Effects of Current Spreading in GaN-based Light-emitting Diodes Using ITO Spreading Pad

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Abstract—In conventional LEDs, a mesa-structure is usually used and it causes the current to be overcrowded in a specific region. We propose a novel structure of GaN-based LED to overcome this problem. In order to distribute the current in an active region, a spreading pad is inserted at the p-type region in the GaN based LED device. The inserted spreading pad helps the current flow because it is more conductive than the p-type GaN layer. By performing electrical and optical simulations, the effects of the spreading pad insertion are confirmed. The results of electrical simulation show that the current spreads more uniformly and more radiative recombination is produced as well. Moreover, from the optical simulation, it is revealed that the ITO is less absorptive material than p-GaN if the condition of specific wavelength sources is satisfied. Considering all of the results, we can conclude that the luminescent power is enhanced by the spreading pad.

Index Terms—Spreading pad, GaN LED, current spreading

I. INTRODUCTION

Recently, the GaN-based LED has received much attention for its high efficiency and long life expectancy [1-4]. Moreover, it has been improved in aspects of material quality and extraction efficiency to become a general light source [5, 6]. Typical LED devices usually take a shape of the mesa-structure [7-9]. The reason is that the mesa structure has advantages in that contacts are readily implementable, based on the epi-grown p-n junction [10, 11]. The performance of LED devices with a mesa structure depends on lateral carrier injection. However, the major problem of using the lateral carrier injection is that it can lead to a non-uniform current spreading in the GaN based LEDs [12, 13]. Non-uniform current spreading can significantly degrade the performance of GaN-based LED in that the current becomes overcrowded in a localized region of the device. This problem is caused by the difficulties in manufacturing a heavily doped p-type material [14-16]. Since non-uniformity occurs due to the lateral resistance of p-type layer, modification of physical thickness might not be the right solution. Many researches have tried to solve this problem by using spreading layers [17-19]. Until now, indium-tin-oxide (ITO) has been used broadly as a current spreading layer for its transparency and low resistance [20-22]. Although the ITO in the LED device makes current spread widely toward the active region, however, the non-uniformity of current spreading has not been solved completely [23, 24]. The reason is that as the ITO layer becomes thicker, the problem of non-uniform current in the LED can be improved. Meanwhile, emitting light through the ITO layer gets also lowered. To be specific, in case of operating the device with high bias, the current, injected into the typical LED, can be overcrowded in the region near n-type contact due to the difference of the resistance between current spreading layer and p-type GaN layer. Therefore, for the purpose of
improving the uniformity of current spreading, the structure of the LED needs to be redesigned.

In this paper, we propose the insertion of a spreading pad in order to increase uniformity of current in the GaN-based LED device. To confirm the effects of inserting spreading pad, the electrical and optical TCAD simulations were performed. In addition, optical simulation was performed to find out how the generated light in the proposed structure influences on external quantum efficiency. From the simulation, it was confirmed that the generated light in the active region can be emitted through the inserted spreading pad when it is with specific wavelengths.

II. DEVICE STRUCTURE

Fig. 1 shows the schematic cross-view of the GaN-based LED device in which spreading pad is inserted. The used LED device is the conventional one with mesa structure and the undoped layer is used as a substrate. The cross-section area of the undoped GaN layer is 10 x 1 μm\(^2\). On the undoped GaN layer, the n-type GaN layer is set and its depth is 0.5 μm. On the n-type GaN layer, the active layer whose cross-section area is 9 x 0.001 μm\(^2\). This active layer consists of InGaN, which radiates blue light through electron-hole pair recombination. The next step is to form n-type Al contact on top right of n-type and p-type layers respectively. Finally, the p-type GaN layer is set on the active layer and its depth is 0.1 μm. Doping concentration of the p-type GaN and n-type GaN are 1 x 10\(^{17}\) cm\(^{-3}\) and 2 x 10\(^{18}\) cm\(^{-3}\), respectively.

In order to spread current, the ITO layer is put on the p-type GaN layer and its depth is 0.05 μm. On top left of it, Al is deposited to form the contact as a p-type contact. The cross-section area of Al contact metal is the same as 0.5 μm x 0.5 μm respectively. After completing the conventional LED setting, a spreading pad which consists of ITO is inserted within the p-type GaN layer. In the simulation process, the dimension of spreading pad is varied for confirming how current-flow changes in each case. Contact resistivity between ITO and p-GaN is 50 mΩ•cm\(^2\) and the conductivity of ITO is 2.4 Ω•μm.

III. ELECTRICAL DEVICE SIMULATION

The purpose of performing electrical device simulation is to confirm the electrical effects occurring on the active layer. SILVACO\(^\text{TM}\) ATLAS is used as a simulation tool. At first, the TCAD electrical simulation is performed by inserting spreading pad. The active layer is a single layer with 1 nm In\(_{0.2}\)Ga\(_{0.8}\)N. The recombination parameters are set as follows: Shockly-Read-Hall (SRH) coefficient is 5.0 x 10\(^9\) s\(^{-3}\) and the radiative recombination coefficient is 1.0 x 10\(^{-11}\) cm\(^{-3}\)s\(^{-1}\). Then auger recombination coefficient is 2.0 x 10\(^{-31}\) cm\(^{6}\)s\(^{-1}\).

First, spreading pad is inserted into p-type layer, specifically at the positions of 5–8 μm, in order to identify the changes of currents and radiative recombination. Fig. 2 indicates the current density and radiative recombination rate when the spreading pad is inserted.
inserted at the center of the p-type layer. The point on the graph (Fig. 1), the left edge of the pad, represents the pad’s position in Fig. 2. As spread pad’s location becomes increased, it is shifted toward the n-type contact. The width and depth of the spreading pad is 0.5 μm and 90 nm respectively. In the active layer, the impacts of inserting the pad appear as the increase of total current, which is the sum of electron current and hole current and radiative recombination rate. From this total current and radiative recombination results, it can predict changes of optical power by inserting spreading pad. From the simulation, the enhancement of current spreading is observed and also the number of radiative recombination is increased as well. Thus, improved current spreading can be verified in the proposed structure. First, the enhancement of current spreading happens due to the differences in resistance. To be specific, the pad is made of ITO and its resistance is less than that of p-GaN. Therefore, in the proposed structure, more current can be supplied through the pad to the active region below the pad. Second, the increased number of radiative recombination is due to the increased current in the active region.

Furthermore, to maximize the effect of current spreading in the active layer, the physical dimension of pad is adjusted. The effect of current spreading pad depends on the physical dimensions since the physical dimension of the spreading pad can affect the current flow in the active region. Therefore, the width, depth and the location of spreading pad needs to be optimized as well.

The results of the simulation by varying the location and depth of the spreading pad are illustrated in Fig. 3(a). With the fixed width of the pad, 0.5 μm, the deeper the location of spreading pad is, the more the luminescent power increases. As illustrated in Fig. 3(a), once the pad is inserted over the p-type GaN, however, the luminescent power sharply decreases since the holes are injected directly in the n-type region. The reason is that deeper location of spreading pad enhances carrier injection in the active region. The simulation is performed to observe how the luminescent power changes as the location of spreading pad is varied. At the position of 5.5 μm, the highest luminescent power is obtained. If the spreading pad is located less than 5.5 μm away from the p-type contact, the luminescent power

![Fig. 3. Luminescent power versus spreading pad location with various (a) depth (at 0.2 A current), (b) current, (c) Luminescent power versus applied current with various width, (d) Illustration of the current crowding in the wide spreading pad.](image-url)
shows just a little enhancement compared with the conventional LED structure since the resistance under the p-type contact is too high to reduce by adapting a spreading pad. Meanwhile, as the location moves more than 5.5 μm away from the p-type contact, meaning that the spreading pad is located near the n-type contact, the luminescent power drops dramatically. This is because the spreading pad located closer to the n-type contact makes the current to be crowded. This can explain the reason why the current flow spreads less uniformly in the active region.

In addition, to confirm the properties of different LED operating current, both high and low current need to be considered (Fig. 3(b)). At low current level, the luminescent power increases as the pad moves closer to the n-type contact. This phenomenon occurs as more current is concentrated in the active layer near the n-type contact. Injecting the low current is not appropriate for maximizing luminescent power in the active layer. Thus the closer the spreading pad locates to the n-type contact, the more the current crowded and the efficiency increases. At high current level, however, as the spreading pad moves close to the n-type contact, the total luminescent power decreases due to the current crowding effect. In this case, the current crowding effect increases the carrier concentration to such a high level that Auger recombination dominates. Then, most of the carriers recombine non-radiatively by Auger recombination mechanism, resulting in the reduction of the luminescent power. From the results, it is confirmed that the location of the spreading pad, should be adjusted by operating current.

Next, we characterized the effects of the pad width. As shown in Fig. 3(c), the highest luminescent power is observed when the width of spreading pad is 1.5 μm. When the width becomes larger than 1.5 μm, the luminescent power decreases due to the current crowding as the current increases. Consequently, the best efficiency of luminescent power can be obtained at the point of 1.5 μm, considering the current crowding and lowered improvement of resistance. As the width of spreading layer becomes narrower, the current is pushed to the narrow region. If the width becomes too large, however, the current redirection effect of the pad would be compromised, since the current crowding can occur within the width of the pad (Fig. 3(d)). Thus, the whole current doesn’t flow uniformly and that results in the decrease of radiative recombination.

**IV. OPTICAL DEVICE SIMULATION**

The ITO and GaN materials mentioned above have been assumed to be fully transparent and the reflection and absorption is ignored in the previous electric simulation. In other words, all the results are obtained assuming that the external quantum efficiency is close to 1. However, the ITO and GaN materials are somewhat absorptive in the visible region of the optical spectrum-[25, 26]. In addition, the light derived from the active layer can be reflected depending on the structure. Therefore, the amount of externally emitted light cannot be accurately calculated by the electronic simulation alone. Moreover, the inserted spreading pad can have some effects on the reflection or absorption of the light. Consequently, performing optical simulation is required.

We chose the COMSOL as a tool for optical simulation. Considering the shape of the active layer in the proposed structure, we insert the optical source with the same shape (Fig. 4). Then, the refractive indexes of GaN and ITO are set. The refractive index is composed of a real part and an imaginary part [27]. The real part is related to the refraction between bordered materials. The imaginary part reveals the optical extinction [28] (Eq. 1).

\[
\chi = \chi' + j \chi''
\]

where \(\chi'\) represents the refractive coefficient and \(\chi''\) represents the extinction coefficient. The refractive index is shown in Fig. 5 [29-31]. After optical light source with power 1 W is inserted, the width and depth of pad is

![Fig. 4. Illustration of simulated results.](image-url)
varied. The extracted luminescent power is measured over the top of the LED. As shown in Fig. 6(a), more than 40 nm of depth does not lead to decrease of luminescent power with 450 nm light source.

Another simulation is performed when the depth of spreading pad is 80 nm. The luminescent power increases. These observations certify that as we insert the spreading pad more deeply, more light can be emitted externally. In other words, as the spreading pad gets closer to the active layer, the amount of luminescent power increases. In addition, as the width of spreading pad becomes wider, the luminescent power increases linearly. Since the spreading pad absorbs the light less than p-type GaN layer, the spreading pad can help the luminescent power increase.

To identify more effects of extinction coefficient, 350 nm light source and its reflective index are utilized in the simulation (Fig. 6(b)). According to the simulation results, the overall luminescent power increases when using 450 nm light source compared with 350 nm light source. As shown in Fig. 5, the difference of extinction coefficient between ITO and GaN causes this happen. The difference becomes much bigger when using 350 nm than using 450 nm of light source. The refraction and extinction coefficient depend on the wavelength for GaN and ITO.

To summarize, inserting spreading pad can lead to increase of the luminescent power. Such increase of optical power, however, is observable only with the specific wavelengths. The wavefunction of the generated light from the active layer becomes

$$U(z) = A \exp(-j \chi z)$$  \hspace{1cm} (2)

where $z$ is the distance from the active layer and $A$ is amplitude. The optical intensity is the absolute square of its wavefunction.

$$\text{Optical intensity} = |U(z)|^2$$  \hspace{1cm} (3)

It was shown in Eqs. (2) and (3), the intensity of the generated light is exponentially decreased with thickness through the media and extinction coefficient [32]. Therefore, in the wavelength from 250 nm to 450 nm, the extinction coefficient of ITO becomes smaller than that of GaN and the penetration of light through the spreading pad can be enhanced. Consequently, the spreading pad would be advantageous in the LED whose active layer radiates the light at 250 nm ~ 450 nm. Additionally, we tried to divide the spreading pad into half and used both in the simulation, intending to extend the boundary lines and find out whether their reflection effects are influenced or not. As shown in Figs. 6(a) and (b), effects of the reflectance by boundary can be ignored.

In summary, in order to manufacture LED devices with spreading pad, we need to consider both the extinction coefficient of spreading layer and the luminescent power on the active region. In the GaN-
V. Conclusion

A novel structure in the GaN-based LED with a spreading pad is proposed in order to overcome the current crowding problem in the conventional LED. The inserted spreading pad helps the current to be distributed better because it has less resistance than the p-type GaN layer. In order to confirm the effects of the spreading pad insertion, electrical and optical simulations are performed for internal and external efficiency calculation. The results of electrical simulation show that the current spreads more uniformly and more radiative recombination is produced. From the optical simulation, ITO is revealed as less absorptive material than p-GaN with the specific wavelength sources. As a result, luminescent power is enhanced by the spreading pad.

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References

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