Designing of p-$Al_xGa_{1-x}N/Al_yGa_{1-y}N$ super lattice structure as the p-contact and transparent layer in AlGaN UVLEDs

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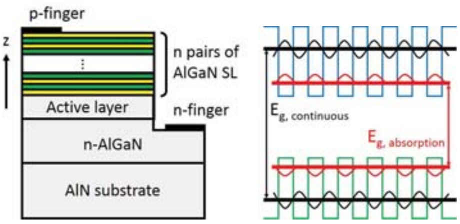
***Abstract*—A series of the p-$Al_xGa_{1-x}N/Al_yGa_{1-y}N$ super lattice structure has been examined as the p-contact and transparent layer for different ultra-violet light emitting diode (UVLED) with a self-consistent 1D Poisson and Schrödinger solver. The optimized condition for different UV wavelength has been found for UVLED for 223 nm to 355 nm. By calculating the absorption coefficient of the SL structure, we confirmed that the proper SL structure has the enormous potential of being used in AlGaN UVLEDs.**

***Index Terms*—AlGaN, deep ultraviolet, light emitting diode, super lattice, transparent contact layer.**

I. Introduction

The external quantum efficiency (EQE) in AlGaN UVLEDs is extremely low today. One important issue is the low light extraction efficiency (LEE) which is due to the large absorption coefficientof the top p-GaN contact. To obtain high LEE, Allerman et. al. [1] presented a structure of Mg-doped, short-period SL grown by MOVPE, suggesting that the SL structure could be used as the wide bandgap p-contact layer in AlGaN UVLEDs. However, it is difficult for experimentalists to decide the suitable AlGaN SL structure for different emitting wavelength. To solve this problem, we focus on simulating a series of the heavily doped p-$Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SL structure with different Al compositions and different barrier/well thickness and try to find the optimized condition for p-type transparent contact layer in UV region.



(a) (b)

Fig. 1. Schematically views of (a) a lateral AlGaN LED structure with n pairs of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SL structure being used as the p-contact layer and (b) the definition of the effective bandgaps.

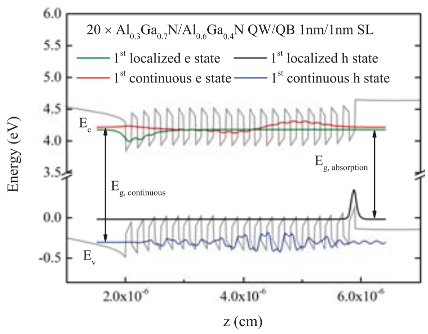


Fig. 2. Band diagram of a 20 pairs AlGaN SL structure with alternate $Al_{0.3}Ga_{0.7}N$ well and $Al_{0.6}Ga_{0.4}N$ barrier layers, the thickness of each well and barrier layer is 1 nm.

II. Results and discussion

To solve the $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SL structure, a self-consistent 1D Poisson and Schrödinger solver [2–4] is uesd. The absorption bandgap $E_{g,absorption}$ of a given SL structure can be defined as the energy difference between the electron localized state and the hole localized state as shown in Fig.1(b), which leads to the absorption bandedge. The energy difference between the electron continuous resonant state and the hole continuous resonant state is defined as $E_{g,continuous}$ that carriers begin tunneling through the SL.

Fig.1(a) illustrates the UVLED structure with a SL being used as the p-contact layer. It consists of 20 pairs of alternating $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ layers ($0 < x$, $y < 1$), the thickness of both well and barrier varies from 0.5 nm to 2 nm. Fig.2 shows the calculated band diagram of a SL structure. Not only the continuous states but also the lowest electron and heavy hole states are shown in this figure. These localized states preventing carries from diffusing. They also lead to photon absorption, so we calculated the absorption coefficient of 3 cases of SL structure as shown in Fig.3. We can see that the absorption coefficient will be sharply increased as the wavelength decreases once the photon wavelength is less than the cutoff value. For the case of $Al_{0.3}Ga_{0.7}N/Al_{0.6}Ga_{0.4}N$ SL structure, the cutoff wavelength is 284.8 nm which means the $Al_{0.3}Ga_{0.7}N/Al_{0.6}Ga_{0.4}N$ SL structure is suitable for the p-contact transparent layer without any absorption above 281.8 nm. The other two cutoff wavelengthes of $Al_{0.6}Ga_{0.4}N/Al_{0.9}Ga_{0.1}N$ SL structure and $GaN/Al_{0.4}Ga_{0.6}N$ SL structure are 243.4 nm and 322.5 nm,

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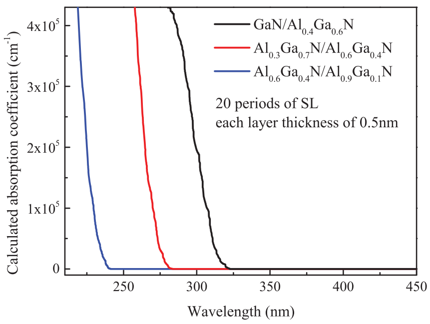

Fig. 3. The calculated absorption coefficient of GaN/$Al_{0.4}Ga_{0.6}N$, $Al_{0.3}Ga_{0.7}N/Al_{0.6}Ga_{0.4}N$, and $Al_{0.6}Ga_{0.4}N/Al_{0.9}Ga_{0.1}N$ SL structures as a function of photon wavelength.

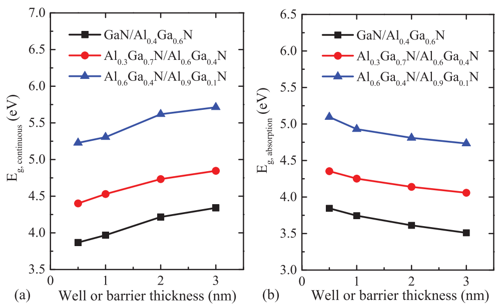

Fig. 4. (a) $E_{g,continuous}$ and (b) $E_{g,continuous}$ of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SL structures as a function of well and barrier thickness.

respectively.

A comparison among the GaN/$Al_{0.4}Ga_{0.6}N$, $Al_{0.3}Ga_{0.7}N/Al_{0.6}Ga_{0.4}N$ and $Al_{0.6}Ga_{0.4}N/Al_{0.9}Ga_{0.1}N$ SL structures with different periodicity is shown in Fig.4. The absorption bandgap $E_{g,absorption}$ decreases slightly when the thickness of well and barrier increases due to a smaller quantum confinement effect. But the continuous bandgap $E_{g,continuous}$ is higher in a thicker barrier because it is much harder to make resonant tunneling to form a real SL. For the case of $Al_{0.3}Ga_{0.7}N/Al_{0.6}Ga_{0.4}N$ SL structure, $E_{g,continuous}$ increases from 4.40 eV to 4.85 eV when $E_{g,absorption}$ decreases from 4.35 eV to 4.06 eV as the layer thickness increases from 0.5 nm to 3 nm. This means that the thinner barrier in SL structures, the energy difference between $E_{g,continuous}$ and $E_{g,absorption}$ is smaller while the carriers are easier to tunnel through barriers instead of forming localized state, which is good for device application.

Therefore, we modeled a series of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ structure with the layer thickness of 0.5 nm. The continuous bandgap $E_{g,continuous}$ and the cutoff wavelength are shown in Fig.5. The diagonal white line in these two sub figures means the Al composition in both well and barrier is the same, which is not SL structure. From Fig.5(b), we can see that to achieve a same cutoff wavelength, there are several choices with different combination of well and barrier. Although these choices result in the same cutoff wavelength, $E_{g,continuous}$ of these cases are different, thus we can choose

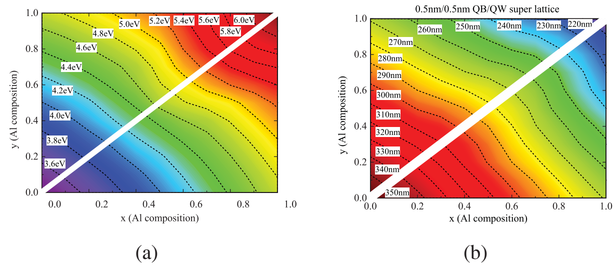

Fig. 5. $E_{g,continuous}$ (a) and absorption cutoff wavelength (b) as a function of composition x and y in $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SL structure, each well and barrier layer is 0.5 nm.

the case with minimum $E_{g,continuous}$ from Fig.5(a) as the best condition. In addition, we calculated the cutoff wavelength of $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SL structure with 1 nm and 2 nm layer thickness. The total range of cutoff wavelength in AlGaN SL structures is from 223.3 nm to 355.4 nm.

III. Conclusion

In summary, we present a complete numerical study on the $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SL structures for using as the top p-contact transparent layer in AlGaN UVLEDs. Because the energy difference between $E_{g,continuous}$ and $E_{g,absorption}$ would be reduced with the decreasing of the well and barrier thickness in AlGaN SL structures, it would be easier to form the continuous state thus making carriers easier to transport through the SL structures. The cutoff wavelength of AlGaN SL structures are ranging from 223.3 nm to 355.4 nm which covers nearly the whole UV region. The absorption analyses showed a great transparency performance compared to the conventional p-GaN layer especially in UV-C band. Therefore, there would be a marked enhancement in LEE due to the p-$Al_xGa_{1-x}N/Al_yGa_{1-y}N$ SL contact layer, and further improving the EQE in AlGaN UVLEDs.

IV. Acknowledgements

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