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厦门大学

博 士 后 学 位 论 文

高效率大功率LED的材料外延和器件研制

Growth and device development of high efficiency and high power LED

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专业名称：凝聚态物理

答辩日期：2012年7月

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摘 要

GaN基大功率LED作为第四代电光源，具有体积小、低电压、寿命长、效率高、节能等优良特性，但目前还存在转换效率低、光通量小、可靠性差等缺点。这主要是由蓝宝石异质外延GaN晶格质量较差、GaN材料强烈的极化效应、p型GaN激活效率低等原因造成。本论文利用高分辨X光衍射（HRXRD）、光荧光（PL）与芯片测试等技术，设计并优化了底层GaN、有源区和p型层等关键结构的生长工艺，有效地改善大功率LED的光电性能，主要结论如下： 1.PSS衬底外延GaN晶格质量的提升：研究了湿法制作图形化蓝宝石衬底，并在其上外延GaN和LED全结构。PL测量结果显示PSS衬底上外延GaN的本征峰发光强度要明显强于普通蓝宝石衬底上生长的GaN的本征峰的强度；XRD扫描结果表明，PSS衬底上GaN样品的晶体质量相对于普通蓝宝石衬底上的GaN得到明显提高。对PSS衬底上外延LED全结构的研究表明：相同规格的PSS衬底，无C面LED比有C面LED包灯光功率高，随着PSS图形深度增加，LED光功率增加，但深度增加到一定程度时，由于外延生长困难度的增加，晶体生长质量下降，反面会引起LED亮度的下降。另外，随着PSS衬底图案间距的减小及PSS衬底图案尺寸的增大，LED光功率也会增加。 2.有源区超晶格结构的生长与分析：研究了InGaN/GaN应力释放层的生长和规律，发现随着SL loop数的增加，亮度呈现先上升后下降的趋势，是因为SL厚度较薄时缓冲作用占主导，继续增加厚度时SL晶格质量变差占主导；研究了MQW的亮度和电压随QB厚度的变化规律，发现随着MQB的厚度增加，亮度也呈现先上升后下降的趋势，是因为MQB厚度较薄时，垒对晶格质量的改善占主导作用，厚度继续增加时，垒对空穴迁注入的抑制占主导作用；研究了采用p型AlGaN/InGaN超晶格对亮度和电压的影响规律，发现随着p-AlGaN/p-InGaN loop数增加，亮度呈先上升后下降的趋势，是因为p-Al SL结构阻挡了跃迁进入p-GaN的电子，减少非辐射复合的作用占主导，loop数继续增加时，p-Al SL结构对空穴的阻挡作用占主导。

3.p型接触层的生长与分析：随着高掺p型GaN（p++）厚度的增加，LED电压先降低后升高，这是因为金半接触会产生很高的势垒，而高掺的p++层可以使势垒区宽度变薄，从而增强隧穿效果以降低电压。但是载流子隧穿几率随势垒变宽而明显下降

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，导致电压升高；另一方面随着Mg掺杂的提高，空穴浓度增加，电阻率减小，电压降低。最后过高的Mg掺杂恶化了晶格质量，自补偿效应显著，空穴浓度变低，势垒厚度变大，载流子隧穿几率变小，导致电压升高；在p型InGaN接触层，当InGaN接触层由0.9 nm加厚至2.3 nm时，InGaN层提供的空穴浓度得到提升，有利于降低接触电阻从而降低电压，但是当InGaN层进一步加厚时，势垒高度和宽度进一步增加，隧穿效应变弱，导致电压逐渐升高。 4.高效率大功率LED的设计与性能：根据上述各关键层生长条件优化的结果，在优化后的PSS衬底上外延GaN层， 20周期的InGaN/GaN超晶格作为应力释放层和10周期的MQW有源区为发光层，6周期的p型AlGaN/InGaN超晶格作为电子阻挡层和200nm的p型GaN，接触层包括p++GaN和p型InGaN层。制作的50 mil*50 mil大功率LED芯粒全测LOP均值在430 mW左右，VF均值在3.1-3.3 V之间分布。包白灯亮度在140-150 lm，光效在130-135 lm/W，色温5000 K，显色指数70附近，色坐标数据正常，已经达到110 lm/W的项目指标。结果得到700 mA电流驱动下室温老化96小时，光衰小于-10%，老化1008小时，老化光衰小于-15%，老化IR数据正常。

关键词：金属有机化合物气相沉积；X光衍射；光荧光；大功率LED；图形衬底；应力释放层；InGaN/GaN多量子阱；接触层

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Abstract

GaN-based power LEDs as the fourth generation of the electric light, have many advantages such as small size, low voltage, long life, high efficiency, energy saving and so on. However, there are still some shortcomings involving low conversion efficiency, luminous flux, and poor reliability, which are mainly caused by poor quality of GaN epifilm heteroepitaxial on sapphire, strong polarization effect of GaN materials and low activation efficiency of p-type GaN. In this paper, we applied high resolution X-ray diffraction (HRXRD), photoluminescence (PL) and chip testing technology to design and optimize the growth process of the key structure including the underlying GaN, the active region and the p-type layer. Finally, the optical and electrical properties of the high-power LED have been improved, and the main conclusions are as follows:

1. PSS substrate epitaxial GaN lattice to enhance the quality: sapphire substrates patterned by wet chemical etching and epitaxial growth of GaN and LED on the patterned sapphire substrates were mainly investigated. PL measurements showed the intrinsic luminescence intensity of GaN grown on the PSS was much stronger than the one on the conventional sapphire substrate; XRD scan results showed the crystal quality of GaN on PSS was obviously improved. Study of the LED structure with PSS substrate showed that for the same PPS depth, the enveloped LED on PPS substrate with c-plane had higher optical power than the without one. And following the increase of PPS's depth, the optical power of LED rise. However, increasing the depth to a certern extent, the crystal quality starts to deteriorate, which cause to the decline of the LED brightness. This is because the difficulty of epitaxial growth is increased. In addition, with the space between the PSS patterns decreasing and the size of pattern rising, the optical power of LED continues to rise.

2. Growth and analysis of the active region with superlattice structure: the growth

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and theory of InGaN / GaN strain release layer were studied, and the LED brightness firstly increased and then reduced with increasing superlattice loop. This is because the strain releasing effect plays a major role when the superlattice total thickness is thin, and then brightness starts to decrease with the superlattice growing thicker and becoming worseThen we researched the rule of LED brightness and voltage with QB thickness variation. The brightness has a first upword and then downward trend with the increasing QB the thickness. This is because the influence of crystal quality from thicker barrier plays a dominant role at the first stage, and then thicker barrier inhibites the hole injection to MQW at the following stage. P-type AlGaN / InGaN superlattices as an electron blocking layer show similar trend on the brightness and voltage. As the loop number increasing, the LED brightness first increase and then decrease, which is because the

superlattices firstly block the electron injecting to pGaN to reduce non-radiative recombination in p-GaN, and then also block the hole injecting to MQW with increasing loops.

3. Growth and analysis of p-type contact layer: With the high-doped p-GaN (p++) thickness increasing, the LED voltage shows first dropping and then rising. Because the high-doped p++ can reduce the high barrier caused by metal-semiconductor contact so that the tunneling effect becomes stronger and the voltage declines. However, the carrier tunnelling probability through the barrier significantly decreases with the widened barrier, which leads to the rise of voltage. On the other hand, the voltage firstly drops due to the hole concentration increasing and the resistivity decreasing. And obvious self-compensation with Mg overdopping leads to hole concentration decreasing, carrier tunneling probability droping and finally LED voltage rising. For the p-InGaN contact layer, the hole concentration of InGaN layer increases when the InGaN contact layer varies from 0.9 to 2.3nm, which favors to the reduction of the contact resistance and thereby

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the voltage drops. But when the InGaN layer is further thickening, the height and width of barrier increase, which results in the weak tunneling effect and the voltage gradually increasing.

4. The design and performance of high-efficiency high-power LED: A LED structure was obtained based on the the previous design of the PSS substrate, with 20 loops InGaN / GaN superlattices as a stress release layer and 10 loops MQW active region as light-emitting layer. P-type region consists of 6-loop p-type AlGaN / InGaN superlattices, 200nm p-GaN, p++GaN and p-InGaN layer. 50mil * 50mil power LED chips were fabricated with these wafers. The results indicate the average LOP is about 430mW, and VF distributes between 3.1-3.3V. Packaged white LED chips show luminous flux of 140-150lm, luminous efficiency of 130-135lm/W at the average correlated color temperature (CCT) of 5000K, the color rendering index of 70, and the normal color coordinate data, all of which achieve to the subject targets. Under 700mA driving current at room temperature, the aging test results show the the lumens decay is less than -10% at 96 hours point and less than -15% at 1008 hours point, and the IR data have been normal.

Keywords: Metal organic chemical vapor deposition(MOCVD); X-ray diffraction (XRD); photoluminescence (PL); high power LED; Patterned sapphire substrate (PSS); the stress release layer; InGaN / GaN multi-quantum well (MQW); contact layer

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