# Influences of Random Alloy Fluctuation to the Efficiency of $\mu$LED and Optimization of Efficiency with Vertical Type Contact

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***Abstract*—$\mu$-LED's efficiency is enormously dependent on the chip size, which is believed to be the influence of sidewall traps. However, the decrease of IQE in AlInGaP based red LED is much stronger than nitride based LEDs. This paper examines the role of random alloy fluctuation with our 2D simulation software for the whole LED chip size to extract the major factors leading to the large IQE discrepancy between nitride-based and AlGaInP based LEDs. The design rule of the vertical LEDs to avoid the sidewall influences of $\mu$-LED will be proposed in the presentation.**

***Index Terms*—InGaN, AlInGaP, sidewall effect, random alloy fluctuation, $\mu$LED, piezoelectric effect**

## I. Introduction

THe light-emitting diode size is shrinking to pursue a higher resolution for mini displays such as AR/VR applications or display with a transparent area. However, many studies have shown the efficiency of $\mu$-LED will decrease as the chip size shrinks due to the sidewall trapping effects. Hence, many technologies have been proposed, such as using ALD to deposit oxides for surface passivation. Interestingly, much research work has shown that influences of sidewall trap in $\mu$-LED is more severe in the AlGaInP based red light system. On the other hand, the efficiency decrease in the nitride-based LEDs is smaller. This may be due to the lighter effective mass and larger carrier mobility in the AlGaInP based QW. In addition, the role of random alloy potential has also been proposed since it might affect the carrier diffusion efficiency. The inhomogeneous distribution of the bandgap and polarization potential due to fluctuation will enhance the carrier localization and limit the carrier diffusion. However, the polarization field will play an opposite role which would increase the diffusion length due to the decrease of radiative recombination rates. Hence, it would be interesting to investigating the role of each factor with a proper simulation tool. Our past research has used 3-dimensional simulation tool to study the phenomenon of fluctuation in nano-scale and demonstrated the influence of the alloy disorder without any approximation [3]. However, due to the limitation of memory usage in 3D simulation, it is impossible to do 3D simulation in the $\mu$m scale, including atomic-scale random alloy fluctuation. Hence, 2D simulation considering random alloy fluctuation is an alternative way to study these factors. In this work, We will use 2D simulator to approximate the random alloy fluctuation to model the $\mu$-LED behavior. The whole structure of LED will be modeled with this program.

## II. Methodology

To simulated random alloy fluctuation device properly, we have used in-house developed fully 2-dimensional drift diffusion charge control solver (2D-DDCC) to analyze the electrical, carrier distribution, and other properties. Firstly, we will use random number generator to generate random atom distribution and use Gaussian averaging method to get local indium composition in the QW. Then the local material parameters such as bandgap, polarization diople will be put into the simulation program according to the local indium compositions. In addition, the localization landscape (LL) instead of Schrödinger equation solver will be used to obtain the effective quantum potential and solve the problem more efficiently. The algorithm detail can be found in Ref.[1][3]. Finally, the 2D solver can be applied and analyze the results. In the following discussion, we will simulate the aluminium gallium indium phosphide (AlGaInP) system as red $\mu$-LED and indium gallium nitride (InGaN) system as blue $\mu$-LED. Besides, the alloy fluctuation would only be applied on blue $\mu$LED since the potential variation would be larger than the other. The bandgap distribution and the conduction distribution of blue $\mu$-LED were shown in Fig. 1(a) and Fig. 1(b) separately.

## III. Result and Discussion

The result discussion will be divided into two parts. The first part would be discussed between red and blue $\mu$-LED and the influence of the carrier mobility to the blue $\mu$-LED with random alloy fluctuation. The other part is about the factors which caused the difference of internal quantum efficiency (IQE) between two kind of $\mu$-LEDs.

### *A. The shrinking size to the red and blue $\mu$-LED and the distribution of mobility to the blue $\mu$-LED*

In InGaN $\mu$-LEDs, the lateral diffusion ability might be strongly related to potential fluctuation due to the disordered random compositions [1]. In this part, we first implement the

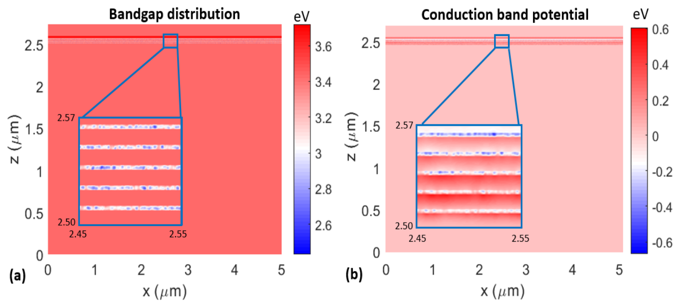


Fig. 1. (a) The bandgap distribution of the whole $\mu$LED with the random alloy fluctuation. The small picture is the enlargement of the InGaN LED quantum wells, where the composition fluctuation can be observed more clearly. (b)This is the conduction band potential of the whole $\mu$LED with the random alloy fluctuation. The small picture is the enlargement of quantum wells. The undulating potential is lead by inhomogeneous distribution of bandgap.

composition fluctuation into the 2D simulation and compare their influence to the IQE versus the case with different chip sizes. The simulation for different chip sizes in blue and red (AlInGaP based) LED are simulated. The comparison is shown in Fig. 2(a). We could find out the IQE in red $\mu$-LED decreased a lot as size shrinking[2]. For the 5$\mu$m chip size of red $\mu$-LED, the efficiency is almost 0% at low current density. For the blue $\mu$-LED, the shrinking would also affect the efficiency, but it could maintain the IQE at about 50% at $20A/cm^2$ for the 5$\mu$m chip size. To explain this situation, the large difference in mobility for carriers in QWs might be one of the key factors, which would make the carrier diffused to sidewall much faster. However, when we assume the carriers in InGaN QW has the same mobility as AlInGaP, the influence of IQE in InGaN QW is not as severe as the red LED, shown as Fig. 2(b), which means some hidden factors not found in this comparison.

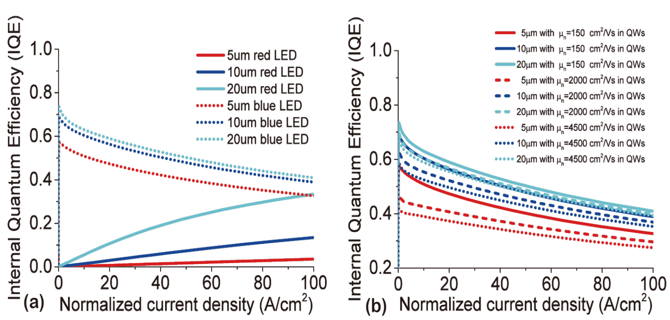


Fig. 2. (a) The IQEs of three kinds of chip size between red LED and blue $\mu$LED. (b) The influence of different carrier mobility in blue LED QWs with consideration on random alloy fluctuation.

### *B. The influence of Random alloy potential fluctuation, piezo-electric field, and p-n layer mobility.*

Since the influence of mobility is not the primary factor in the decrease of the IQE for red LEDs, the influence of random alloy fluctuation effect and polarization-induced QCSE will be discussed. First, the effect of piezoelectric polarization and random alloy fluctuation was removed in the simulation of nitride-based LEDs since the AlGaInP system doesn't have these effects (case 1). Then the effective mass in QWs (case 2) and the mobility in quantum barriers (case 3) are set to be the same between blue and red LEDs for comparisons, as shown in Fig. 3. When the random alloy fluctuation and piezoelectric effects were removed, the IQE drops significantly. The IQE peak shifts to a much larger current density and the droop effects disappear. The SRH at the sidewall area becomes the dominant role. The effective mass and even mobility in QB (which might affect the current spreading also) will also reduce the IQE. Hence, not only one factor to keep IQE low in red $\mu$-LEDs. Therefore, to improve the IQE in red LED for $\mu$-LED applications, reducing the carrier mobility in all layers (QW/QB) is needed. Some deep QD structures might also help provide a similar advantage as the nitride-based LEDs, which will be discussed more during the conference presentation.

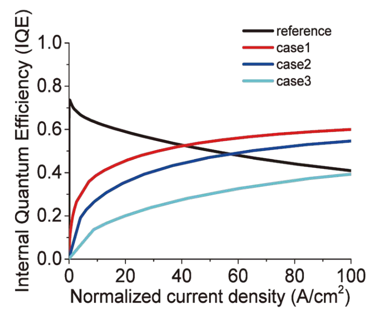


Fig. 3. Influence of different parameters to the IQE between blue LED and red LED. Reference is the case shown in Fig. 2(b) as cyan solid line. Case1 is the 20 $\mu$m blue LED with $\mu_n$=4500 cm$^2$/Vs and $\mu_p$ =190 cm$^2$/Vs in QWs. The random alloy potential fluctuation and piezoelectric polarization was removed. Case 2 is similar to case 1 but effective mass is set the same as red LED. Case 3 is further change the electron and hole mobility of QB to be $\mu_n$ =4000 cm$^2$/Vs and $\mu_p$ =180 cm$^2$/Vs, respectively.

## IV. Conclusion

The influence of random alloy potential fluctuation in nitride system was analyzed and compared to the AlGaInP red LEDs system. The results show the potential fluctuation and mobility (which may also affected by alloy fluctuation) plays the key role. However, mobility in QB and pn layers are also important since they affect the carrier diffusion into QWs.

## V. Acknowledgments

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