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Simulation and Design of High Efficiency InGaN/AlInGaN Based Light-emitting Diodes

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Abstract: InGaN-based LEDs with InGaN/AlInGaN and InGaN/GaN multiple quantum wells (MQWs) were theoretically studied and compared by using the Advanced Physical Models of Semiconductor Devices (APSYS) simulation program, respectively. The carrier concentrations in quantum wells, radiative recombination rate in active region, light-current performance curves, and the internal quantum efficiency were investigated. The simulation results show that higher efficiency realized in the strain-free AlInGaN barrier instead of GaN.

Key words: GaN; LED; efficiency droop

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高效 InGaN/AlInGaN 发光二极管的结构设计及其理论研究

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摘要: 利用 Advanced Physical Models of Semiconductor Devices (APSYS)理论对比研究了 InGaN/AlInGaN 和 InGaN/GaN 多量子阱作为有源层的 InGaN 基发光二极管的结构和电学特性。与 InGaN/GaN 基 LED 中 GaN 作为垒层材料相比,在 AlInGaN 材料体系中,通过调节 AlInGaN 中 Al 和 In 的组分可以优化器件的性能。当 InGaN 阱层材料中 In 组分为 8% 时,可以实现无应力的 $In_{0.08}Ga_{0.92}N$/AlInGaN 基 LED。在这种无应力结构中可以进一步降低大功率 LED 的"效率下降"(Effciency droop)问题。理论模拟结果显示,四元系 AlInGaN 作为垒层可以进一步减少载流子泄露,增加空穴注入效率,减少极化场对器件性能的影响。在 $In_{0.08}Ga_{0.92}N$ /AlInGaN 量子阱中的载流子浓度、有源层的辐射复合率、电流特性曲线和内量子效率等方面都优于 InGaN/GaN 基 LED。无应变 AlInGaN 垒层代替传统的 GaN 垒层后,能够得到高效的发光二极管,并且大电流注入下的"效率滚降"问题得到改善。

关 键 词: 氮化镓; 发光二极管; 效率下降

1 Introduction

InGaN-based light-emitting diodes (LEDs) have been widely used for many important applications, such as full-color display, LCD back-lighting, illumination, and mobile platforms[1-5]. The conventional InGaN/GaN QW structure has already received extensive studies because it can be used as

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the active layer of the light emitting devices[6-8]. However, the existence of strong electrostatic field may lead to quantum confined Stark effect (QCSE), poor overlap of the electron and hole wave function as well as the degraded radiative recombination rate, internal quantum efficiency (IQE), and optical performance of the light-emitting diodes[9-10]. The polarization related effect results from the spontaneous and piezoelectric polarization. Polarization is a crucial issue for electrical and optical characteristics of LEDs. To improve the quantum efficiency of InGaN-based LEDs, previous reports used AlInGaN in the quantum barrier instead of GaN to deal with the polarization, strain, material quality, and interfacial abruptness issues[11-20]. However, the optical performance of the LEDs could be largely weakened by the piezoelectric effect, which causes the strong electrostatic field and band bending situation in the active region. The strain engineering could be achieved by varying lattice parameter of the $In_xGa_{1-x}N$ template. For the barrier $Al_xIn_yGa_{1-x-y}N$ with $0 < x < 0.26$ and $0 < y < 0.11$, the structure $In_{0.08}Ga_{0.92}N$/AlInGaN grown would have the barrier having the *a*-axis lattice constant very close to that of $In_{0.08}Ga_{0.92}N$, and the $In_{0.08}Ga_{0.92}N$ QW would be unstrained[21]. Moreover, the strain in the QW can be controlled by the lattice parameter and thus the composition of $In_xGa_{1-x}N$. Strain free QW can be achieved for $x = 0.08$. If $x > 0.08$ or $x < 0.08$, the resulting QWs are under tensile stress and compressive stress, respectively. In this paper, the properties of the strain-free $In_{0.08}Ga_{0.92}N/Al_{0.075}In_{0.045}Ga_{0.88}N$ MQWs LED and the conventional $In_{0.08}Ga_{0.92}N$/GaN MQWs LED were compared, the simulation results indicated high efficiency realized in strain-free $In_{0.08}Ga_{0.92}N/Al_{0.075}In_{0.045}Ga_{0.88}N$ MQWs LED.

2　Simulation Results

In order to reduce the polarization effect inside the active region of the original LED structure, the polarization-matched AlInGaN barriers are proposed to replace the original barrier layer.

The simulation InGaN-based LED device was designed on a *c*-plane Al_2O_3 substrate. A 3 μm thick Si-doped n-GaN layer with a doping concentration of 5×10^{18} cm^{-3} was used to be the n-type bottom contact layer. The active region consisted of five periods of undoped InGaN/$Al_{0.075}In_{0.045}Ga_{0.88}N$ MQWs with 15-nm barrier and 2-nm well. On top of the active region was a 200 nm thick Mg-doped p-GaN with a doping concentration of 3×10^{17} cm^{-3}. A 20 nm thick Mg-doped p-GaN contact layer with a doping concentration of 5×10^{18} cm^{-3} was designed to complete the structure. The schematic structures of the simulated samples are shown in Fig. 1. In addition to quaternary samples with InGaN wells and AlGaInN barriers, a reference sample with the conventional $In_{0.08}Ga_{0.92}N$ wells/GaN barrier active region is taken as reference design with the same structure as the quaternary samples.

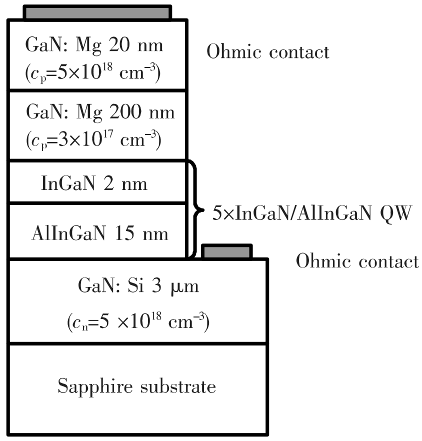

Fig. 1　Schematic structure of the simulated InGaN/AlInGaN MQWs LED

The simulated carrier concentrations of the two samples in multi-quantum wells (MQWs) cut from the n-side to the p-side are plotted in Fig. 2(a) and (b).

The electron and hole concentrations are very high in the last quantum well near the p-side indicating the large electron leakage and poor holes transport efficiency in InGaN/GaN MQWs LED. However, InGaN/AlInGaN active region reduced the electron leakage of this LED, which implies the enhanced electron confinement in the device. Moreover, as illustrated in Fig. 2(b), the overall holes concentration in the MQW region is also increased substantially, which suggests that electrons can be confined in MQWs and holes injection efficiency can be improved markedly in InGaN/AlInGaN than

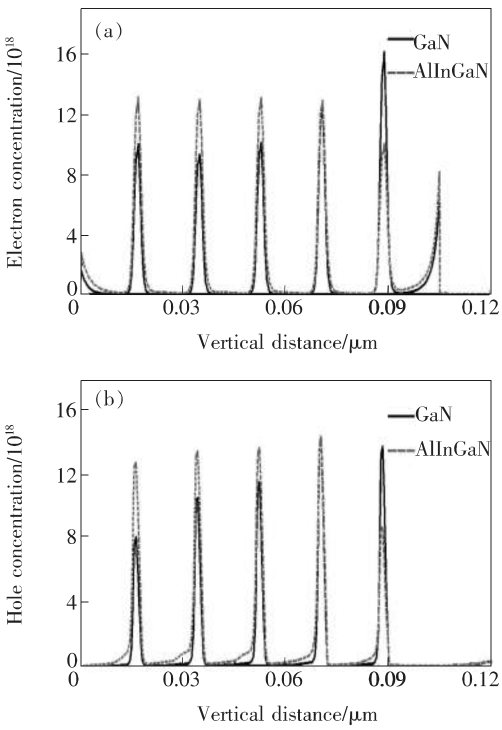

Fig. 2 Distribution of electron (a) and hole (b) concentrations of InGaN/GaN and InGaN/AlInGaN MQWs LED

InGaN/GaN MQWs LED. When the strain free InGaN/AlInGaN MQWs are applied, the electron and holes concentration increases in the QW and the distribution of carrier becomes more uniform than InGaN/GaN case. In InGaN/GaN MQWs LED, much more severe band bending was induced by the larger polarization field, leading to the amount of electrons increased in the last well. AlInGaN barrier sample has better carrier transportation and this is also more obvious in the hole distribution. The direct consequence is the enhanced radiative recombination rate and light output. On the other hand, in sample with traditional GaN barrier the holes are concentrated locally in the last QW, which causes the unbalanced hole distribution between different wells and thus leading to the reduction in radiative recombination rate. The distribution of carrier of InGaN/InAlGaN becomes more uniform than InGaN/GaN structures. Under high current density, the carrier distribution of both electrons and holes determines how efficient the photon-emission process will be. InAlGaN barrier sample is reduced due to better carrier transportation and this is also more obvious in the hole distribution. The direct consequence is the increasing radiative in the traditional GaN barrier samples. Comparing electrons with holes, holes suffer more as a result of this nonuniformity due to their large effective mass and low mobility. Thus, our InAlGaN design can reduce the carrier leakage and increase electron-hole pair radiative recombination, especially for the distribution of holes.

The curves of the light output intensity *versus* the injection current of the two samples are shown in Fig. 3. It is shown that the light output power is significantly enhanced in this structure with InGaN/AlInGaN active region. The results show that the light output power of the two devices both increase as forward injection current increasing.

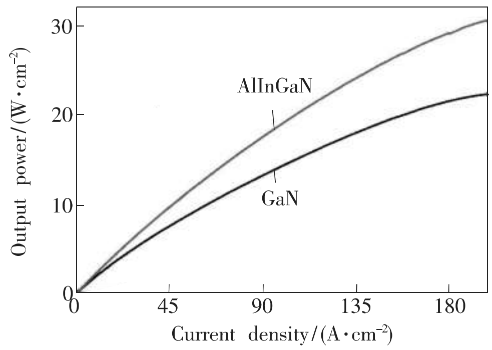

Fig. 3 Light output power as a function of forward current density for InGaN/AlInGaN and InGaN/GaN MQWs LED

The increase rate of the two structures is just the same at low injection current. The difference light output power between the two samples is enlarged at high forward current when the injection current further increased. The output power of InGaN/GaN MQWs LED increases slowly as the forward current increases, thus AlInGaN/InGaN quantum well LED, the output power increases rapidly. Comparing with the original LED structure, the new LED structure possesses higher output power under same current density.

Fig. 4 presents the simulated IQE curves of InGaN/GaN and InGaN/AlInGaN MQWs LED. As the forward current increases, IQE of the two LED structures show similar variation trend. As the forward current increases, both samples show an obvious efficiency droop in IQE. However, the efficiency droop in LED with AlInGaN barrier is much smaller than that of LED with GaN barrier, which means the efficiency droop can be ameliorated by using AlInGaN barrier.

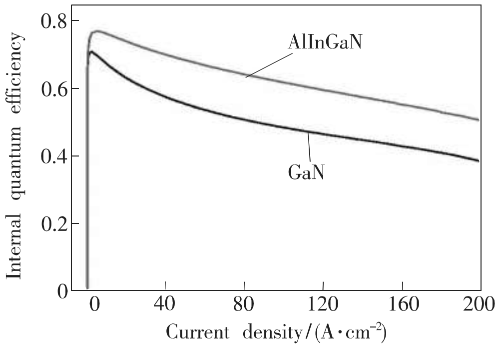

Fig. 4 Simulated IQE *vs.* current of InGaN/AlInGaN and InGaN/GaN MQWs LED

InGaN/GaN MQWs LED exhibits a serious efficiency droop. However, the overall optical performances of LED with InGaN/AlInGaN active region are improved and smaller efficiency droop is observed as GaN barriers are changing to AlInGaN. The possible reason is that AlInGaN barriers can block the electrons effectively and increase the holes injection efficiency. The polarization induced energy band bending of this device can greatly affect the carrier transport, and thus influence IQE. The quantum efficiency decrease can be understood if the emission mechanism for InGaN/GaN MQWs LED is the excitonic recombination from localized states formed by the indium variation in the QW. In this case, the carrier capture into localized states followed by emission is faster than the nonradiative recombination. However, since the density of these localized states is limited due to strain free, the non-radiative recombination caused by the large polarization field decreases the quantum efficiency. This results show that the electron leakage current due to the polarization field is one of the dominant mechanisms in efficiency droop. For InGaN/AlInGaN MQWs LED, it can eliminate the polarization effect between the barriers and wells, and further reduce the electron leakage. This can be explained that the alleviated polarization field induce band bending and the poor electron-hole wave function overlap that leads to the effective blockage of electrons and the radiative recombination was enhanced in the active region.

Fig. 5 illustrates the radiative recombination rates in the QW for the two LED. As can be seen, the radiative recombination rates in the QW are more uniform for LED with InGaN/AlInGaN active region than GaInN/GaN MQWs LED. In InGaN/GaN MQWs LED, because of the non-uniform carrier distribution in QWs, most of the radiative recombination happens in QWs close to p-side. The electrons and holes in AlInGaN LED distribute more uniformly than that in InGaN/GaN MQWs LED owing to the improvement of current spreading. This indicates that GaInN/AlGaInN MQWs LED can improve the hole injection and electron confinement compared to GaInN/GaN MQWs LED. Thus, the radiative recombination rates in InGaN/AlInGaN MQWs LED are enhanced.

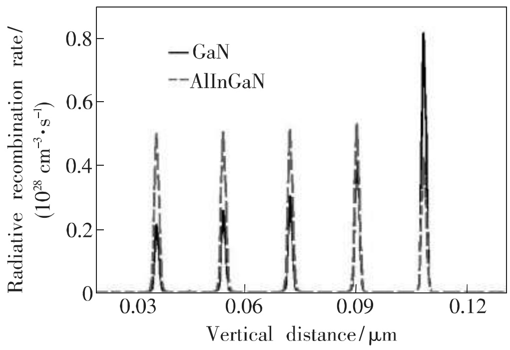

Fig. 5 Radiative recombination rates of InGaN/AlInGaN MQWs LED and InGaN/GaN MQWs LED

3 Summary

The strain-free LED with InGaN/AlInGaN MQWs and GaInN/GaN MQWs LED are studied by APSYS simulation program. The simulation results show that the quaternary barriers can reduce the current leakage and increase the hole injection by removing the polarization field in the QWs. Thus, InGaN/AlInGaN MQWs exhibit higher radiative recombination rate and reduced efficiency droop at a high injection current.

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