Proxima Centauri-Emulating InGaN LED: Our Path to Extraterrestrial Agriculture

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Abstract

InGaN is a robust and reliable material that can be designed to emit photons with energies ranging from 0.7 eV [1] to 3.44 eV [2]. InGaN is a direct bandgap material throughout its range, which enables increased relative efficiencies at any given energy level. Due to the small bandgap of InN, red and near-IR wavelengths have the potential to be produced with InGaN structures. This range of InGaN makes it a good choice to emulate light as it can be found on other worlds. Recreating the light on other worlds enables experimentation into extraterrestrial agriculture from Earth. Investigation of extraterrestrial agriculture is critical for a space-faring humanity to sustain itself [3]. The closest star to ours is Proxima Centauri and the closest potentially habitable planet outside our solar system orbits it, Proxima Centauri b [4]. Investigation into InGaN is done as a potential material and hole transport issue are overcome. Three light-emitting diode (LED) quantum well (QW) structures are shown at various points in the red to near-IR spectrum. A multi-quantum well (MQW) structure with carrier injection tuned wavelength is shown. Finally, an application of InGaN LED emulating peaks of other stars is shown using the solar irradiance spectrum of Proxima Centauri.

Introduction

Agriculture is one of the most critical developments in all of human history. It was through farming that humans first became sedentary around 20,000 years ago and through innovation in agriculture that societies have continued to progress forward. From the utilization of animals on farms to the massive tractors we see today, with every innovation more efficiency in food production is had which over time allowed less people to be farmers and more specialization in the labor market. Most recently, between the year of 1948 and 2015, agricultural output tripled, and the number of farmers decreased by 75% [5]. Agricultural technology and innovation are the sole source of this achievement.

Plants are receptive to the sun's spectrum in at similar wavelengths to the human eye, however, are more sensitive to the blue and red light, as can be seen in Figure 1 [6]. Within the chloroplasts of plants there are chlorophyll and carotenoids which converts solar energy into the fuel for the plant. Chlorophyll and carotenoids are sensitive to blue and red spectrums, respectively. The fine tuning of plant response to Sol, our sun, makes agriculture within the solar system doable without changing which wavelengths are responsive (though the level of responsiveness would need to increase as intensity is less the farther a planet is from the sun). However, this does pose issues for extraterrestrial agriculture under non-Sol solar irradiance.

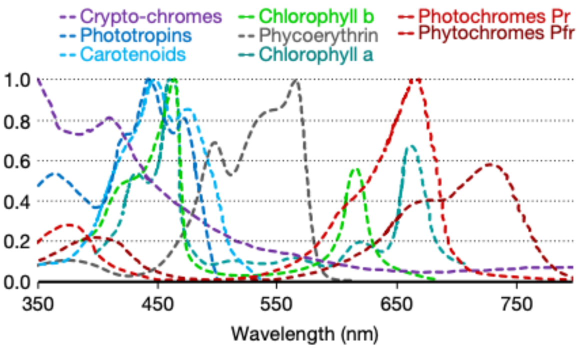

Figure 1: Plant Photosensitivity Spectrum for Molecules in Plants [6].

Just as farming was critical for the first development of cities, extra-terrestrial agriculture will be critical for the development of an inter-planetary and inter-solar system humanity. Current research in extraterrestrial agriculture focuses on modifying plants to grow using less water in soil anticipated on other worlds. However, these efforts ignore differences in solar intensity and wavelengths between planets [7]. Not considering solar irradiance is a critical oversight in current research because the growth of plants is strongly affected by the sunlight they receive. Further, many stars produce little to no irradiance within blue wavelengths, including the next star closest to us, Proxima Centauri, which will greatly impact photosynthesis.

Orbiting Proxima Centauri is Proxima Centauri b, the closest potentially habitable planet outside of our solar system [4]. Proxima Centauri is one such star that has almost no irradiance in the blue to UV range which can be seen in Figure 2. This will make current agriculture immensely difficult to scale if LED arrays mimicking Sol are needed for production. If a solution to extraterrestrial agriculture that has crops tuned to ‘local’ star wavelengths is not able to be scaled to the levels it is on Earth, interplanetary civilization will not be possible. To accomplish this, other star light imitation systems need to be created on earth to enable the development of future extraterrestrial crops as a first step towards developing complex human civilizations across the universe.

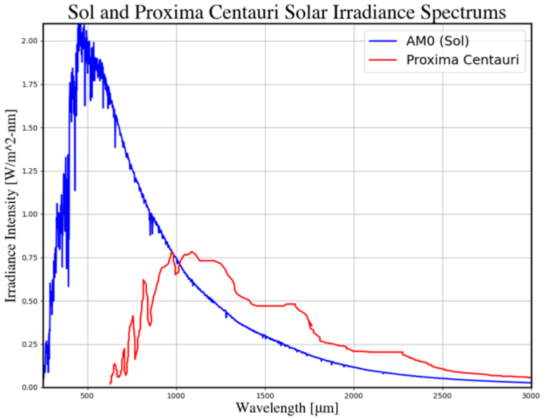

Figure 2: Extrapolated Solar Irradiance Spectrum of Proxima Centauri and AM0 of Sol

Materials that should be used to produce LEDs that emulate other stars must be able to cover a wide range. These materials can include ternary compounds using GaN, AlN, and InN, which can cover from 0.7 eV to 6 eV when combined [2]. Due to the red to near-infrared (NIR) spectrum of Proxima Centauri, I will be investigating the use of InGaN to produce the desired solar irradiance spectrum for extraterrestrial agriculture on Proxima Centauri b.

Technical Background

The key feature that will be utilized in the design of the LEDs within this project is quantum wells. Quantum wells (QWs) are nano-scale structures that confine carriers, such as electrons and holes, to one dimension. This confinement creates a "well" of potential energy that contains quantized energy levels which hold the carriers. An example of a QW structure can be found in Figure 3. Engineering of the band structure within QWs enables specific energy levels to be chosen and thus specific wavelengths emitted when radiative recombination events occur.

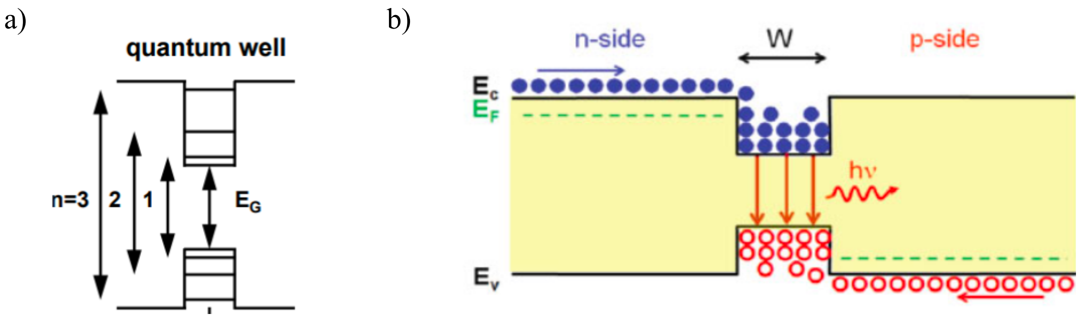

Figure 3: a) Quantum Well Energy Levels. b) Carrier Movement Within Quantum Wells

LED structures can utilize the properties of QWs to achieve efficient light emission at desired wavelengths. LEDs are minority carrier driven devices that also utilize the inherent properties of p-n junctions to generate current. When quantum wells are placed within the barrier of the p-n junction, the carrier diffusion becomes confined by them with electrons being injected from the n-side and holes being injected from the p-side. This confinement promotes the recombination of electron hole pairs (EHPs). As the EHPs recombine, they emit photons with wavelengths corresponding to the energy levels in which the EHP came from. For ternary compounds, the bandgap, and therefore the emitted photon wavelength, can be tuned using Vegard's Law. The equation for Vegard's law for a ternary compound $A_xB_{1-x}C$ for bandgap, E_g, can be seen below.

$$E_g(ABC) = E_g(AC)x + E_g(BC)(1-x) + bx(1-x) \tag{1}$$

Where b is the bowing parameter which is unique to each material. Vegard's law without the bowing parameter can be used to determine any given parameter of a ternary compound based on the material parameters of its component compounds. This fact will be later used to obtain more precision within the model of the Proxima Centauri-emulating LED.

Two important ways to characterize LEDs are by looking at their internal quantum efficiency (IQE) and their power efficiency (PE).

IQE is defined as the ratio of the number of photons emitted by the active region of the device per second to the number of electrons injected into the device per second. One way of calculating the IQE is by taking the ratio of radiative recombination to total spontaneous recombination within the device. The equation for this is seen below [9]:

$$\mathrm{IQE} = \frac{\mathrm{R_{rad}}}{\mathrm{R_{spon}}} = \frac{\mathrm{Bn^2}}{\mathrm{An + Bn^2 + Cn^3}} \tag{1}$$

Where R_{rad} is radiative recombination, R_{spon} is spontaneous recombination, A is the Shockley-Reed-Hall recombination coefficient, B is the radiative recombination coefficient, C is the Auger recombination coefficient, and n is the number of excess carriers.

PE is defined as the ratio of power outputted by the device, P_{out}, to power inputted into the device, P_{in}. The equation can be seen below [9]:

$$\mathrm{PE} = \frac{P_{out}}{\mathrm{P}_{in}} = \frac{P_{photons}}{IV} \tag{3}$$

Where P_{photon} is the power emitted by photons from the device, I is the operating current of the device, and V is the operating voltage of the device.

High In Percentage InGaN LED Modeling In Crosslight

To make an LED using InGaN at the desired wavelengths for Proxima Centauri a large In percentage within the material is required. It is known in literature that high In content creates issues for carrier diffusion. These issues are caused in part by localization due to In clustering, high defect density, non-radiative recombination sinks, and small diffusion constants due to low hole mobility, which causes quick consumption of excess carriers [10, 11, 12]. The first two issues arise from fabrication processes so the later one will be what is focused on the modeling within this project.

This issue can be seen in the InGaN MQW LED in Figure 4. The band diagram and hole concentration of this device can be seen in Figure 4b, and 4c respectively. It can be clearly seen in the figure that the holes were not being transported throughout the MQW structure. This caused only one of the QW to contribute to radiative recombination and made the others effectively useless. If a monolithic InGaN LED is to be created that can capture the spectrum of stars, the hole transport issue needs to be resolved.

Three potential solutions to this issue were found through rigorous experimentation and literature review. One solution is to increase the electric field within the QWs to increase the kinetic energy of the holes which should increase the mobility of the holes and thus increase the hole injection [12]. A way to recreate this kind of behavior using the Crosslight software is to enable polarization within the device. This method on its own proved to help a bit with structures that had large quantum barriers (QB) but was not necessary when smaller QBs were used. Figure 4 was done under these conditions and as it was stated before, the hole diffusion issue was still clearly present, despite the small improvement.

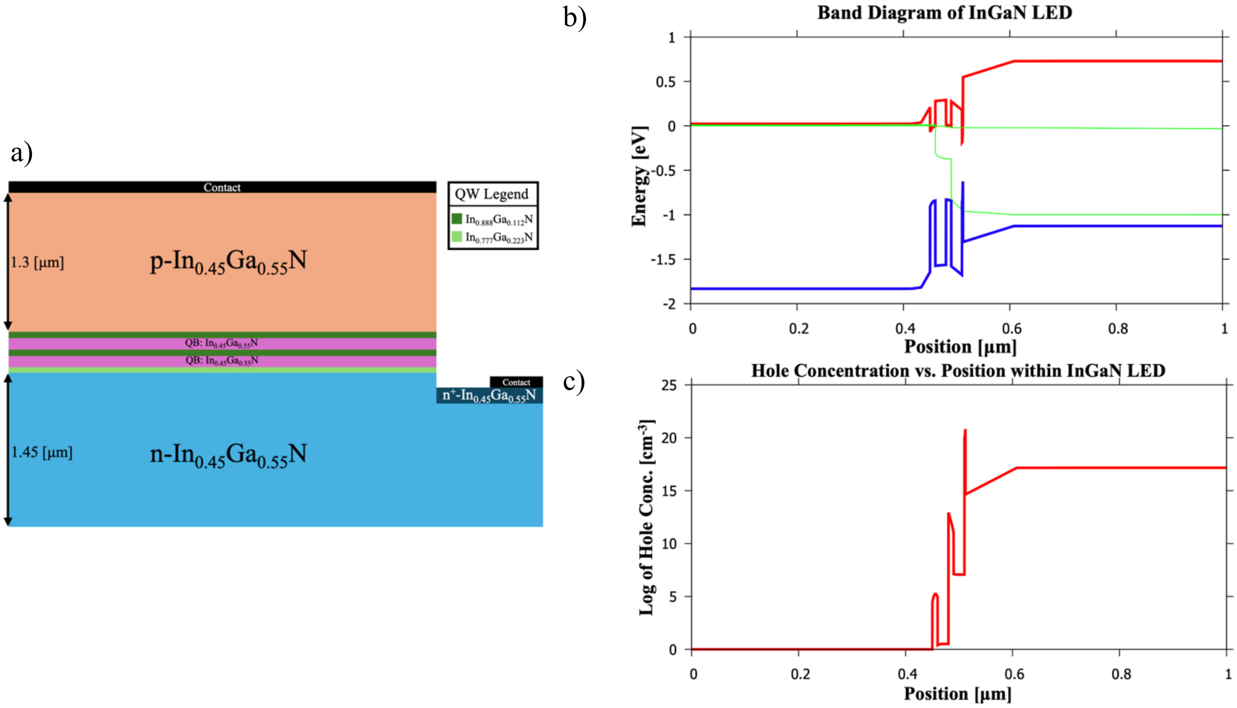

Figure 4: a) Poor Hole Diffusion LED Structure, b) Band Diagram of Structure During Operation, and c) Hole carrier concentration throughout device.

Another solution was to increase carrier injection into the device. This solution was found experimentally with the idea being there if more carriers injected, there would be a greater probability of holes going farther within the structure. This solution worked for MQWs targeted at producing both single and multiple wavelengths. When multiple wavelengths are desired to be emitted, high carrier injection is required.

The most effective solution to promoting radiative recombination throughout all the QWs is to decrease the QB [13, 14, 15]. Decreasing the QB enabled greater IQE for single frequency LEDs due to more of the QWs being populated. Decreasing the QB also enabled monolithic InGaN structures that could emit light from multiple wavelengths when under high carrier injection. Working LEDs with these changes are seen throughout the rest of the section.

With a working solution to the hole carrier transport issue, InGaN red to NIR LEDs could then be produced. The band gaps chosen were 0.85, 1.6, and 2.3 [eV] which both corresponds to peaks within the Proxima Centauri Solar spectrum and show InGaN's use in red and NIR. Using Vegard's law as described in equation 3, $E_g(InN) = 0.7$ [eV], $E_g(GaN) = 3.44$ [eV], and a bowing parameter of -1.43 [eV] (which is what is used in the Crosslight software), In percentage for each of the given wavelengths was determined. The calculated results were 0.965, 0.777, and 0.555, respectively.

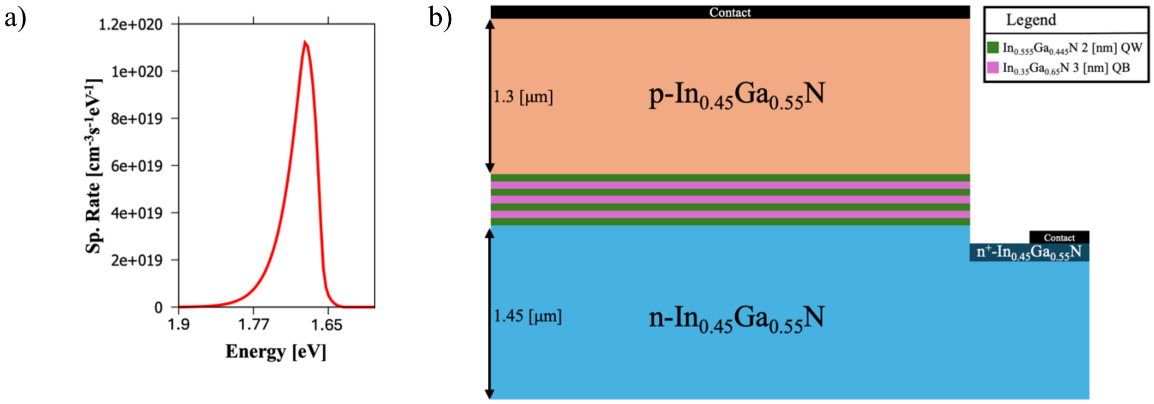

Figure 5: a) SP Rate of InGaN LED with 55.5% In b) InGaN LED Device Structure with 55.5% In

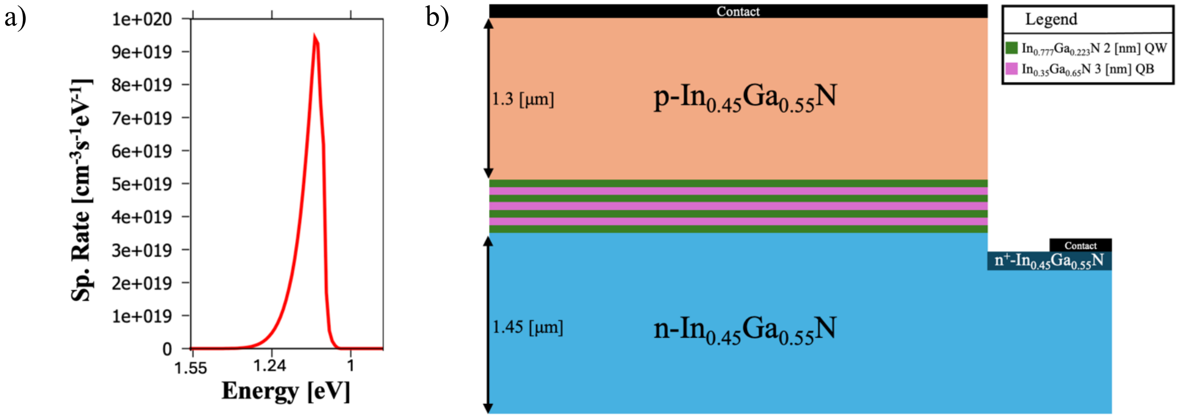

Figure 6: a) SP Rate of InGaN LED with 77.7% In b) InGaN LED Device Structure with 77.7% In

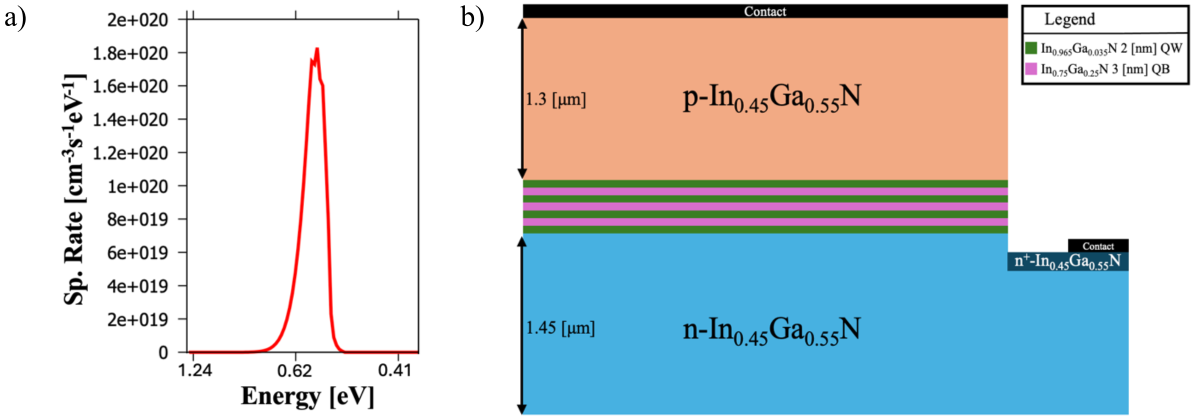

Figure 7: a) SP Rate of InGaN LED with 96.5% In. b) InGaN LED Device Structure with 96.5% In

The models' peaks deviated from the predicted energy levels, however still proved InGaN's use for red to NIR. One reason that could have led to the deviations is some InN constants within the material library used outdated values, or values corresponding to GaN as default. For the final creation of the Proxima Centauri LED, different material parameters were used.

An interesting side effect of the hole transport difficulties within InGaN LEDs is the ability to shift the energy of emitted photons by varying the carrier injection. As the carrier injection is increased, a blue shift occurs in the emitted photon wavelength. This kind of shift within hetero-structures is called the quantum-confined Stark effect [16]. This effect can be amplified by creating a MQW structure that has different emitted energies built into it. Through experimentation with the Crosslight model, an InGaN LED was developed that could have its peak emission shifted from 0.7 to 1.1 [eV]. The structure of the LED and the emitted energy as a function of carrier injection can be seen in Figure 8.

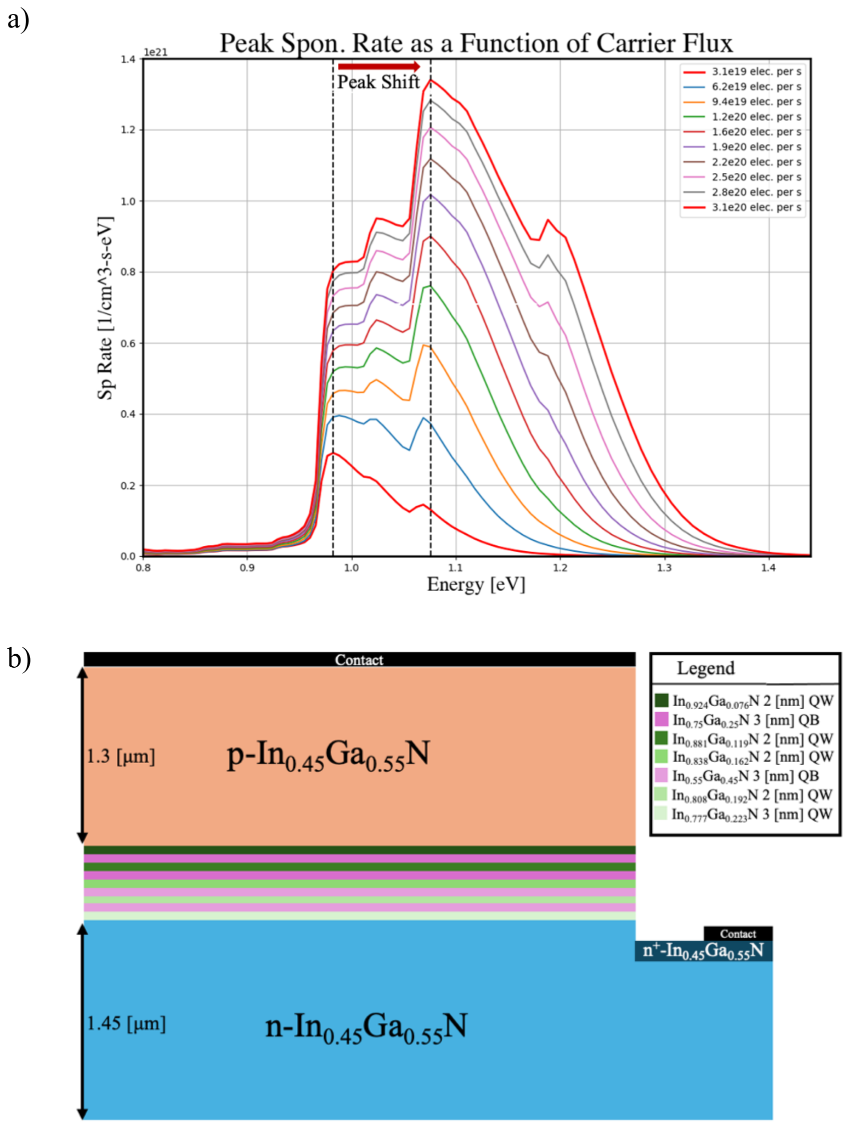

Figure 8: a) Spectrum Peak Shift with Respect to Current Injection, and b) InGaN LED Monolithic Structure used to test peak shifting.

Emulating Proxima Centauri On Crosslight

Now to prove InGaN is a useful material for extraterrestrial agriculture, I used it to emulate the solar spectrum of Proxima Centauri. The energy spectrum that Proxima Centauri covers ranges from 0.25 to 2 [eV]. In the monolithic InGaN LED, photon emission energies of 0.75, 1.25, and 1.75 [eV] were targeted. Using Vegard's law and through experimentation it was found that QWs with In percentages of 92.4, 83.8, 77.7, and 55.5 were required.

Vegard's law, equation 1, without the bowing parameter adjustment was used to find more realistic material parameters. Specifically, hole mobility, hole effective mass, and electron effective mass were adjusted. Other material parameters were experimented with, however showed little to no change from default parameters within Crosslight. Table 1 contains the initial parameters used for InN and GaN to make the adjustments.

Mat. Param.	**InN**	**GaN**
μ_h	250	440
m^*_h	$1.63m_0$	$0.8m_0$
m^*_e	$0.11m_0$	$0.2m_0$

Table 1: Material Parameters for InN and GaN [16].

Based on the findings in the previous section, the Proxima Centauri LED was made with 3 [nm] QBs and 2 [nm] QWs, which can be seen in Figure 9a. The band diagram for the device under operation can be seen in Figure 9b. The quasi-fermi level placement in the band structure can be seen to have good distribution of carriers throughout each of the quantum wells. The device was operated at high carrier injection levels to facilitate the greatest transport of holes. Optimal operating conditions were found to occur when the carrier injection level was $1.25\text{x}10^{20}$ [electrons / m-s] which can be seen if Figure 9c.

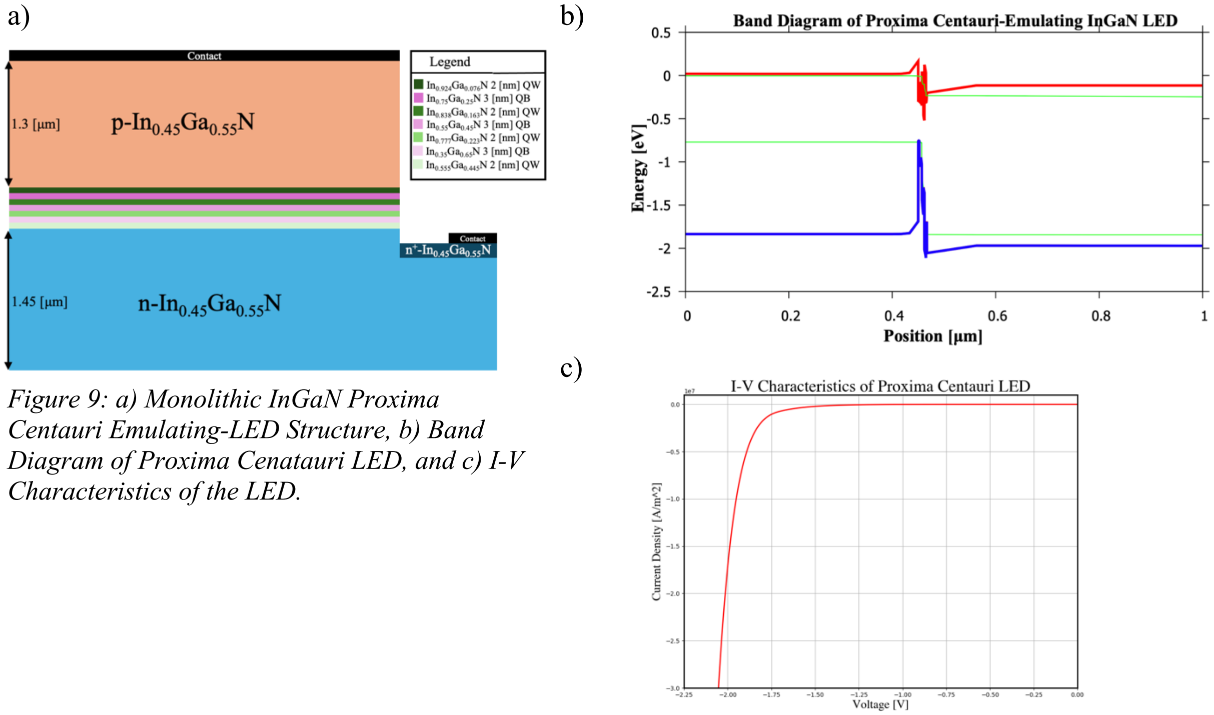

Figure 9: a) Monolithic InGaN Proxima Centauri Emulating-LED Structure, b) Band Diagram of Proxima Cenatauri LED, and c) I-V Characteristics of the LED.

The result included emission peaks at approximately 1.65, 1.3, and 0.7 [eV] as can be seen in Figure 10a. These peaks correspond to locations in the irradiance spectrum of Proxima Centauri. Figure 10b contains a labeled plot of the solar irradiance of Proxima Centauri showing where each of the peeks can be found.

The operation of this device at higher carrier injection came with the tradeoff of efficiency. Both the IQE and PE peak well before the operating point of the device and have efficiencies of 34.3% and 20.8%, respectively, at the optimal carrier injection. Plots of both efficiencies can be found in Figure 11.

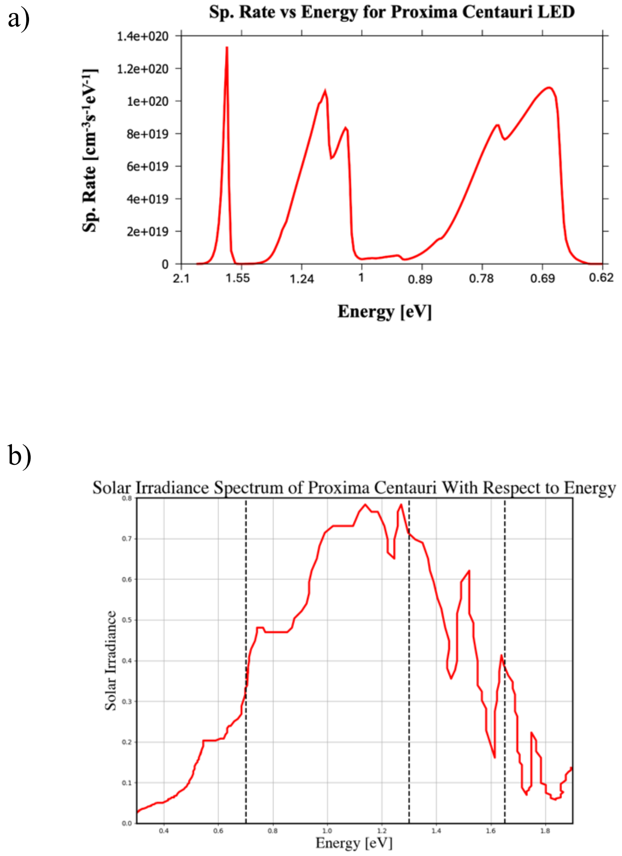

Figure 10: Proxima Centauri-Emulating LED sp rate at given energies. b) Corresponding peaks on the Proxima Centauri Irradiance Spectrum.

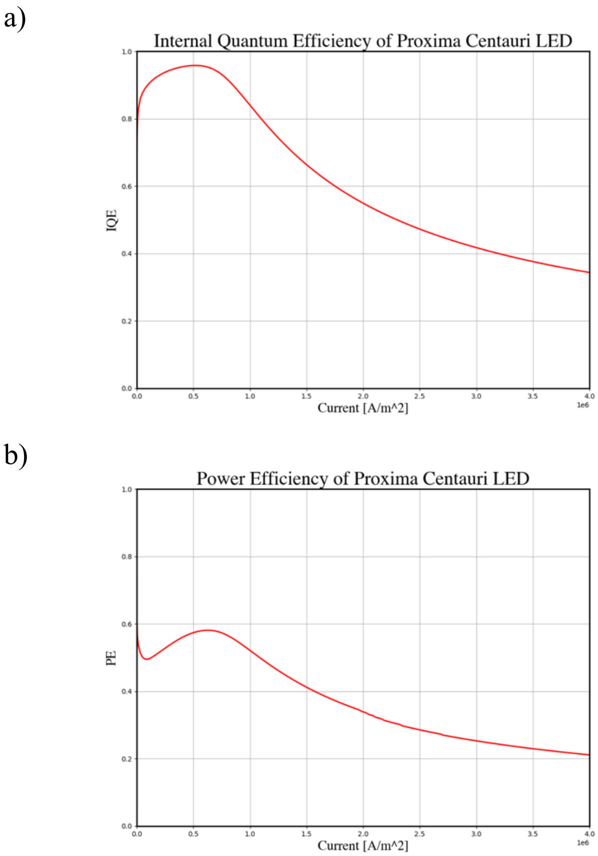

Figure 11: Proxima Centauri-Emulating LED a) Internal Quantum Efficiency, and b) Power Efficiency

Nevertheless, a working LED that emulates portions of the irradiance spectrum of Proxima Centauri is shown. The carrier transport issue was thoroughly investigated, and solutions were found to get the desired operation. Further optimizations can be done to improve these efficiencies. The device in its current form could still be operational and promote investigation into extraterrestrial agriculture.

Conclusion

InGaN is a difficult material to develop LEDs with in the red to NIR range. The major limitation of InGaN comes from the difficulty in carrier, specifically holes, transport throughout this material. The reasons are derived from the intrinsic properties of In which place great limitation on hole diffusion. That being said, there are multiple solutions to this issue, as shown throughout the report, and design tradeoffs can be made to enable functionality. The greatest solutions include increasing carrier injection into the device and decreasing the width of the quantum barriers. Using these methods efficient and effective single energy emission LEDs were shown throughout the red to NIR range.

Designing a monolithic LED that emits photons with energies throughout the red to NIR wavelengths posed great difficulty as well. Beyond the normal transport issues associated with high In content in InGaN, the polarization within the MQW structure creates a blue shift within the spectrums caused in part by quantum-confined Stark effects due to there being greater influence between QWs because the QBs had to be made so thin. This required fine tuning during experimental modeling in order to reach the desired spectrum from the LED. The trade-offs associated with this fine-tuning cause efficiencies to be low under operation conditions. Further work could be done to increase these efficiencies with temperature regulation and QB doping being potential solutions.

Despite the difficulty in designing InGaN LEDs from red to NIR, the impact made could be profound. As shown in this report, InGaN can be used to create LEDs that emulate spectrums of stars other than our own. Specifically, I have shown an InGaN LED design that emulates parts of the spectrum of Proxima Centauri. Such LEDs can be critical innovations to enable humanities expansion throughout the galaxies. Enhancing researchers' abilities to overcome the great obstacles that extraterrestrial agriculture face pushes humanity further towards its dream of being amongst the stars. Moreover, if terraforming occurs within our solar system, then the use of local materials in the atmospheric creation may also create situations where the wavelengths reaching the surface are different in intensity and location than on Earth, making this system a solution for crop production in these emerging environments as well.

Humanities future must be fueled by sustainable agriculture regardless of the star shining on us. The problem of developing extraterrestrial agricultural systems robust enough to sustain human civilization on other planets must be solved on Earth ahead of any colonization. Through this report I am suggesting a novel direction for developing extraterrestrial crops. Instead of designing LEDs to mimic the sun to get plants to grow, we should design plants to respond to irradiances throughout the solar system and galaxy. InGaN LEDs like the one shown in this report, and their application into extraterrestrial agriculture, can be first steps towards allowing future humans to call Proxima Centauri b home.

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