Emission Rate Variation and Efficiency Measurement in TiO_2 Light Emitting Diode

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Abstract. Titanium dioxide light emitting diode was successfully designed and characterised. An approach in developing TiO_2 was based on cylindrically symmetric configuration with shorter computation time. The main goal of the research was to look into the performance of light emitting diode by using titanium dioxide and compare its validity with the standard or common criteria. The circular chip of titanium dioxide with 60 μm diameters was made with a circular active region formed by p and n-type dopants. The drastic reduction of internal quantum efficiency droops almost to zero value even though the current started to increase by 0.002 mA. The efficient operation within the device was observed that it would occur at the lowest current 0.01 mA while the total emission rate shown linearly increased at axis (0.002 mA, 5.6 (1/s)). This light emitting diode based on titanium dioxide also enabled to operate at lower turn-on voltage as low as 0.5 V. As the increment of voltages, the distribution of emission rate became less concentrated towards the top active of p-type layer of the device. The result also compared the two meshes where it was found that the refined mesh was focused around the p-n junction.

1 Introduction

Light emitting diode (LED) is one of solid state lighting device that emits photons when the electrons and holes are recombining as electric current flow through it [1]. Previously, the fluorescent light bulbs are currently used in daily application. However, due to problem of fluorescent light bulbs in electrical power consumption, lifetime and also reliability have attracted researchers to develop light emitting diode technology as primary lighting source in future. In 1962, as the first inventor of LED, Nick Holonyak believes the time ahead in LED [1].

Various semiconductor materials that are widely used in preparing LED such as Zinc Oxide (ZnO), Gallium Nitrites (GaN), Zinc Selenide (ZnSe), and Gallium Asenide (GaAs). By using these materials, the electrical energy of LED can be converted into lighting energy as the current conducting across the p-n junction. For instance, ZnSe-based white LED was homoepatixally prepared by using ZnSe substrates via molecular beam epitaxy that was reported in [2]. As a result, the greenish-blue emission at origin 483 nm from epitaxial layer

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was observed and is found that the emission wavelength of the LED and the measured chromaticity coordinate were almost independent of the injected current.

Since these materials are most common in LED preparation, the idea of using a Titanium Dioxide (TiO_2) has been proposed. This is due to low cost material, good chemical and thermal stability [3-5]. Generally, the common semiconductor that relates to the band gaps shows 3 eV to 4 eV results in ultraviolet light emitting diode (UV-LED) colour [6]. Compared to other materials as stated above, with the higher of band gap energy which is around 3.2 eV to 3.4 eV [7] and the higher of wavelength for TiO_2 that is $\leq$ 388 nm, hence TiO_2 has been a good candidate for the LED performance enhancement research. These advantages make TiO_2 as a potential material to be used in the UV LED applications due to bandgap energy and wavelength itself.

Two studies are reported in this work; voltage sweep studyand semiconductor initialization study. Voltage sweep study is used to investigate on the internal quantum efficiency (IQE), total emission rate, current-voltage curve and sign dopant concentration. Consequently, IQE graph is used to observe the radiative recombination in the device while total emission rate is specified to investigate the total emission in the device over time that varies with the increment of current. Also, a plot of current-voltage graph is used to determine the turn-on voltage of the device. The voltage bias is swept from 0 V to 5 V. A sign dopant concentration is used to detect the color changes around the p-n junction. Furthermore, semiconductor initialization study is used for electric potential and the drift-diffusion equations for electrons and holes in a semiconductor material. This is to refine mesh adaptively based upon the gradient of the impurity doping concentration. Two different meshes are compared in order to spot the denseness around the p-n junction. In short, these studies are focused on the internal quantum efficiency, total emission rate, current-voltage, sign dopant concentration, emission rate and mesh analysis that results in LED performances

2 Structure of LED

The model structure of LED based on TiO_2 design was illustrated in Fig. 1. The design was started by conducting a two-dimensional axisymmetric with 60 μm diameter circular chip of TiO_2 with 3.42 eV of band gap energy as the main material. A rectangular chip was designed as shown in Fig. 1 below due to the crystalline structure of semiconductor material. The active region that formed by the p and n-type doping was created in a circular pattern. By assuming the r = 0 axis as the axis of symmetry, the LED design was presented by a thickness of 10 μm with 30 μm wide rectangle. The size of designed LED chip was about 60 × 10 μm^2. N-side contact was heavily doped at the bottom of device with thickness of 7.5 μm, while 2.5 μm was doped at the top. This is to ensure the most recombination takes place in p-side. P-type contact was deposited directly on the top surface at the centre of the device with a metal disk. Also, the n contact that was etched down on the n side layer of the device was to allow electrical contact that was deposited onto n-type side of the p-n junction. An auger recombination property has been added into this LED. It functions as a non-radiative recombination and to demonstrate the behaviour of the efficiency of the radiative emission which results in IQE and total emission rate. In order to look into the current-voltage curve, voltage sweep was adopted in the study. The voltage bias across the device was swept from 0 V to 1.5 V to observe the turn-on voltage in LED performance. Apart from that, sign dopant concentration was determined within the device. The emission rate throughout the device was also measured in active region of p-n junction with different of bias voltages. Following that, the model of emission rate was obtained in three-dimensional structure. Finally, the mesh results were analysed.

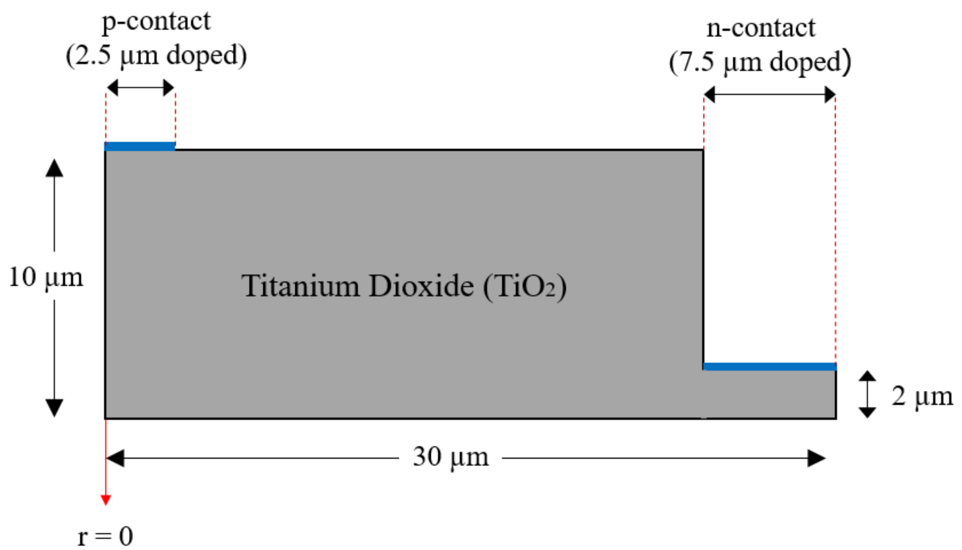


Fig. 1. The basic LED structure based on TiO_2 material

3 Results and Discussion

In order to study the performance of LED based on TiO_2, Fig. 2 was presented. The internal quantum efficiency (IQE) versus current was plotted in order to measure the efficiency of the radiative recombination of the LED device. IQE is the rate of emission variation with electrons injection. Generally, IQE gives the part of injected electrons that radioactively recombine to emit the LED light. In other words, the number of generated photons in the active region of p-n junction per electrons injection. Since the IQE only measures the efficiency of radiative recombination within the device, the actual efficiency of LED needs to consider other parameters such as size or thickness of the design.

Figure 2 depicts that IQE droops as current density increased. This IQE droops are also known as LED droops. Generally, LED droop is known as the LED efficiency decreases with the driving current [8]. LED droop can cause the amount of emitted light increases linearly with the increase of bias current. Apart from that, the drastic reduction of IQE droops almost to zero even though the current is increased by 0.002 mA. This indicates that the efficient operation of LED would occur at the lowest current 0.01 mA. This is due to the IQE results that show a decrement in LED efficiency as the current density increases in Fig. 2.

Generally, the amount of LED emission increases with bias current. Fig. 3 illustrates the evolution of total emission rate as a function of current. As a consequence, the total emission rate shows a linear increment starts from axial point of 0.002 mA, 5.6 (1/s). This indicates the total emission rate was increased with the higher current.

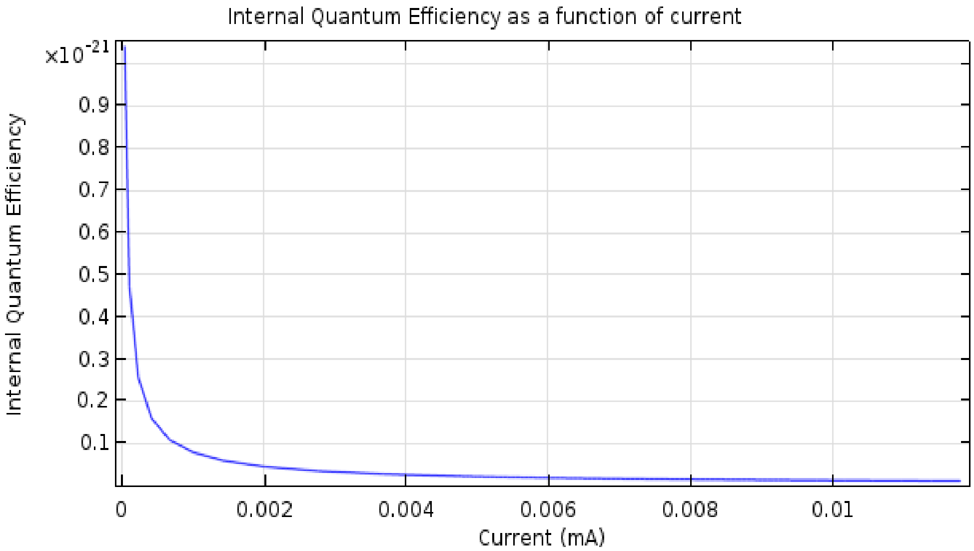


Fig. 2. The internal quantum efficiency as a function of current.

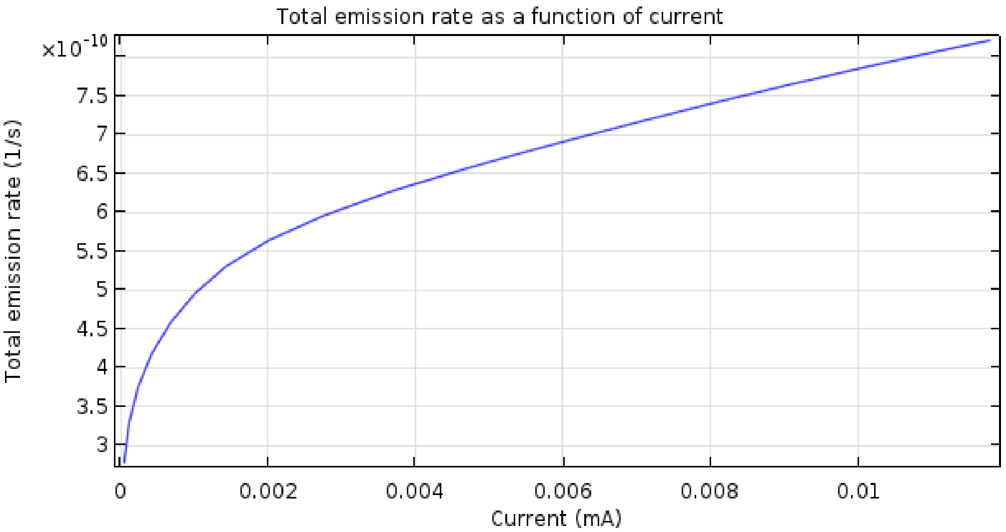


Fig. 3. Evolution of total emission rate as a function of current.

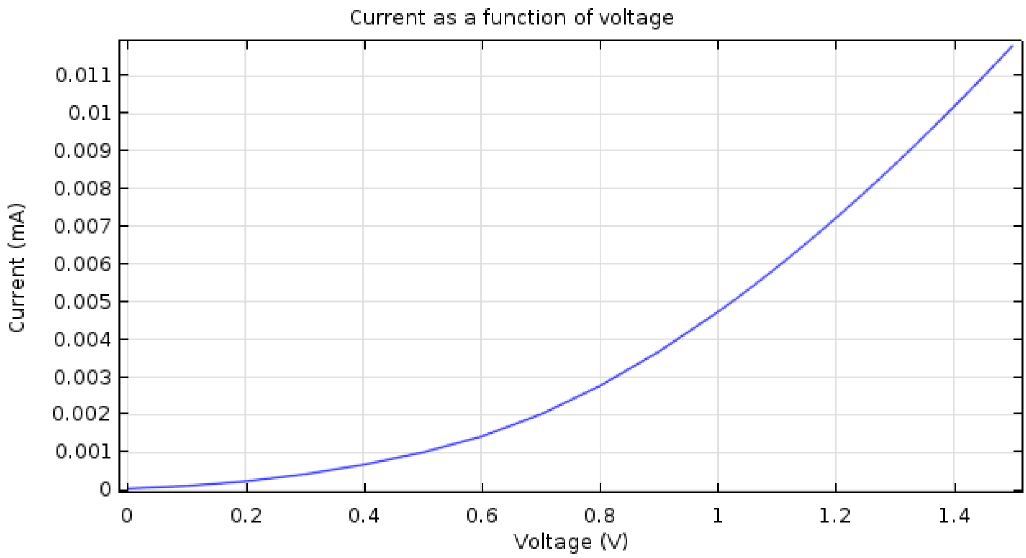


Fig. 4. Development of current as a function of voltage.

Despite of internal quantum efficiency and total emission rate that varies with bias current are important in LED designing, current versus voltage plot also plays important role in the performance of LEDs. Fig. 4 shows the development of measured current-voltage (IV) characteristics of the LED based on TiO_2. It was found that the voltage increased as the injection current increased. This shows that the LED could operate at lower of turn-on voltage as low as 0.5 V. This indicates that the LED starts to conduct current as the bias voltage is above 0.5 V. Moreover, closer to above 0.5 V of bias voltage, the current grows rapidly up to 1.5 V as a function of voltage.

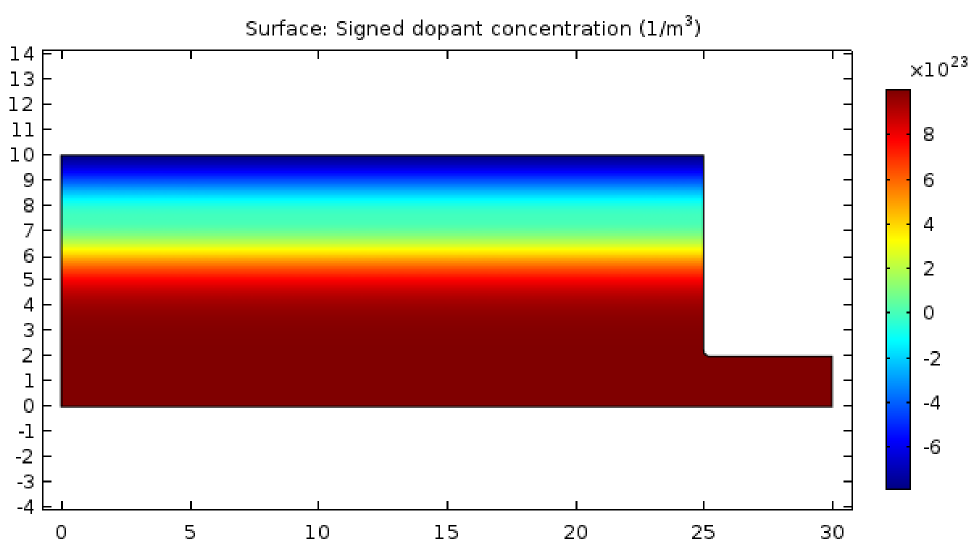
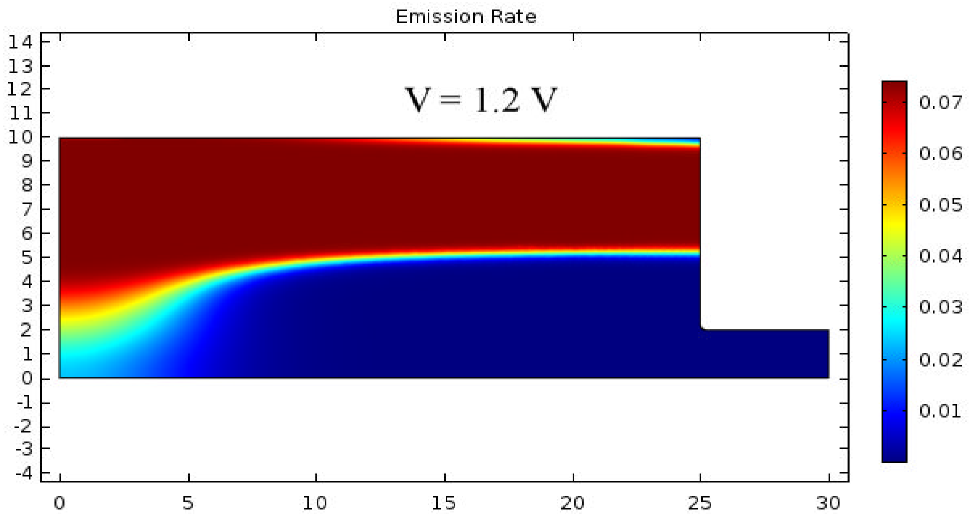
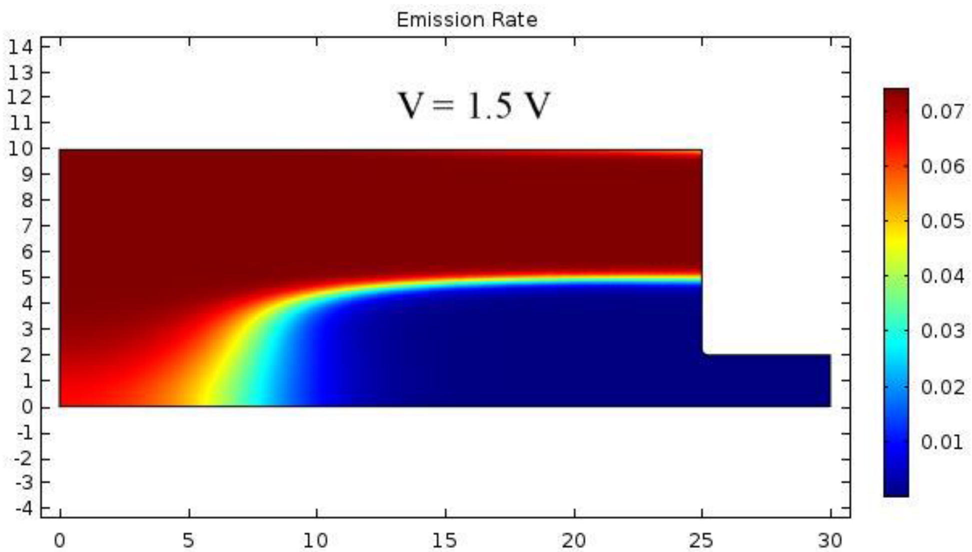


Fig. 5. Evolution of signed dopant concentration.

In the sign dopant concentration, the distribution of radiative emission within LED device was investigated with an increment of bias voltage. The sign dopant concentration relation was used to observe the changes of the spatial light emission that distributed towards the p and n-type layer of LED device. Fig. 5 shows default result obtained in a two-dimensional form of LED based on TiO_2 model where the doping concentration was transited from n-type surface layer to p-type layer in which LED light can occur. Different colours in the figure indicate the different log of dopant concentration. The blue area designates a lower of dopant concentration, while red denotes a higher of dopant concentration. This specifies higher doping concentration results at n-type layer in red while lower doping concentration at p-type layer in blue. Therefore, the changes of doping colour that transit from n-type layer to p-type layer will create a region of the light emission within the device.



(a)



(b)

Fig. 6. Correlations emission rate at voltage bias at (a) V = 1.2 V and (b) V = 1.5 V.

As the bias voltage was applied, the emission rate showed the colour changes of doping concentration throughout the device. This correlation was depicted in Fig. 6 where the emission rate was observed at bias voltages of 1.2 V and 1.5 V. Thus, as bias voltage of 1.2 V and 1.5 V were applied, both of the colour regions of p-type layer were changed from blue to red. This denotes that the light emission within the device occurs. In addition, it can be seen that as the increment of voltage, the distribution of emission rate for both voltage biases becomes less concentrated towards the top active of p-type layer of the device.
However, even though the emission rate does not distributed towards the p-type layer of the device, the light emission of within LED device still can occur. This indicates that by increasing the current the light of the device will be emitted as well as there is increment of current and voltage. To be more apparent, Fig. 7 illustrates the spatial distribution of emission rate in three-dimensional version. The circular active region of LED based on TiO_2 model was formed.

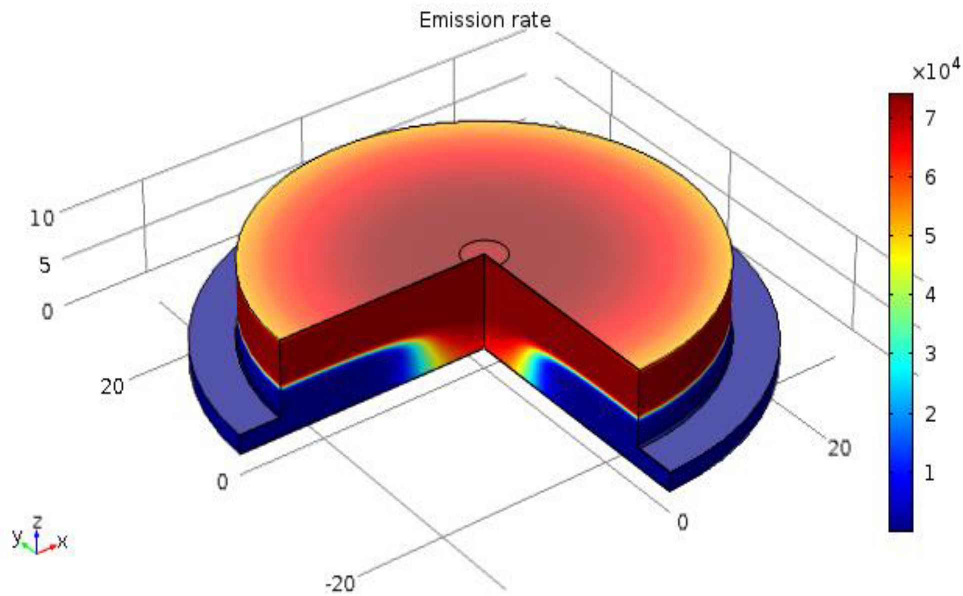
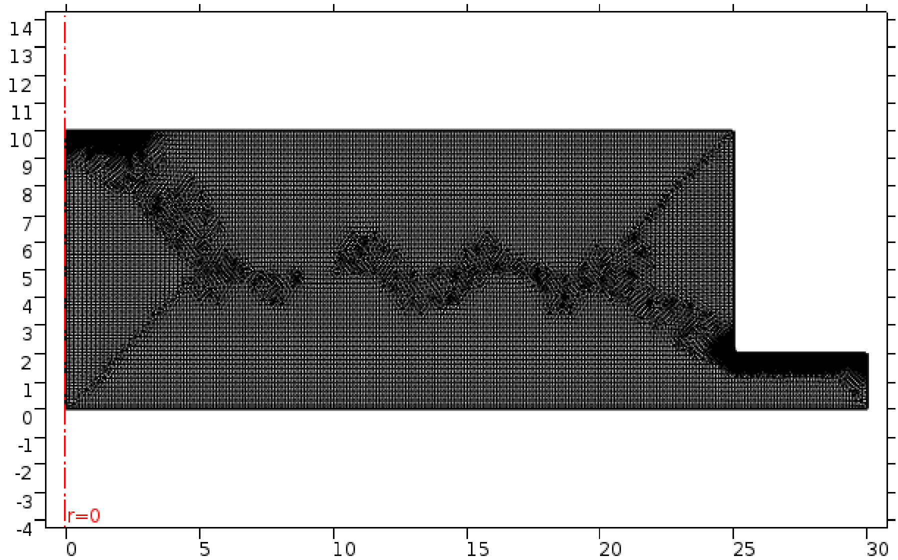
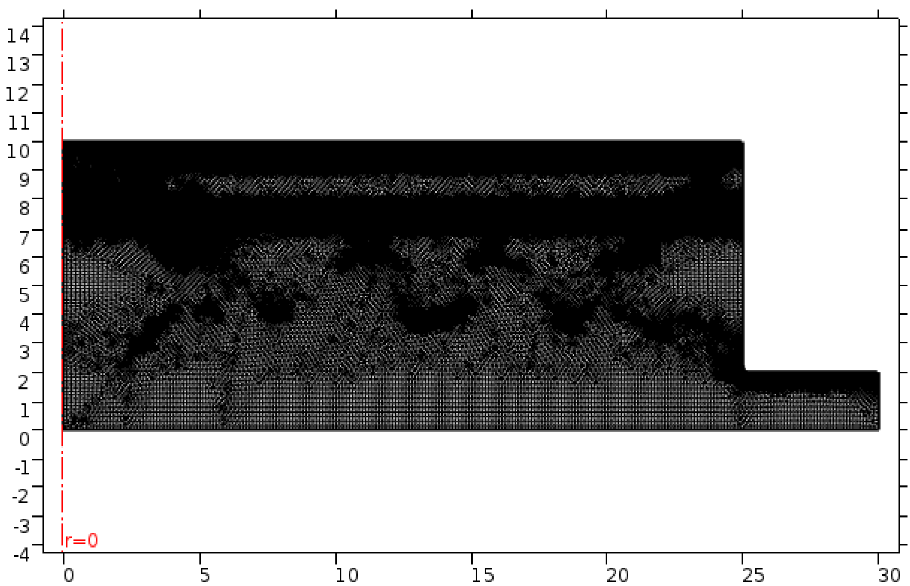


Fig. 7. Magnified view 3D model structure of emission rate.

In brief, from Fig. 2 to Fig. 7, some results have been computed to the observation that relates with the voltage study sweeps. Consequently, the LED material, high efficiency, current voltage characteristic, as well as emission rate have a certain degree of effects in producing LED device. In short, these factors play important role on LED performances. Following that, Fig. 8 represents the mesh refinement which is to observe the semiconductor initialization study. The study was focused on the observation to refine the mesh around the region of dopant concentration. Mesh is defined as a geometrical object that used as a set of finite elements in LED based on TiO_2 modelling [9]. Fine mesh was studied in order to observe the mesh in the impurity of doping concentration. This mesh provides a fine mesh at the p-n junctions which requires a higher resolution in order to see the changes of mesh. The results were compared between two meshes where the mesh was set to default mode which denoted as Fig.8 (a) and mesh that was set in fine mode indicated as Fig. 8 (b). It can be seen that the refined mesh graph was denser around the p-n junction. As a result, the gradient of mesh density increased in the p-n junction region. This indicates the positions of the highest gradient electrostatic potential at p-n junction and the current flows were changed.



(a)



(b)

Fig. 8. Evolutions of (a) mesh 1 is the default mesh and (b) mesh 2 is the refined mesh output.

4 Conclusion

We have successfully demonstrated a LED structure based on TiO_2 material. It was found that drastic reduction of IQE droops almost to zero as the current was increased by 0.002 mA. Following that, it was observed that efficient operation of LED based on TiO_2 material would occur at the lowest current of 0.01 mA. The total emission rate shows a linear increment axis (0.002 mA, 5.6 (1/s)). This LED based on TiO_2 design shows that the LED could operate at lower turn-on voltage as low as 0.5 V and below. In addition, it was noticed that as the voltage was increased, the distribution of emission became less intensed towards the top active of p-type layer of the device. The refined mesh was more dense around the active region of p-n junction in comparison with other mesh.

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