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博　士　学　位　论　文

GaN 基蓝紫光激光器制备的理论与关键技术的研究

Research of the theory and key technology for fabrication of the GaN-base bule violet laser diodes

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摘　要

宽禁带Ⅲ－Ⅴ族 GaN 基半导体材料在发光二极管、激光器、光电探测器以及高温、高频和大功率电子器件等方面有着诱人的应用前景和巨大的市场需求，是近年来光电子材料领域研究的热门课题。特别是发光波段在 400～410nm 的 GaN 基蓝紫光激光器是高密度光存储系统中最有希望的光源，因此制作蓝紫光短波长的激光器一直是人们研究的焦点，但 GaN 基激光器材料的生长和器件的制备方面还存在一些困难，特别是 GaN 基材料的 P 型掺杂、厚且无裂的 AlGaN 材料生长、高质量的 P 型 GaN 欧姆接触等。

本文针对以上一些问题并结合 GaN 基激光器的研制工作开展了一系列的相关的研究，比如：一维光场模拟、相关材料的生长和低 P 型欧姆接触的研究。主要包括以下内容：

1）采用传输矩阵的方法对GaN基激光器的光场分布进行一维理论模拟，并分析了各层材料及结构对GaN基激光器光场分布的影响。模拟发现：当增加N型限制层$Al_xGa_{1-x}N$/GaN SLS的厚度和Al组分，或者在N型限制层较薄的情况下适当增加波导层厚度时，都能抑制反波导行为；而在保证质量的情况下，N型接触层的厚度则是越薄越好。值得一提的是，研究中首次发现，当波导层采用InGaN或InGaN/GaN SLS结构时，对光的限制能力将会明显提高，相应地阈值电流密度会降低。以获得大的光场限制因子和低的阈值电流密度为目标，优化出了各层材料参数：分别取N和P型接触层GaN的厚度为2000nm和200nm情况下，N型限制层$Al_xGa_{1-x}N$/GaN SLS厚度600nm（120对超晶格），Al组分为0.22；N型波导层GaN厚度90nm，有源区$In_{0.14}Ga_{0.86}N$/GaN量子阱数为2；P型电子阻挡层$Al_{0.2}Ga_{0.8}N$厚度10nm ；P型波导层GaN厚度70nm；P型限制层$Al_xGa_{1-x}N$/GaN SLS厚度300nm（60对超晶格），Al组分为0.22。

2）研究了TMAl的流量和生长温度对AlGaN材料的的影响，重点研究如何获得厚且无裂AlGaN材料，本文采用AlGaN/GaN超晶格代替厚的AlGaN的生长，获得厚且无裂的限制层材料。

3）理论分析InGaN/GaN MQW有源区发射波长与阱和垒的组分、厚度关系，发现通过适当组合阱和垒的In组分与厚度，可以调整发射波长。并通过生长LED结构来优化有源区，改变有源区阱的生长温度，发现其温度变化与发射波长呈线性关系，由此可以通过调节阱温，获得特定发射波长，并且还讨论了变温生长对InGaN/GaN MQW光学特

性的影响。

4）研究了获得p-GaN欧姆接触的低接触电阻方法。

①对p-GaN表面预处理方法和合金化的时间、温度、氛围进行了优化。

②在对该工艺优化的基础上，对比分析了两种不同材料的欧姆接触，即体材料p-GaN和采用p-InGaN/p-GaN超晶格薄层为顶层的P型材料。研究发现，在p-GaN上直接沉积一层p-InGaN/GaN超晶格薄层材料能够有效降低欧姆接触电阻，并在优化接触工艺为550℃、氧气氛围下合金30分钟的条件下，获得较低的比接触电阻率$1.99\times10^{-4}\,\Omega\,cm^2$。

③对p-InGaN/p-GaN超晶格薄层形成低阻欧姆接触的原因进行了理论分析，首次研究了超晶格薄层中p-GaN层温度变化对欧姆接触的影响，以及超晶格层生长过程中以p-GaN或者p-InGaN作为终止层时对欧姆接触性能的影响。发现在较低温度下生长p-GaN有利于欧姆接触的形成，而值得注意的是，以p-InGaN作为终止层可以获得更低的欧姆接触，针对此结果，文中进行了较为深入的分析。

④应用应变平衡理论，首次提出用p-InGaN/p-AlGaN超晶格代替p-InGaN/p-GaN超晶格层做p-GaN的顶层，并获得更低的欧姆接触电阻，其比接触电阻率为：$7.27\times10^{-5}\,\Omega.cm^2$。并从能带和空穴电荷密度两个方面分析接触电阻降低的原因。最后把应变补偿效应的超晶格材料应用在发光二极管（LED）上，相对常规LED而言，获得较低的工作电压。

关键词：GaN基蓝紫光激光器；MOCVD；AlGaN；InGaN/GaN多量子阱；p-InGaN/p-AlGaN超晶格；应变补偿；应变极化效应；P型欧姆接触。

Research of the theory and key technologyfor fabrication of the GaN-base bule violet laser diodes

Abstract

GaN based Ⅲ-Ⅴ nitrides as a wide band gap semiconductor has played a key role in the research field of opoelectronic materials and devices, due to its promising appliciations and great potential market in LEDs,short-wavelength laser diodes,ultraviolet detectors, high temperature and high power electronic devices.Especially, GaN based bule-violet laser diodes with wavelength from 400 nm to 410 nm is the most promising light resource for high density storage system, therefore fabricating bule-violet short-weavelength laser is research focus of people.While for GaN base lasers, there are still some difficulties in growthing the related materials and fabricating devices, in particular,p-type GaN doping,crack-free thick AlGaN growth, high quality p-type ohmic contact.

For exploring the above-mentioned problems, a series of studies were carried out on GaN base laser diodes, including simulation on one-dimension optical field, growth of related materials, investigation on low-resistance ohmic contact to p-GaN.The main contents were as followings:

1) Through adopting transfer-matrix, one-dimension optical-field of GaN-base laser diodes was simulated, and the effect of each layer on GaN-base laser diodes was analysed. It was found that the thickness and Al component of n-typed AlGaN/GaN superlattice layer(SLS) should be increased in order to avoid the anti-waveguide behavior, If a thicker cladding couldn't be grown, approximate fundamental mode operation could be obtained by increasing the thickness of the GaN waveguide slightly.In the condition of good quality, the thinner the thickness of the n-type contact layer was, the smaller the optical confinement factor was. It is the first time to propose that through adopting InGaN or InGaN/GaN SLS as waveguide layer optical can be confined better, and lower threshold current density can be obtained.When the maximum optical confinement factor and the lowest threshold current density were chosen as object functions, the AlGaN/GaN/InGaN separate confinement heterojunction(SCH)MQW layer structure was optimized.When the thickness of the n-type contact layer GaN was assumed to

be 2000nm, the p-type contact layer thickness is 200nm, which can be devided as follows: n-type cladding layer AlGaN/GaN SLS thickness is 600nm (120 pairs SLS), Al composition is 0.22; n-type waveguide layer thickness is 90nm, the number of the quantumwell of active layer is two; the p-type electron blocking layer AlGaN thickness is 10nm; p-type waveguide layer GaN thickness is 70nm;p-type cladding layer AlGaN/GaN SLS thickness is 300nm (60 pairs SLS), Al composition is 0.22.

2) the effects of The TMAl flow rate and growth temperature on AlGaN qualtity were investigated.We focused on how to obtain crack-free thick AlGaN material. In the thesis, AlGaN was substituted by AlGaN/GaN SLS, and free-crack thick cladding layer was obtained.

3) The relationship between the emitting wavelength of InGaN/GaN MQW active region and the composition, the thickness of well and barrier was analyzed theoretically.It was found adjusting the composition and thickness of well and barrier properly, the wavelength needed can be obtained.In experiment, the active region was optimized through growthing LED structure.Through changing the well growth temperature, we found that the relationship between emitting wavelength and well temperature was a linear function, Thus, we can obtain special emitting weavelength through adjusting well temperature.Finally, we discussed the effect of changing well temperature on the optical character of InGaN/GaN MQW.

4) The methods to obtain low ohmic contact to p-GaN was investigated.

①The surface treatment, annealing temperature and time and atmosphere of p-GaN were optimized.

② Base on the above mentioned optimization condition, comparing Ni/Au contacting p-GaN with p-InGaN/p-GaN SLS as capping layer directy, we found that Ni/Au contact p-InGaN/p-GaN SLS can produce lower specific contact resistivity.When the temperature was chosen to be 550℃, the time of alloying in oxygen atmosphere was 30 minute, the lower specific contact resistivity(ρc) was $1.99\times10^{-4}\Omega cm^2$.

③The reason of p-InGaN/p-GaN SLS forming low specific contact resistivity was investigated further.Firstly, the influence of temperature change of p-GaN in p-InGaN/p-GaN SLS on ohmic contact is discussed.It is found that the growth temperature of p-GaN in p-InGaN/p-GaN SLS increased, the contact resistance increased.Moreover, the effect of

surface layer of capping p-InGaN/p-GaN superlattices on the contact to p-GaN was discussed. It was found that the specific contact resistance (ρ_c) to p-type InGaN was lower when p-GaN was used as the surface layer.

④Using strained-balance theroy, substituteing p-InGaN/p-GaN SLS by p-InGaN/p-AlGaN SLS as p-GaN capping layer was proposed firstly, and lower specific contact resistivity was obtained. the value of ρ_c was $7.27\times10^{-5}\,\Omega\,cm^2$ at room temperature.Furthermore, from the aspects of the band and the hole charge density, we analysed the reason of reduction on the contact resistance.Finally, we obtained low turn-on voltage and series resistance of InGaN–GaN LEDs using strained-compensated and strain-induced piezoelectric p-InGaN/p-AlGaN superlattice as contact layer.

Key Word： GaN base bule-violet laser diode;LP-MOCVD;AlGaN;InGaN/GaN MQW;p-InGaN/p-AlGaN SLS;strained-compensated effect; strain-induced piezoelectric effect;p-type ohmic contact

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