STUDY OF GRATING LAYER LOCATION OF A GAN NANO-GRATED LED AND COMPARISON OF TRIANGULAR AND SQUARED ITO NANO-GRATING OF GAN LEDS

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ABSTRACT

Reducing energy consumption is one the most critical and necessary actions being continually worked towards by many. According to the U.S. department of Energy, solid-state lighting (SSL) has the potential to reduce the light consumption in the United States by nearly one half and that light-emitting diodes (LEDs) will change the way of lighting in our homes and businesses [1]. Gallium Nitride (GaN) based light emitting diode (LED) technologies are continuing to have a fast growing contribution to various applications in today's society. GaN LEDS are already replacing the esteemed incandescent light bulb, and are transforming traffic lighting, optical interconnects, backlight displays and general lighting purposes [2-4]. Unlike conventional light sources, gallium nitride based LEDs have many advantages. This study systematically studies the effects of two methods to enhance light extraction efficiency of gallium nitride (GaN) LEDs: nano-grating photonic crystal structures and ITO nano-gratings atop GaN LEDs. For the photonic crystal gratings, each simulation varies in filling factor, grating cell period, grating cell width, and grating layer location and provides a result of total transmission across the device. For the ITO nano-gratings, again each simulation varies in filling factor, grating cell period, grating cell width, and grating layer location, but also geometric shapes of triangles and squares. The simulations provide result of total transmission across the device. These results are used to calculate improvement over the non-grated surface GaN LED.

ABBREVIATIONS

CAD – computer aided design
FDTD – finite difference time domain (analysis)
GaN – gallium nitride
ITO – indium tin oxide
LED – light emitting diode
LEE – light extraction efficiency
MQW – multiple quantum well (light emitting region of LED)
RCWA – rigorous coupled wave analysis
SSL – solid-state lighting

I. INTRODUCTION

Reducing the world's energy consumption of electricity through a higher level of quality and efficiency is highly desired. Solid-state lighting has the potential to do just that. SSL has already proven over 10 times more efficient than incandescent lighting and twice as much as fluorescent lighting according to a report by the U.S. Department of Energy. Compared to fluorescent and incandescent lighting, solid-state lighting is superior due to its features of low power consumption, longer life source, low maintenance, and reducing greenhouse gas emissions [5].

Gallium nitride (GaN) LEDs play an important role in the transition to solid-state lighting since they show to continually increase in efficiency every coming year. However, they still have yet to reach their full potential. There are many design barriers that still need to be overcome and this study seeks to address them. This study focuses on improving the light extraction efficiency of GaN LEDS.

Background

There is tremendous need to reduce power consumption, minimize heat generation, and increase luminosity [6,7]. To achieve an industry desirable LED, optimization of internal quantum efficiency and external quantum efficiencies, also known as light extraction efficiency, are required. These parameters are significant because they determine the efficiency of light generation inside and outside of the semiconductor material. The main limitation of GaN LEDs is its poor light extraction efficiency, which is defined by the ratio of the number of photons generated in the active region of the semiconductor, to the amount escaping from the device into free space [3]. This is due to the high refractive index of GaN relative to that of air. As defined by Snell's Law, light can only radiate into the ambient medium when the incident angle is smaller than the critical angle. The low critical angle of GaN results in total internal reflection (TIR), which causes large portions of the photons generated in the device to be trapped in the multiple quantum well (MQW) of the device and to never escape [3,4,6,8,9]. Inefficiencies of GaN LEDs also include the absorptions of light with the device due to dislocation and defection within the GaN crystal. Light trapped and absorbed in the semiconductor is a crucial aspect of light extraction efficiency because they generate heat within the device. The generation of heat within the device limits the lifetime of the LED and causes it to consume more energy [6,9]. Reducing the absorption within the LED is crucial to achieve high performance. Therefore, it is important to extract light from the device as fast and in the greatest numbers possible [8]. Grating structures on the surface of devices help solve the issue of the low critical angle of GaN by taking advantage of the Brag diffraction providing more angle of escape for photons and overcoming the limitation of light extraction efficiency [3,6,11].

II. SIMULATION ENVIRONMENT

The LED models used this study are built in RSoft's CAD environment and simulated using RSoft's rigorous coupled wave analysis (RCWA) software, DiffractMOD, and finite difference time domain (FDTD) software, FullWAVE. The models assumes plane wave incidence and lossless material, with light propagating in the positive z direction, and originating from the MQW layer. The 460 nm wavelength of light is used to simulate emission from the source, because GaN emits in the blue light frequency range.

DiffractMOD

DiffractMOD is a design tool for diffraction 2D of 3D optical structures such as surface gratings, photonic bandgap crystals, and subwavelength periodic structures. It calculates the diffraction efficiency and field distribution of these structures. Its algorithm is based on rigorous coupled wave analysis (RCWA), which represents the electromagnetic fields as a sum over coupled waves. Using Fourier harmonics, a periodic permittivity function is presented. Each coupled wave is related to a Fourier harmonic. This allows the full vectorial Maxwell's equations to be solved in Fourier domain. From the Fourier harmonics, the spatial field distributions are derived [11].

FullWAVE

FullWAVE is another simulation tool for studying the propagation of light in a wide variety of photonic structures. Its algorithm employs the finite difference time domain (FDTD) method for the simulation process. The FDTD method decomposes space and time into separate components and employs Maxwell's equations to accurately simulate the effects of nano-gratings in the LED such as reflection, transmission, and scattering [12].

III. GRATING LAYER LOCATION

One method to increase the light extraction efficiency (LEE) is to introduce nano-surface gratings. It has been proven when nano surface gratings are present, an increase in diffraction efficiency and thus LEE appears at the surface compared to that of a planar surfaced design [3,7,13-18]. This study will introduce photonic crystal gratings on top on the LED structure. The grating structure will provide more angles at which the photons can escape thus improving the extraction efficiency [7]. Light extraction enhancements of nano-grating photonic crystal surface with fill factors ranging from 0-100% are investigated.

Simulation Model

It is a challenge to determine the optimized parameters for LEE optimization and the performance enhancement of grating assisted GaN based LED structures due to the amount of parameters. In order to design the optimal structure, thickness of the GaN, the position of the multi-quantum wells (MQW) source, filling factor, lattice constant, and depth are all important parameters that need to be analyzed. However, due the numerous amounts of computations there would be to perform, this study focuses on the enhancement of LEE by optimizing the filling factor of the surface grating.

In order to study the effects of fill factors on the total light transmission across the device, rigorous coupled wave analysis (RCWA) was used. The simulations allowed us to enhance the light extraction efficiency by optimizing the device parameters. The simulation model consisted of a two-dimensional (2-D) model of the GaN LED with square unit grating cells in a crystal lattice arrangement. An illustration of the GaN LED model is shown in Figure 1*: Nano-grating GaN LED model*.

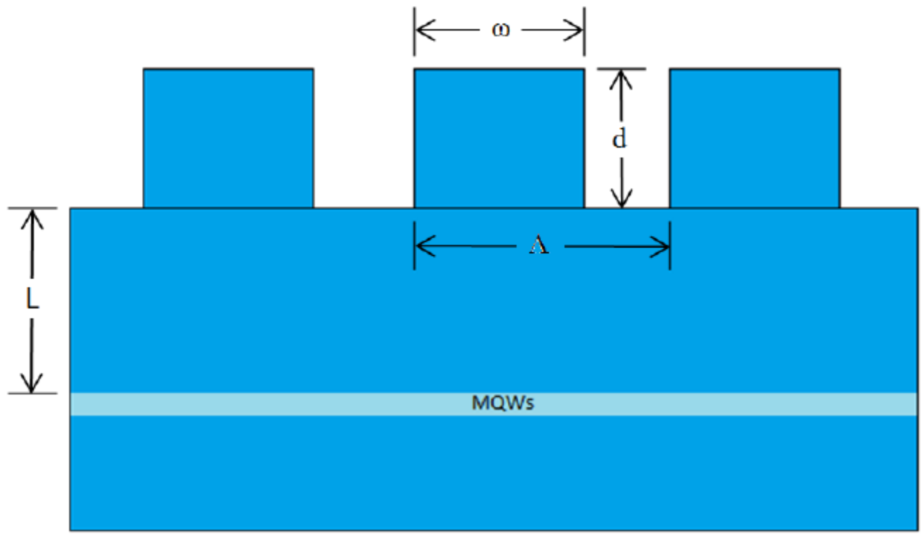

Figure 1: Nano-grating GaN LED model

The model assumes plane wave incidence and lossless material, with light propagating in the positive z direction, and originating from the MQW layer. The 460 nm wavelength of light is used to simulate emission from the source, because GaN emits in the blue light frequency range. The grating height (d) is fixed at 150nm, and the value of the grating width (ω) varies with the grating period and filling factor (f). The period (Λ) of the gratings for simulation vary between 0nm and 2000nm at intervals of 50nm and the grating location (L) vary between 50 and 600nm. Also included in the simulation are period values described by Peking University in accordance with their experimental data. An overview of the parameters is presented in TABLE 1. The RCWA simulation generates a value of the total transmission for light incidence ranging from 0 to 90°. Then the values are normalized and the summation value is used to generate the final transmission data, which are displayed in Figure 3.

TABLE 1

STRUCTURAL PARAMETERS OF THE SIMULATION DEVICE

Parameter	Variable	Value (nm)
Wavelength	Λ	460
Grating Width	Ω	0.5Λ
Grating Height	d	150
Grating Period	Λ	50-2000 (at intervals of 50) and also 230,460,690,920
Location	L	50,200,400,600
Duty Cycle	f	10%, 30%, 50% 70%, %90

RCWA Analysis

First, we analyze the effects of the filling factor has on the amount of light extracted from the device. The filling factor is incrementally increased from 10-90% with a step size of 20%. Figure 2 depicts the output power of light extracted versus the grating period at a location of 150nm. It is noticed that as the grating period is increased beyond 1000nm, the output power does not have much variation. Much of the variation is located between the grating periods of 50 and 1000nm. Also, more light comes out around 50 to 1000nm period compared to 1000 to 200nm period. For this reason, we can conclude that nano-grating is better than macro-grating. Nano-grating provides a higher resolution and better representation of the output power we would not see otherwise if macro-grating was implemented. In the following calculation, we will continue to analyze only the grating periods ranging from 50-1000nm.

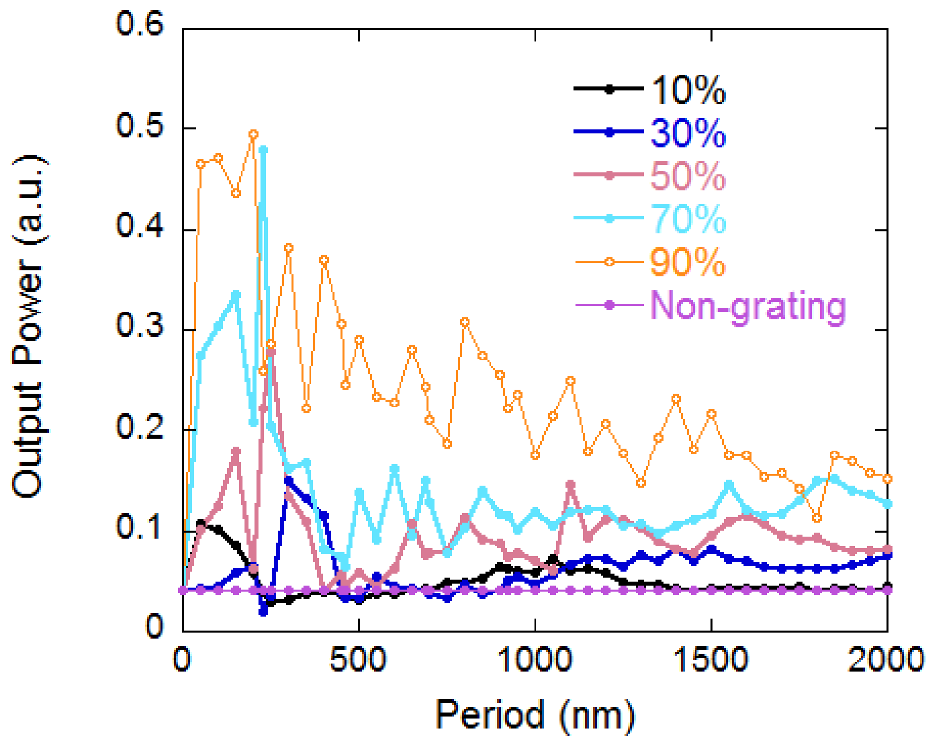

Figure 2: Output power extracted plotted against grating period at a location of 150nm

Finally, we analyze in more detail the effects of the filling factor. The findings show that there is a strong dependence of the light extraction on the duty cycle of the device as well as the location. Figure 3 shows the output power of each grating period and how it varies when the location and duty cycle changes.

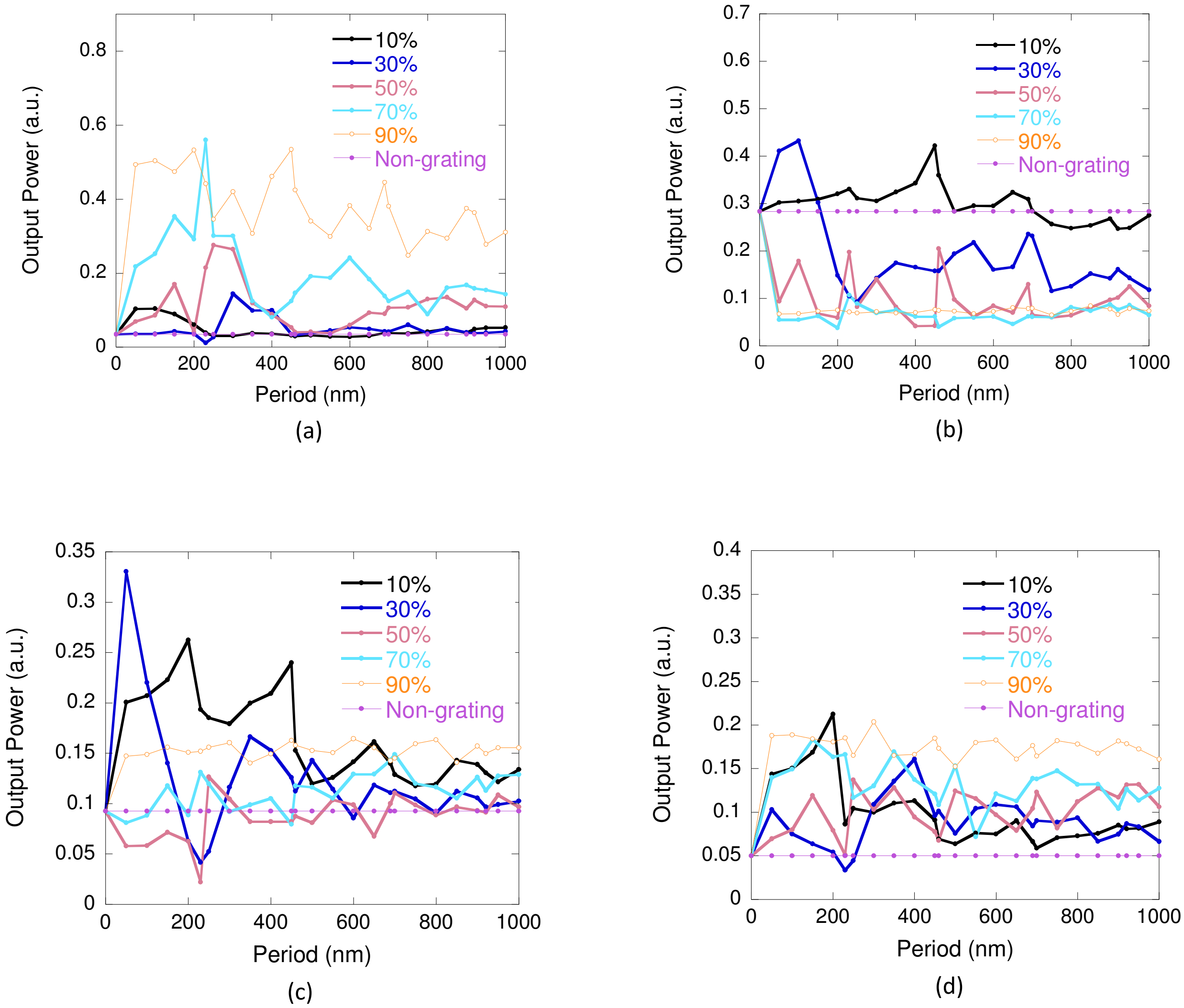

Figure 3: Output power for the grating location case: (a) L=50nm, (b) L=200nm, (c) L=400nm, (d) L=600nm

In general, when observing all grating periods, 50-1000nm, it appears that a filling factor of 90% increases the transmission over the device for most of the grating locations. However, this does not hold true for the grating location of 200nm as can be seen in Figure 3(b). This figure shows that at a 200nm grating location, there is not much light extraction improvement compared to the non-grating case. Only at a couple of filling factor do we see an increase in transmission, while at other it proves detrimental. We see that a 10% duty cycle appears to improve the LEE compared to the other duty cycles as the grating period increase to 690nm. However, the most light extraction occurs at a 30% duty cycle with a 100nm period and an enhancement of 52.65%. Figure 3(a) displays the output power for a 50nm grating location as the grating period varies. It shows that an increase in the duty cycle has a linear relationship with the amount of light extraction is obtained. 90% duty cycle largely achieves a greater transmission as the grating period increases. However, there is a large fluctuation between 200 and 250nm period when the duty cycle is at 70%. That makes 70% duty cycle case give the greatest light extraction improvement. With a filling factor of 70% and a period of 230nm, a light extraction improvement of 1521.12% is achieved. Figure 3(c) displays the output power for a grating location of 400nm. The figure reveals again that transmission improvement only happens at certain duty cycles and periods, while others prove unfavorable. Yet, it does show a better improvement than that of the 200nm gratings location case. The greatest light extraction is achieved at a 30% duty cycle and a 50nm period. At these optimized parameters at a 400nm grating location, a 256.66% transmission improvement is achieved. Figure 3(d) displays the output power for a grating location of 600nm. The data shows a favorable improvement in light extraction compared to the non-gating case. The data reveals an enhancement of 325.09% when the filling factor is 10% and grating period is 200nm. For each grating location, Table 2 shows the filling factor and grating period that provides the most light extraction improvement over the device. The table shows that optimized grating location is highly dependent on the duty cycle of the gratings.

TABLE 2

INCREASED LIGHT EXTRACTION FOR DIFFERENT GRATING LOCATIONS

Grating Location (nm)	**Grating Period (nm)**	**Duty Cycle (%)**	**Output Power non-grating case (a.u.)**	**Output Power grating case (a.u.)**	**Percent Increase (%)**
50	230	70	0.03451	0.55945	1521.12
200	100	30	0.28328	0.43244	52.65
400	50	30	0.092646	0.33402	256.66
600	200	10	0.049971	0.21242	325.09

Figure 4 displays the values of transmission of grating cases at 90% duty cycle and 600nm period compared against the non-grating case as the location is varied. A 90% duty cycle proves to increase the light extraction for most grating locations and grating periods as they are increased. A 600nm period was chosen due to the steady value it preserves when the duty cycle and location is varied. Observing locations varying form 50-600nm, about 58% of the nano-grating cases increase the transmission while at others it proves detrimental. Maximum improvement was achieved at a 50nm location with a 1006.75% improvement, while a minimum 23.62% improvement was achieved at a 350nm location. Nano-grating is generally improving the transmission as the previous study has proved and LEE still proves to be highly dependent of the grating location.

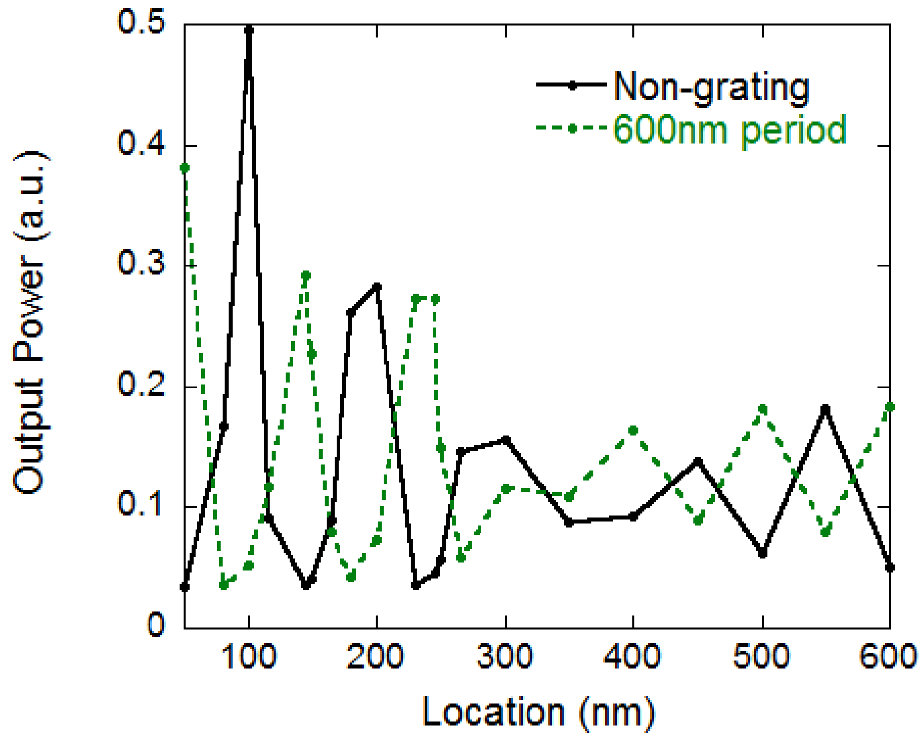

Figure 4: Transmission value varying with location

RCWA Conclusion

Model analysis of the GaN nano-grated LED provides fascinating results when observing the effects that the grating duty cycle has on the transmission of the device. This study reveals which filing factor, grating location and grating period will increase or detriment LEE. From the previous findings, we found a high dependence of LEE on the distance between the nano-grating and the multiple quantum well active layer as well as the grating period. Grating location proved to be detrimental to LEE at particular cases, but now with the new study, we know that we can improve the transmission of those grating cases which yielded less light extraction than the non-grating case by changing the duty cycle of the gratings. Achieving a high LEE with an optimized location is highly dependent on the duty cycle of the gratings. No correlation with the location and duty cycle proves to be consistent as the location is increased. Some duty cycles prove to enhance LEE in particular grating cases, while in others it proves detrimental.

The findings show that with the four grating locations observed, the greatest overall light extraction is achieved at a 50nm location, 230nm period, with a 70% duty cycle and an improvement of 1521.12%. Therefore, when trying to achieve a high LEE, it is important to optimize the grating location and duty cycle at the same time due to the high dependency location has on duty cycle.

IV. TRIANGULAR AND SQUARE ITO TOP NANO-GRATINGS

To resolve the limitations of GaN LEDs, several efficient approaches have already been introduced, such as nanoporous and pattern nano-porous structures [3,19], surface roughening [20], and flip chip [14]. Grating structures on the surface of devices have proven to help solve the issue of the low critical angle of GaN by taking advantage of the Brag diffraction providing more angle of escape for photons and overcoming the limitation of light extraction efficiency [3,6,10]. This study investigates and compares the light extraction enhancements of square and triangular surface nano-scale gratings with filling factors ranging from 0-100% and ITO layer thicknesses of 78nm, 230nm and 260nm.

Simulation Model

In order to study the effects of top transmission gratings on GaN LED light extraction efficiency, finite difference time domain (FDTD) method was used. We explore multiple ITO layer thicknesses and square transmission grating patterns and compare to triangular transmission gratings. The simulation model allowed us to enhance the light extraction efficiency by optimizing the device parameters.

The model assumes plane wave incidence and lossless material, with light propagating in the positive z direction, and originating from the MQW layer. The simulations use a field source defined along the center of the MQW region to emit and incident plane wave with 460nm wavelength. The device consists of a two-dimensional model of GaN with square grating cells arranged in a crystal lattice atop an ITO layer thickness. We use a fixed thickness of 10 μm sapphire substrate and define air as the surrounding medium. The illustration of the LED model shown in Figure 5 consists of an ITO top square grating with ITO layer thickness, p-GaN layer, MQWs, n-GaN layer, and a sapphire substrate. An overview of material thickness and refractive indices of each layer is shown in TABLE 3.

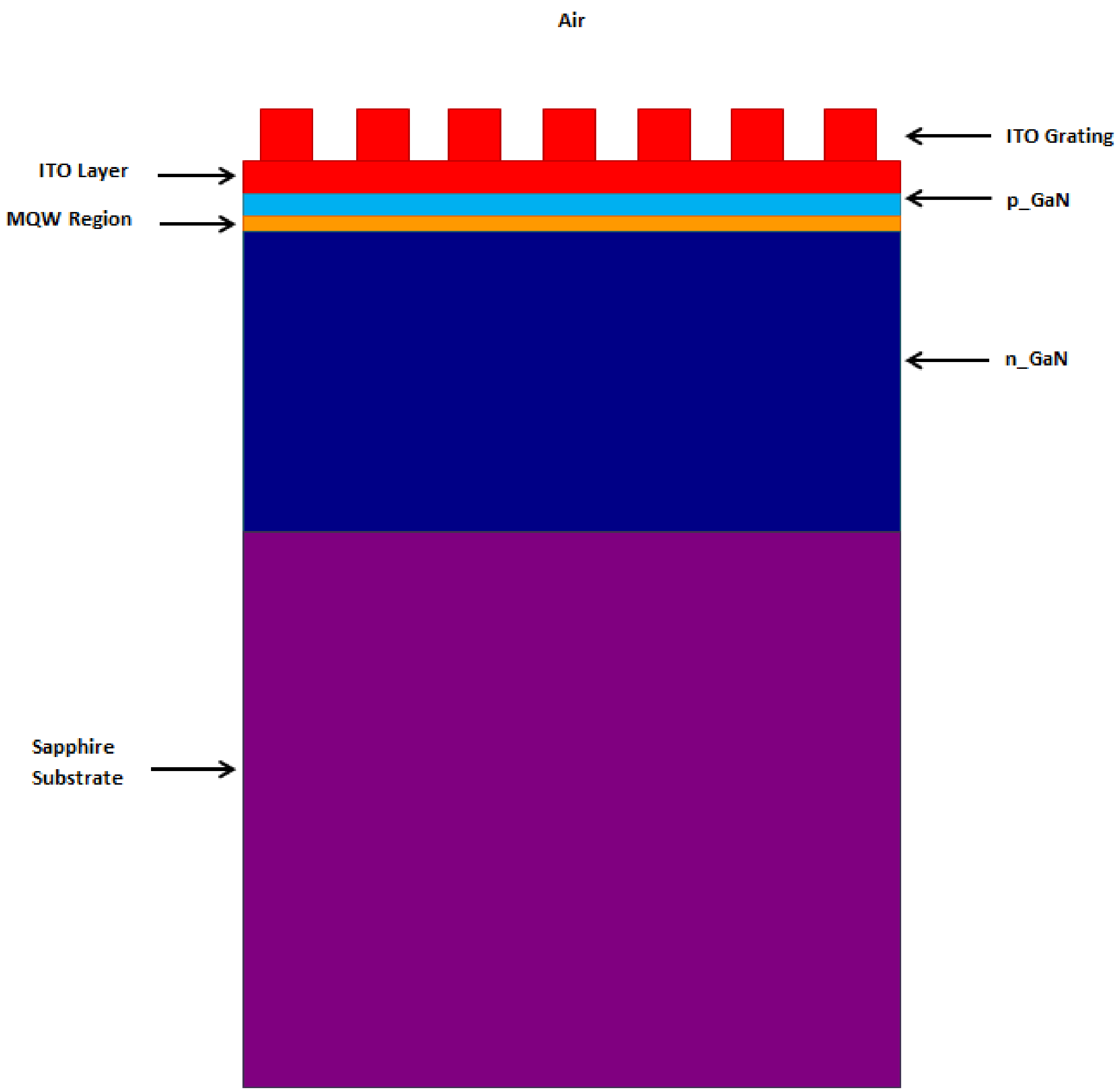

Figure 5: ITO based grating LED simulation model

TABLE 3

MATERIAL PROPERTIES OF SIMULATION DEVICE

Material	Thickness (µm)	Refractive Index
p-GaN	0.2	2.5
MQWs	0.1	2.6
n-GaN	5	2.5
Sapphire	10	1.78
ITO Layer	0.078 / 0.23	2.1
Air	>10000	1

The GaN LED grating model shown in Figure 6 illustrates the parameters that influence the top grating structure. Three ITO layer thicknesses: 78nm, 230nm, 260nm and three grating width cases: 125nm, 230nm, 460nm are simulated with duty cycle varying form 0-100%. These ITO layer thicknesses and grating width cases were best cases determined by the previous study [21,22]. The ratio of the grating width and duty cycle defines the grating period. The ratio of the width of the LED (10.5µm) and the grating period defines the number of square gratings for each simulation. We include the light collected not only from the top of the LED, but also emissions from the sides and bottom to reveal their influence on top emissions and to also reveal the distribution within the LED.

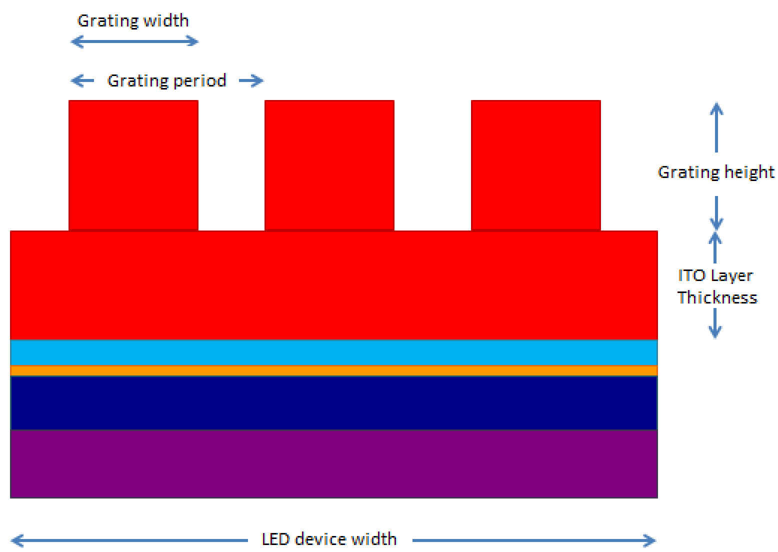

Figure 6: Transmission grating GaN LED model

FDTD Analysis

First, we analyze the effects of the filling factor of top square gratings on the amount of total light extraction of the device. The filling factor is increased from 0-100%, with 0% duty cycle being the non-grating case, for three grating cell width cases of 125nm, 230nm, and 460nm. The grating period is increased from 125nm to 1250nm, 230nm to 2300nm, and 460nm to 4600nm. Figure 7 depicts the output power of light extracted versus the filling factor for an ITO layer thickness of 78nm. As shown in Figure 7(a), it is noticed that for a cell width of 125nm, improvement of total light extraction occurs for 0-30% duty cycles. The data reveals the greatest light extraction occurring at 20% duty cycle with an improvement of 4.00% compared to the non-grating case. Duty cycles from 40-100% reveal a negative linear relationship as they are increased and prove detrimental. As shown in Figure 7(b), for a cell width of 230nm, total light extraction improvement occurs for duty cycles 0-20%. The greatest light extraction occurs at 10% filling factor with an improvement of 12.43% compared to the non-grating case. Duty cycles 20-100% prove to be detrimental. For a cell width of 460nm, improvement in total light extraction occurs for duty cycles 0-30%, as shown in Figure 7(c). The greatest light extraction occurs at 10% improving by 19.93% compared to the non-grating case. It is noticed as the cell width of the gratings increase, the percent improvement also increases in relation to the optimized filling factor. This is due to the increase of surface area of the cell width which undoubtedly provides trapped photons more angles of escape. Conclusively, for a 78nm ITO layer thickness, the greatest light extraction efficiency occurs with a 460nm cell width and 10% duty cycle with a 19.93% improvement in comparison to the non-grating case.

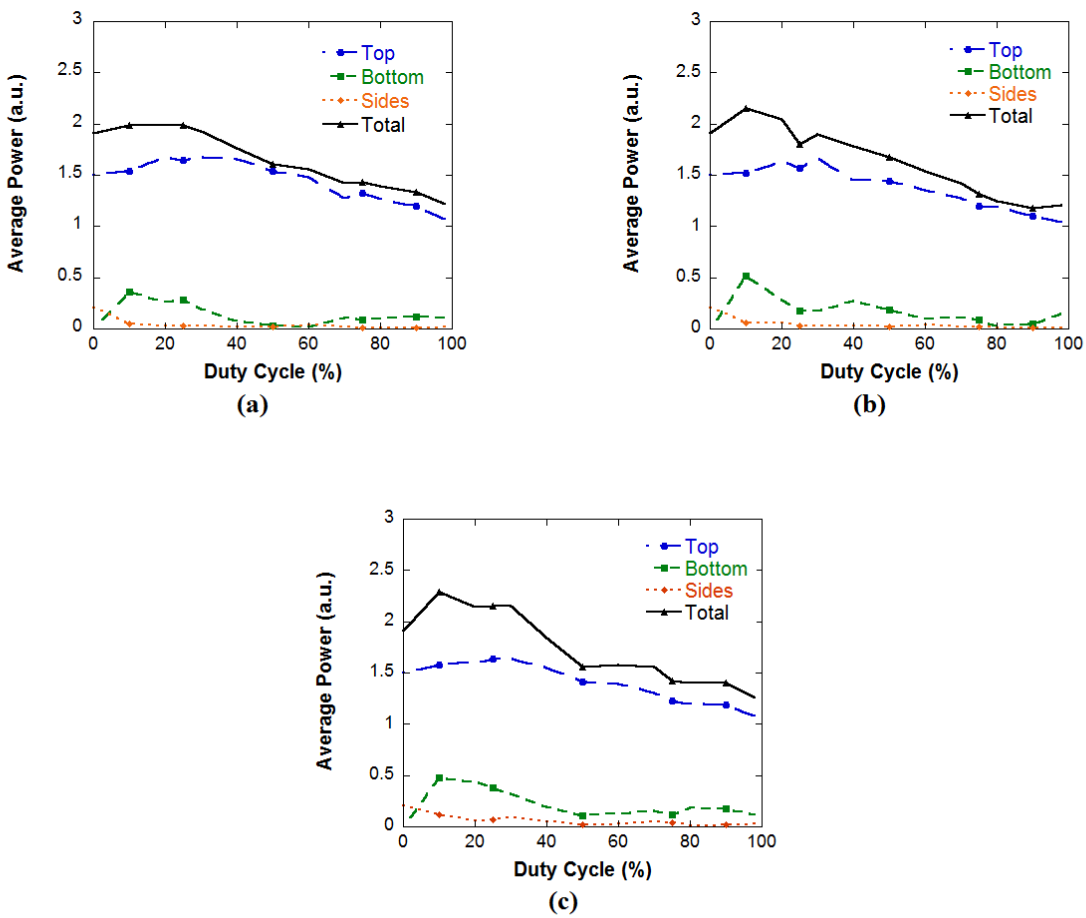

Figure 7: Output power for grating width: (a) 125nm, (b) 230nm, (c) 460nm with an ITO layer thickness of 78nm

Next, using an ITO layer thickness of 230nm, we again analyze the effects of the filling factor of top square gratings on the total amount of light extracted from the device. The duty cycle is increased within the same range of 0-100%, with 0% duty cycle representing the non-grating case, for three grating cases of 125nm, 230nm and 460nm. The grating period is increased from 125nm to 1250nm, 230nm to 2300nm, and 460nm to 4600nm respectively. Figure 8 depicts the output power of light extracted versus the filling factor for an ITO layer thickness of 230nm. As shown in Figure 8(a), for a grating cell width of 125nm, there is no improvement in light extraction when compared to the non-grating case. Hence, a grating cell width of 125nm proves detrimental for an ITO layer thickness of 230nm. Now, observing a 230nm cell width, as shown in Figure 8(b), it is noticed that light extraction efficiency improves for duty cycles 0-10%. The greatest light extraction occurs at a 10% filing factor with a 7.16% improvement. Duty cycles form 10-100% prove detrimental. For a grating cell width of 460nm, total light extraction efficiency improves for duty cycles 0-20%, as shown in Figure 8(c). The greatest light extraction occurs at a 10% duty cycle with an improvement of 11.71%. Again, we see the linear relationship between increasing the grating cell width and percent improvement compared to the non-grating case. Conclusively, for an ITO layer thickness of 230nm, the greatest total light extraction efficiency occurs with a 460nm grating cell width and 10% duty cycle with an 11.71% improvement compared to the non-grating case.

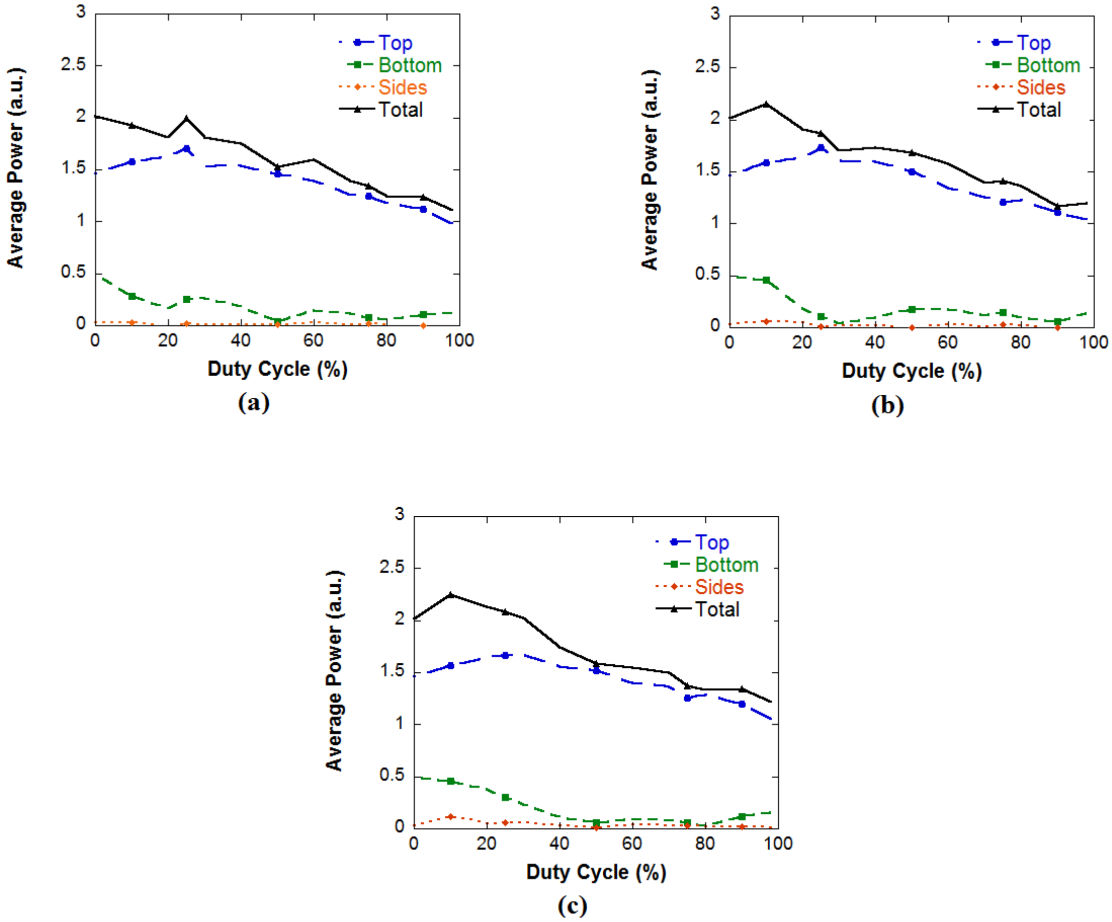

Figure 8: Output power for grating width: (a) 125nm, (b) 230nm, (c) 460nm with an ITO layer thickness of 230nm

Next, we use an ITO layer thickness of 460nm, and again analyze the effects of the filling factor of top square gratings on the amount of total light extraction from the device. The filling factor is increased from 0-100%, with 0% duty cycle being the non-grating case, for three grating cell width cases of 125nm, 230nm, and 460nm. The grating period is increased from 125nm to 1250nm, 230nm to 2300nm, and 460nm to 4600nm respectively. *Figure 9* depicts the output power of light extracted versus the filling factor for an ITO layer thickness of 460nm. For a grating cell width of 125nm, as shown in Figure 9(a), total light extraction improvement occurs only for 25% duty cycle with a percent increase of 3.853%. As shown in Figure 9(b) for a grating cell width of 230nm, improvement in total light extraction is seen from 0-10%. The greatest light extraction improvement occurs at 10% with a 10.07% increase compared to the non-grating case. For a grating cell width of 460nm, improvement in total light extraction efficiency take places from duty cycles 0-30%. The greatest improvement occurs at a duty cycle of 10% with an increase of 14.33% in comparison to the non-grating case. Again, we see the linear relationship between increasing the grating cell width and percent improvement due to the increase of the grating cell width surface area. Conclusively, for an ITO layer thickness of 260nm, the greatest light extraction efficiency occurs with a 460nm cell width and 10% duty cycle with a 14.33% improvement compared to the non-grating case.

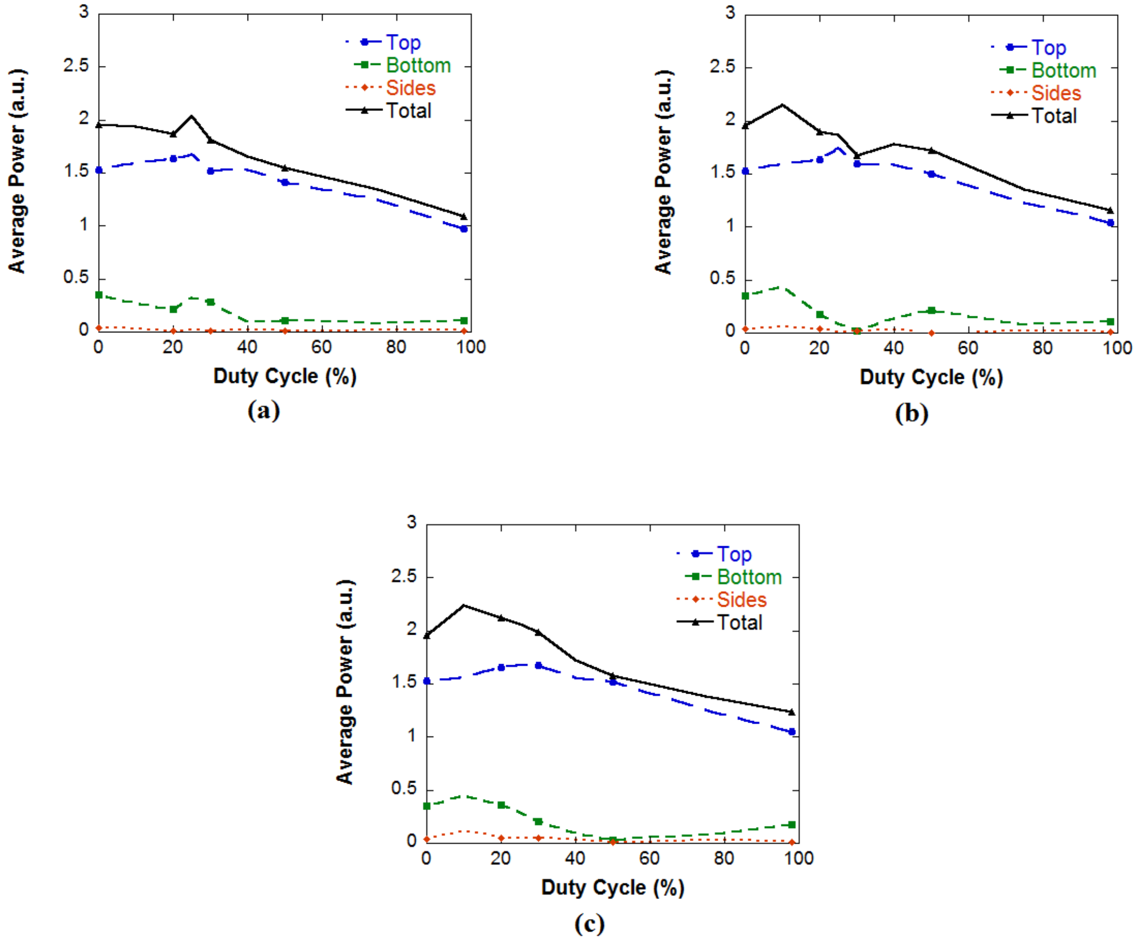

Figure 9: Output power for grating width: (a) 125nm, (b) 230nm, (c) 460nm with an ITO layer thickness of 260nm

Comparing Figure 7, Figure 8, and Figure 9, we see the same linear relationship between the growing grating cell width and percent improvement of the total light extracted. However, it is noticed that each of the three grating cell widths emit relatively the same average power output.

Finally, we compare the results from the square nano-gratings to the previous findings of triangular gratings atop gallium nitride LEDs. Figure 10 illustrates the findings of the output power versus the duty cycle for both triangular and square gratings for an ITO layer thickness of

230nm and grating cell width cases of 125nm, 230nm and 460nm. The left column of this figure displays the triangular nano-gratings and the right column displays the square nano-grating.

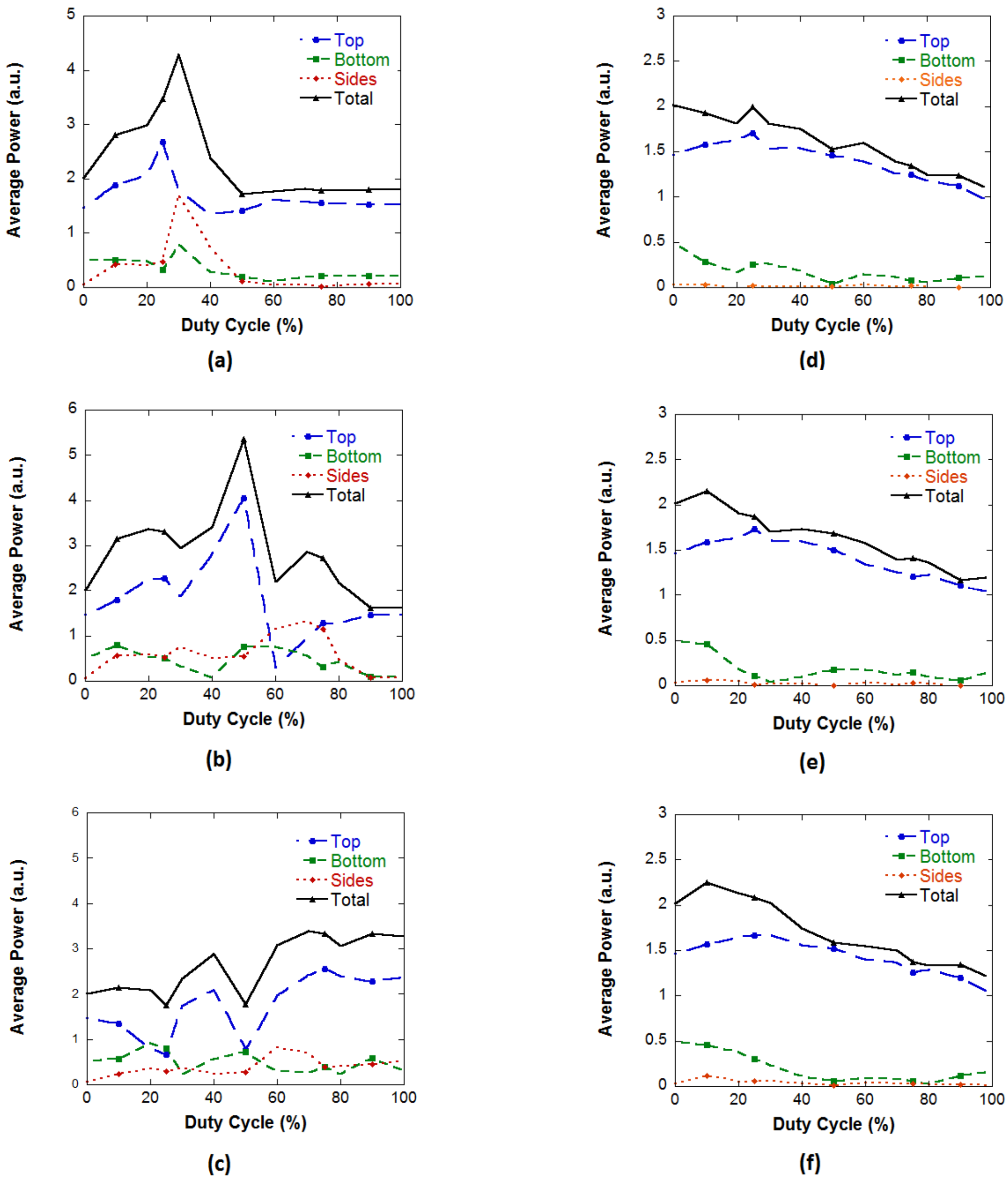

Figure 10: Output power for triangular (a-c) and square (d-e) gratings for grating width: (a,d) 125nm, (b,e) 230nm and (c,f) 460nm with an ITO layer thickness of 230nm

From Figure 10, we notice with triangular gratings, a much larger improvement in total light extraction is achieved in comparison to the device with square gratings. As shown in Figure 10(a), for a cell width of 125nm the device with triangular gratings achieves its greatest light extraction at 30% duty cycle with a 113.01% improvement while the square grating case does not exhibit any improvement as shown in Figure 10(d). For a cell width of 230nm, with triangular gratings the greatest light extraction occurs at 50% filling factor with a 165.67% improvement, as shown in Figure 10(b). Meanwhile, with the square gratings the greatest light extraction occurs at 10% filing factor with only a 7.16% improvement, as shown in Figure 10e). For a cell width of 460nm, with triangular gratings the greatest light extraction occurs at 60% filling factor improving by 68.01%, as shown in Figure 10(c). Meanwhile, with the square gratings the greatest light extraction occurs at 10% filing factor with only an 11.71% improvement, as shown in Figure 10(f). This significant variance between their light extraction efficiencies is due to the greater surface area the triangular gratings provide over the square gratings as the duty cycle is increased. With the square gratings, we do not see much variation when changing the duty cycle. This reveals for fabrication purposes the triangular gratings are superior. However, from Figure 10, we can see a lot of deviation for with the triangular gratings as the duty cycle is changed. This reveals its high dependency on the duty cycle as compared to the square gratings. For fabrication, if there is not much capability of precise control over the duty cycle, one would consider using the square gratings over the triangular, however, at a great cost of decreased total light extraction efficiency.

FDTD Conclusion

Model analysis of the GaN square nano-grated LED provides fascinating results when comparing to the GaN triangular nano-grated LED. This study reveals a linear relationship for the square gratings that as the surface area of the grating cells increase, so does the amount of total light extraction efficiency. This study also reveals, as the duty cycle is increased, the triangular gratings provide greater surface area than the square gratings. This results in the triangular gratings providing far greater improvements in light extraction in comparison to the square gratings. With an ITO layer thickness of 230nm and cell width of 230nm, the triangular gratings greatest improvement of light extraction is 165.67% as compared to the 11.71% provided by the square gratings. That is a 158.51% improvement difference. Therefore, to achieve high light extraction efficiency, the triangular ITO nano-grated LED is far superior for fabrication than the square ITO nano-grated LED.

V. CONCLUSION

This study used two different methods to improve light extraction of GaN LEDs. The first method was changing the filling factor of square photonic crystal gratings on top of a LED structure. The second method was changing the ITO nano-gratings shape. Both methods showed promising results for improving solid-state lighting.

The first portion of the study indicated that LEE is highly dependent on the duty cycle of the nano-gratings. Changing the grating duty cycle can improve light extraction efficiency and can also prove to be detrimental. From method one, the greatest light extraction improvement was achieved with a 1521.12% increase compared to the conventional LED. The second portion of the study shows that the geometry of the nano-gratings effect the light extracted. Comparing the triangular and square gratings, triangular gratings can improve the total light extraction 158.51% more than square gratings. This significant increase comes from triangular gratings providing greater surface area than the square gratings. From method two, the greatest light extraction improvement was achieved with a 165.67% increase compared to the conventional LED.

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APPENDICES

Appendix A: Senior Project Analysis

Project Title: Study of Grating Layer Location of a GaN Nano-grated LED for Improvement of Transmission Efficiency

Student's Name: Ashli Behill

Advisor's Name: Xiaomin Jin

• Summary of Functional Requirements

The overall function of the project is to increase the light extraction efficiency (LEE) of a gallium nitride LED. This is a theory study dealing with a two-dimensional model of a nano-grated GaN LED. The designed LED should emit blue light with high light emission. The total light transmission of the measurements should be exceptionally accurate.

• Primary Constraints

There are a few limiting factors that have made the study a challenge. Only simulations of a two-dimensional GaN nano-grated LED using the RSoft DiffractMOD software may be performed. Resources to design and fabricate a three-dimensional model are not available. Simulations are nearly accurate, but are definitely not as precise as actually testing a three-dimensional model. There are also model parameters and specifications that have already been previously chosen that have put a limit on my options and approach to the study. This is a research project resulting from collaborated research with Peking University in Beijing, China over this summer. A few of their graduate students have already finished experimental research of designing and fabricating GaN LEDs. They have found optimal device parameters, such as the height of the gallium nitride grating, so some parameters of the GaN device are predetermined.

• Economic

Gallium nitride LEDs would have an immense impact on the economy. in regards to human capital, it can improve employee's labor experience by providing them with knowledge of new and insightful ways of creating a more efficient light sources. in regards to financial capital, gallium nitride LEDs would also have a great impact. When more companies invest into GaN LED commercial products, more people may be interested in investing into their stocks. Gallium nitride based LEDs can produce more light output than usual LEDs with only a thin layer of gallium nitride on top of a sapphire or silicon substrate. Once more companies begin to develop more products with GaN LEDs, interest and demand will increase causing for more products to be manufactured. in regards to natural capital, gallium nitride LEDs used as a light source have optical properties that allow it to have a longer lifetime than regular light bulbs. This would mean less waste to harm the environment.

Costs and benefits of the projects would accrue after it is finished. Since this is a theory study, there is no actual product being made, that would be up to companies interested in the GaN based LED. However, once the LEDs begin to get fabricated the costs will come from fabricating them. Gallium nitride is significantly more expensive than silicon-based or sapphire materials. It is about $500 for one-inch-diameter gallium nitride wafer and only about $35 for a silicon-based wafer. that is a tremendous difference. Finding a way to reduce the cost of developing the gallium nitride would be extremely beneficial to the project. The benefits of the project come once the GaN based devices are out on the market in many different commercial devices. Since gallium nitrides LED brightness is brighter than that of a usual LED, many people will want to have the best thing that is one the market as usual.

The project does not essentially have required inputs since this is a theory study based on simulations of a two-dimensional GaN nano-grated LED. However, one can say the input components are the device parameters which are changed to optimize the light emission from the multi-quantum well of the gallium nitride substrate. These parameters include the height of the substrate, and the width, period and duty cycle of the gratings. Also, there are no parts costs that must be paid since there are no physical components. The $40k software has already been provided by my advisor who received grants to pay for the software keys. as far as how much the project will earn, that cannot be fully determined until there is an actual physical GaN LED with optimized parameters.

The final product would exist longer than commercial light products. for example, incandescent lamps have very low efficiency, high power dissipation and a very short lifetime. Gallium nitride LEDs have an increased brightness and lifetime. as far as development time, that cannot be determined until the final design of the GaN LED is made.

TABLE 1
COST ESTIMATES

Reasearch Project Estimated Costs

	PROJECT TASKS	MATERIAL COST ($)
PROJECT DESIGN	SPIE Photonics West 2014 Registration	$400.00
	Hotel	$350.00
	Travel	$100.00
	Food	$50.00
	Subtotal	**$900.00**

The cost of the software is extremely high. Professor Jin received grants to be able to pay for the software key. There are about 8,800 simulations ran to determine the optimized device parameters. Each simulation takes about 70 seconds to finish and about 10 hours to analyze each grating location.

• **Manufacturing**

I estimate that about 100 billion units of gallium nitride LEDs will be sold per year. Manufacturing coast for each LED is a bit high, about $500 dollars. However, with a high demand, the cost of manufacturing will go down. Estimated price for each device depends on the commercial product. The final product could be a LED TV or a LED picture frame, so costs vary a good deal. Profits per year and cost for the user to operate the device also depend on the commercial product being made.

• **Environmental**

Gallium nitride LEDs will have a big impact on the environment. Their attribute of having a longer lifetime will cause lower waste than commercial lighting and LEDs in the market now. The GaN LED uses natural resources such as water and air when being made in a laboratory during such procedures as etching. It improves light but can harm the environment with its waste. It will improve the lifestyle of different species. for example, lighting will be a big product that these GaN LEDs are used for, which is needed and used by many humans and for different species such as livestock and home pets.

• **Manufacturability**

There are some manufacturing issues as I have discussed previously. The cost of manufacturing gallium nitride wafers are about $500 dollars which is significantly more than the common silicon-based and sapphire wafers. However, costs of manufacturing may go down with the increase in demand and improved design approaches.

• **Sustainability**

There may be issues with maintaining the completed device. These issues include the temperature of the device. Thermal stress can degrade the output light of the device over time. Upgrades that might improve the device are designing different grating shapes. Different shapes may improve the light extraction efficiency. Issues with upgrading the design would be the manufacturing testing time.

• **Ethical**

When designing the GaN LED, an ethical framework that will arise is utilitarian ethics. When designing the LED, decisions will be made to bring about the highest good for everyone involved in the product, especially the customer. However, these decisions for the design may involve bad choices that need to be made to accomplish the overall good. Utilitarian ethics will also come up during manufacture. Another framework is the virtue ethics. When designing, manufacturing and selling the GaN LED products, it is important to be honest about the capabilities and functions of the product to the customers. The manufactures should inform the customers of any endangerment the product may cause to the environment and the public. in the process of design and manufacturing, everyone should be treated as equals no matter the race, religion, gender, national origin, or age. Everyone should assist each other and support them in their professional environment.

• Health and Safety

Bulk GaN is not toxic. It is also biocompatible, so using it in many electronics and as implants in living organisms will cause no harm. However, GaN dust is an irritant to skin and eyes, so that would be a health hazard. Also, the light extraction efficiency of the LEDs may be so high that it can be capable of damaging the eyes if the light is directly shot into them, like a laser. Products will need a safety hazard to warn the customer not directly look at the LED or point it in the eyes of others or themselves.

• Social and Political

Social issues that arise with this product are the manufacturing costs of growing gallium nitride. Compared to silicon-based wafers, gallium nitride wafers are much more expensive, about $400 more in cost. Many people will not be willing to pay a lot of money for a product containing GaN LEDs if the costs of the products are tremendously high. Political issues that may arise are those dealing with the safety of manufacturing gallium nitride. GaN dust is an irritant to the skin, eyes, and lungs. However, even though gallium nitride is non-toxic, dust possibly generated during the fabrication or generated with a product being overused may be harmful to humans and other species.

The project will impact lighting companies and electronic companies such as Samsung. The direct stakeholders will be the manufactures and the companies who actually buy the LED. The indirect stakeholders will be delivery companies such as UPS. The project will benefit both the direct and indirect stakeholders by allowing them to create and obtain products that beat and outweigh the function of silicon-based or sapphire LEDs and fluorescent lighting seen in the market today. They will be able to have a product that will attract customers who are interested in having the next great thing in the market. The project may harm both the direct and indirect stakeholders because of the potential costs of their products made from the GaN LEDs. Stakeholders may not benefit equally. for example, a light company may not profit as much as Samsung after a year of selling their product containing GaN LEDs. Samsung is a higher commercial company than a lighting company.

• Development

New techniques of how to enhance the light extraction efficiency that have been learned independently are to use different materials on top on the gratings or as the gratings. Using different will increase the LEE of the LED with the proper design. Changing the shape of the gratings may also increase the LEE of the device.

LITERATURE SEARCH

Book:

[1] J. Palais, *Fiber Optic Communications*, Prentice Hall, 2004

This source was chosen because I want basic knowledge of fiber optics. This source will help me understand the propagation of light in a fiber and the combining of optic

components onto a single substrate. The source is a textbook used by Cal Poly for EE 403 course.

IEEE Journal:

[2] C. H. Lin, C. Y. Yang, D. M. Yeh, and C. C. Yang, "Light extraction enhancement of GaN-based light-emitting diode through grating-patterned photoelectrochemical surface etching with phase mask interferometry," *IEEE Photonics Technol. Lett.,* vol. 22, no. 9, pp. 640-642, May 2010.

This source discusses the different surface patterns that can be produced to maximize the light extraction of a GaN-based LED. This might help me think of different shapes and patterns I could use to increase the efficiency of my GaN LED device. This source is an IEEE journal paper which was supported by National Science Council and the Republic of China.

[3] M. R. Kranes, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, "Status and future of high-power light-emitting diodes for solid-state lighting," *J. Display Technol.,* vol, 3, no.2, pp. 160-175, Jun. 2007.

This journal informs me of the current status of light-emitting diodes, the demands and the future for these high-power light-emitting diodes for solid state lighting. This journal is credible because it is an IEEE journal paper that has been peer revised.

[4] Y. C. Shin, D. H. Kim, D. J. Chae, J. W. Yang, J. I. Shim, J. M. Park, K. M. Ho, K. Constant, H. Y. Ryu, and T. G. Kim, "Effects of nanometer-scale photonic crystal structures on the light extraction from GaN light emitting diodes," *IEEE J. Quantum Electron.,* vol. 46, no. 9, pp. 1375-1380, Sept. 2010.

This journal informs the reader of the effects of crystals on GaN LEDs. This will help in my study when trying to decide on a more efficient way get more light extraction from the GaN LED device. This journal is credible because it is an IEEE journal paper that has been peer revised.

[5] E. Matoli, E. Rangel, M. Iza, B. Fleury, N. Pfaff, J. Speck, E. Hu, and C. Weisbuch, "High extraction efficiency light-emitting diodes based on embedded air-gap photonic-crystals," *Appl. Phys. Lett.,* vol. 96, p. 031108, 2010.

This journal informs the reader of how to get high light emission from LEDs using photonic crystals in the layout of the LED. This will help in study when trying to get the most light extraction from my GaN LED device. This journal is credible because it is an IEEE journal paper that has been peer revised. It has been cited 48 times.

[6] X. Jin, S. Trieu, F. Wang, B. Zhang, T. Dai, X. Kang, and G. Zhang, "Design simulation of top ITO gratings to improve light transmission for gallium nitride LEDs," *6th Int. Conf. on Info. Technology: New Generations,"* 2009, pp. 1-4.

This journal informs the reader of extracting more light efficiency of a gallium nitride LED with optimizing the device with ITO gratings. This will help in my study when trying to get the most light extraction out of the GaN LED device. This journal is credible because it is an IEEE journal paper that has been peer revised. Also, Professor Jin is the lead author.

[7] W. L. Yeh, C. M. Fang, and Y.P. Chiou, "Enhancing LED light extraction by optimizing cavity and waveguide modes in grating structures," *IEEE Journal of Display Technology,* vol. PP, no. 99, pp. 1-6, 2013.

This journal informs the reader of ways of enhancing the light extractions of an LED. This will help with my study when trying to see which grating structures will extract the most light efficiency. This journal is credible because it is an IEEE journal paper that has been peer revised.

Datasheet:

[8] Bridgelux, "Blue Power Die," DS-C17 datasheet, 2012 [Revised March 14, 2013].

This data sheet provides a diagram of the GaN LED. I will be able to compare my design with Bridgelux's design to achieve greater light extraction efficiency. Bridgelux is a leading developer and manufacturer of technologies and solutions transforming the $40 billion global lighting industry to a $100 billion market opportunity.

Patent:

[9] S. Nakamura, T. Yamada, M. Senoh, M. Yamada and K. Bando, "Gallium nitride-based III-V group compound semiconductor," U.S. Patent 5 877 558, Mar. 2, 1999.

This patent describes different types of gallium nitride fabrication designs. This patent will help me decide what shape and material would be sufficient and cost effective for my device.

Article:

[10] E. Matioli, M. Iza, Y. S. Choi, F. Wu, S. Keller, H. Masui, E. Hu, J. Speck, and C. Weisbuch, "GaN-based embedded 2D photonic crystal LEDs: Numerical optimization and device characterization," *Phys. Status Solid. C*, vol. 6, pp. 675-679, 2009.

This article informs the reader on optimizing the characteristics of GaN-based LEDs. This will help in my study by informing me of other parameters of my GaN LED device I can change in order to get the most light extraction efficiency from my device. This article is credible because it has been cited 13 times and it provided on Cal Poly's Library website.

Appendix B: Project Costs

Reasearch Project Costs

	PROJECT TASKS		MATERIAL COST ($)
PROJECT DESIGN	SPIE Photonics West 2014 Registration		$400.00
	Hotel		$350.00
	Travel		$100.00
	Food		$50.00
	Subtotal		**$900.00**