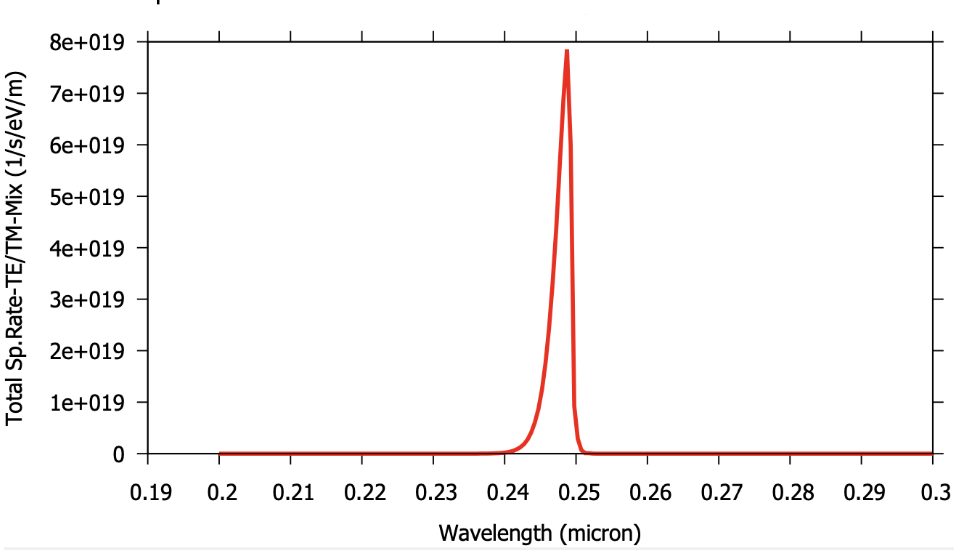


Equilibrium and Forward Bias Band Diagrams:



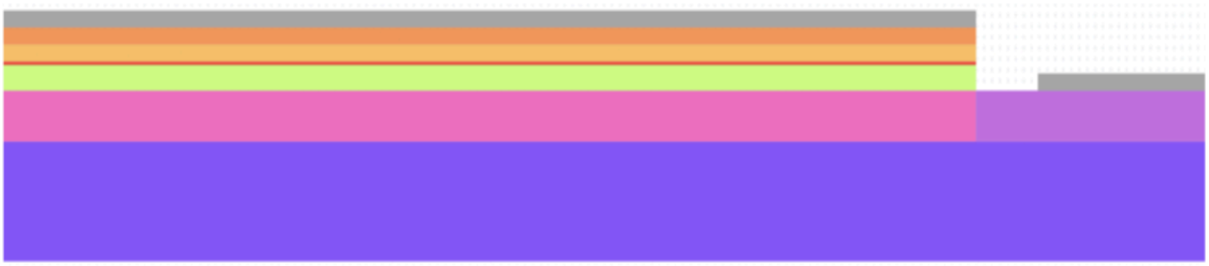


Maximum Spectrum:



Structure of LED:

Structure:



Color	Composition	Doping [m^-3]	Height (um)	Purpose
	AlGaN, x= 0.9	Si:3E+24	2.50E+00	substrate
	AlGaN, x= 0.9	Si:3E+23	5.00E-01	against polarization
	AlGaN, x= 0.9	Si:1E+26	1.50E-01	n+ for contact
	MQW	N/A	7.50E-01	Five quantum wells
	AlGaN, x= 0.95	Mg:5E+24	1.00E-02	PEBL
	AlGaN, x= 0.9	Mg:1E+20	5.00E-02	P junction
	AlGaN, x= 0.9	Mg:1E+20	5.00E-02	Hole Injection
	Metal			Contact

MQW:

Color	Composition	Height (um)	Purpose
	AlGaN, x= 0.93	1.20E-02	Barrier
	AlGaN, x= 0.75	3.00E-03	Quantum Well

VIII. Reference

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