物理学报 Acta Physica Sinica

Chinese Physical Society

Institute of Physics, CAS

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引用信息 Citation: Acta Physica Sinica, **67**, 076801 (2018) DOI: 10.7498/aps.67.20172581
在线阅读 View online: http://dx.doi.org/10.7498/aps.67.20172581
当期内容 View table of contents: http://wulixb.iphy.ac.cn/CN/Y2018/V67/I7

基于GaN同质衬底的高迁移率AlGaN/GaN HEMT材料*

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(2017 年 12 月 4 日收到; 2018 年 2 月 1 日收到修改稿)

研究了表面预处理对GaN同质外延的影响, 获得了高电子迁移率AlGaN/GaN异质结材料. 通过NH_3/H_2混合气体与H_2交替通入反应室的方法对GaN模板和GaN半绝缘衬底进行高温预处理. 研究结果表明, NH_3/H_2能够抑制GaN的分解, 避免粗糙表面, 但不利于去除表面的杂质, 黄光带峰相对强度较高; H_2促进GaN分解, 随时间延长GaN分解加剧, 导致模板表面粗糙不平, AlGaN/GaN HEMT材料二维电子气迁移率降低. 采用NH_3/H_2混合气体与H_2交替气氛模式处理模板或衬底表面, 能够清洁表面, 去除表面杂质, 获得平滑的生长表面和外延材料表面, 有利于提高AlGaN/GaN HEMT材料电学性能. 在GaN衬底上外延AlGaN/GaN HEMT材料, 2DEG迁移率达到2113 $cm^2/V{\cdot}s$, 电学性能良好.

关键词: 金属有机物化学气相沉积, 氮化镓, 热处理, 同质外延

PACS: 68.55.–a, 73.40.Kp, 78.55.Cr **DOI:** 10.7498/aps.67.20172581

1 引 言

GaN材料具有禁带宽度大、电子饱和漂移速度高和介电常数小等特点, 在高频、大功率电子器件应用方面具有巨大的潜力[1–3]. 目前, GaN材料主要通过在SiC, Si和蓝宝石等异质衬底上外延获得, 受限于异质衬底与外延层之间晶格失配和热失配, GaN外延材料位错密度高达10^8—10^{10} cm^{-2}, 严重影响器件性能和寿命[4]. GaN衬底晶格常数和热膨胀系数与外延材料完全匹配, 位错密度可低至10^5 cm^{-2}, 有利于获得高质量GaN材料及高性能器件[5–7]. 近年来, 基于GaN衬底同质外延AlGaN/GaN高电子迁移率晶体管(high electron mobility transistors, HEMT)逐渐引起人们的广泛关注.

GaN表面极易吸附C, O, Si等杂质, 引起GaN缓冲层背景载流子浓度增多[8–10], 导致AlGaN/GaN HEMT器件漏电, 是GaN衬底同质外延AlGaN/GaN HEMT材料的瓶颈. Koblmüller等[11]通过分子束外延方法生长了AlGaN/GaN HEMT, 使用GaN生长/分解的交替过程去除表面的C, O杂质, 获得清洁的生长界面, 界面C, O杂质浓度低于1×10^{17} cm^{-3}. 金属有机化学气相沉积(metal-organic chemical vapor deposition, MOCVD)是生长AlGaN/GaN HEMT材料的常用方法, 通常在生长前采用H_2高温预处理去除表面杂质[12], 可以减少衬底表面杂质对外延材料的影响. 然而, H_2在高温下(> 800 °C)会刻蚀GaN衬底, 粗化衬底表面[13–15], 影响HEMT材料的外延材料粗糙度, 降低AlGaN/GaN HEMT材料二维电子气(two-dimensional electron gas, 2DEG)

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* 国家重点研究发展计划(批准号: 2017YFB0404100)资助的课题.

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的迁移率[16]. Chen 等[17]使用MOCVD同质外延AlGaN/GaN HEMT, 在升温过程中采用“两步法”, 利用低速率生长的GaN缓解H_2对GaN表面的刻蚀, 获得平滑的衬底表面和外延材料表面, AlGaN/GaN HEMT材料2DEG达到2068 $cm^2/V{\cdot}s$, 具有良好的电学性能, 但生长界面的O含量高达1×10^{20} cm^{-3}. NH_3能抑制GaN在高温下分解, 保护GaN表面. Detchprohm等[18]在GaN衬底上生长InGaN/GaN光电二极管, 升温过程中引入NH_3保护衬底表面, 生长的LED材料表面光滑, 表面粗糙度(root-mean-square, RMS)为0.373 nm ($5\ \mu m \times 5\ \mu m$), 但NH_3对GaN表面杂质刻蚀作用较弱.

为降低衬底表面杂质污染物对外延材料性能的影响, 同时避免粗糙表面, 本文采用NH_3/H_2混合气体和H_2交替气氛热处理的方式预处理GaN表面, 研究了交替气氛热处理过程中H_2热处理时间对GaN表面刻蚀以及材料性能的影响, 同时研究了2DEG迁移率变化的物理机理. 将此方法应用在半绝缘GaN衬底上, 获得了表面形貌良好的AlGaN/GaN HEMT材料, 2DEG迁移率大于2100 $cm^2/V{\cdot}s$.

2 实 验

使用MOCVD设备在2英寸(0001)面蓝宝石衬底上生长了GaN模板材料, GaN厚度2 μm, X射线单晶衍射(002)面和(102)面摇摆曲线半高宽分别为240 arcsec和330 arcsec. 衬底预处理具体过程如图1(a)所示. 首先在N_2气氛中升温至800 °C, 通入NH_3以避免GaN分解; 然后继续升温至1030 °C, N_2切换为H_2并保持恒温5 min; 停止通入NH_3, 在H_2中保持恒温0—3 min, 最后继续通入NH_3. 整个热处理过程为10 min. 分别以三甲基镓(TMG)、三甲基铝(TMA)和NH_3作为Ga源、Al源和N源, H_2为载气, 在GaN模板和GaN衬底上生长AlGaN/GaN HEMT结构, 如图1(b)所示. 所用2 inch半绝缘GaN衬底, 厚度为360 μm, 电阻率大于1×10^6 $\Omega{\cdot}cm$.

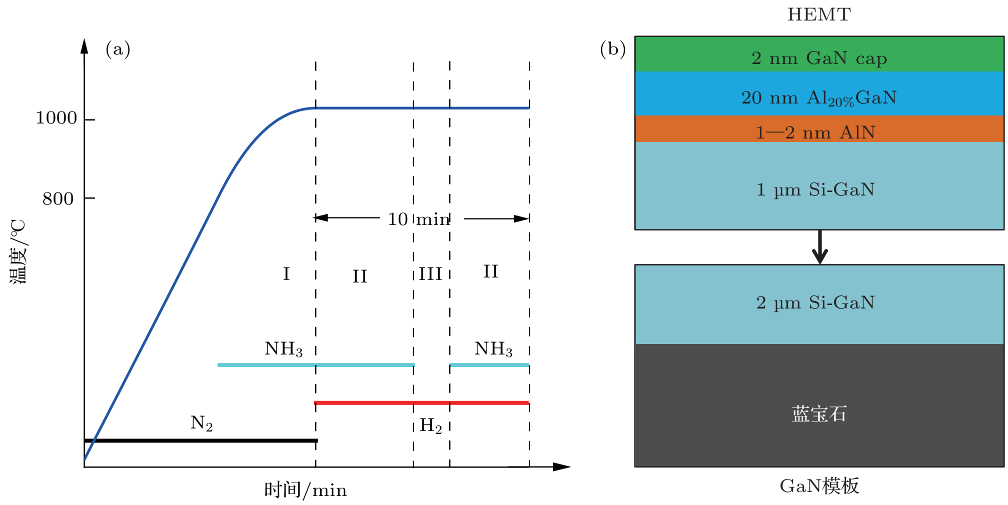

图1 (a) 热处理过程示意图, 包括N_2升温(I); NH_3/H_2混合气体热处理(II和IV); H_2热处理(III); (b) GaN模板生长AlGaN/GaN HEMT结构示意图

Fig. 1. (a) Illustration of thermal treatment process, conclude temperature ramping process in N_2 (I), thermal treatment process in NH_3/H_2 mixed gas (II and IV) and H_2Gas (III); (b) illustration of AlGaN/GaN HEMT structure on GaN templates.

使用光学显微镜(optical microscope, OM)和原子力显微镜(atomic force microscope, AFM)观察GaN模板和AlGaN HEMT结构的表面形貌; 使用霍尔测试仪测试AlGaN/GaN HEMT结构2DEG迁移率; 使用光荧光谱仪(photoluminescence, PL)表征常温下(300 K) AlGaN/GaN HEMT结构光学性能, 激发光源为325 nm He-Cd光器; 使用X射线衍射仪(X-ray diffraction, XRD)测量同质外延GaN材料(002)面和(102)面摇摆曲线半高宽; 使用二次离子质谱(secondary ion mass spectrometry, SIMS)分析GaN衬底与外延层生长界面的C, O杂质浓度.

3 结果与讨论

为了观察NH_3/H_2混合气体和H_2交替气氛热处理对GaN表面的影响, 热处理过程结束后反应室立即停止加热并冷却至室温, 图2(a)—(d)分别为热处理前及H_2热处理0, 1和3 min的GaN表面OM图. 图2(a)与图2(b)中GaN表面光滑, 且外延厚度一致, 表明完全的NH_3/H_2混合气体高温下没有刻蚀GaN表面或刻蚀程度较小; 图2(c)中模板表面出现密集的点状坑, 说明高温下H_2会刻蚀GaN 表面; 图2(d)中模板表面出现网状凹坑, 这是由于H_2热处理时间加长, 加剧了GaN表面刻蚀, 使GaN表面出现较大的网状坑. 图3(a)—(d)分别为热处理前及H_2热处理0, 1和3 min的GaN AFM图. 图3(a)—(c)中, GaN表面平整, 台阶清晰, 表面粗糙度较小(如表1), 说明1 min时间以内的H_2热处理对GaN表面形貌影响较小; 图3(d)出现明显的亮色区和暗色区, 分别代表表面的凸起和凹陷, 且表面粗糙度急剧变大, 这与OM图相对应, 说明长时间的H_2热处理严重刻蚀GaN表面, 导致模板表面粗糙不平.

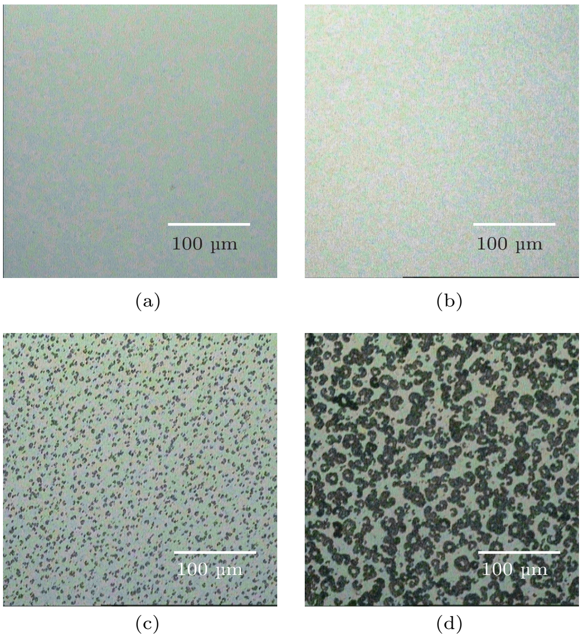

图2 GaN表面OM形貌 (a) 热处理前; (b)—(d) H_2热处理0, 1和3 min

Fig. 2. OM morphologies of GaN templates before (a) and after thermal treatment with H_2 treatment 0 minute (b), 1 minute (c) and 3 minutes (d), respectively.

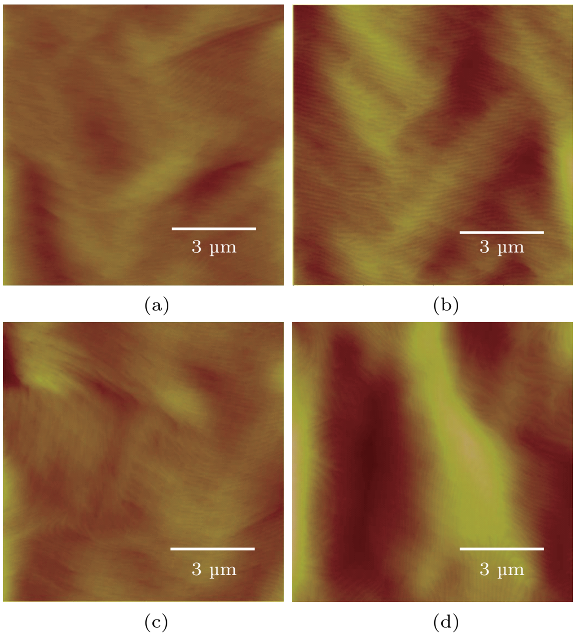

图3 GaN表面AFM(10 μm × 10 μm)形貌 (a) 热处理前, (b)—(d) H_2热处理0, 1和3 min

Fig. 3. AFM (10 μm × 10 μm) morphologies of GaN templates before (a) and after thermal treatment with H_2 treatment 0 minute (b), 1 minute (c) and 3 minutes (d), respectively.

表1 热处理后的GaN模板及原位生长AlGaN/GaN HEMT材料参数

Table 1. Properties of GaN template after thermal treatment and *in-situ* growth AlGaN/GaN HEMT structures.

样品	H_2热处理	GaN模板	AlGaN/GaN HEMT					
	时间/min	RMS/nm	$RMS(10\times10\ \mu m^2)$/nm	迁移率/$cm^2{\cdot}V^{-1}{\cdot}s^{-1}$	(002)/arcsec	(102)/arcsec	I_b/a.u.	I_y/I_b
	热处理前	0.540	—	—	—	—	—	—
A	0	0.615	0.487	1915	235	326	0.08	14
B	1	0.632	0.824	2136	228	312	0.1	6
C	3	1.935	3.276	1790	242	342	0.003	16

采用交替气氛模式热处理GaN模板并原位生长AlGaN/GaN HEMT结构，热处理过程中H_2时间分别为0，1，3 min，样品记为A，B，C. 图4为AlGaN/GaN HEMT表面AFM形貌. 图4(a)显示AlGaN/GaN HEMT表面平滑，$RMS < 0.5$ nm; 图4(b)中AlGaN/GaN HEMT表面出现坑状与丘陵状形貌，表面粗糙度增大; 图4(c)中表面出现明显的凸起与凹陷，甚至出现深坑(黑色区域)，已不能满足器件工艺要求. 对比GaN模板和AlGaN/GaN HEMT表面形貌，随H_2热处理时间延长，AlGaN/GaN HEMT结构的表面形貌与GaN模板的表面形貌变化一致. 说明随着H_2热处理时间延长，模板表面GaN刻蚀程度增大. H_2热处理时间达到3 min后，GaN表面粗糙不平，导致AlGaN/GaN HEMT材料表面形貌严重恶化. 图4(d)—(f)为样品A，B，C扫描范围为2 μm × 2 μm的表面AFM形貌，从图4(d)和图4(e)中可以看到明显的GaN台阶流生长形貌，说明在H_2热处理1 min内的GaN模板上生长了高质量的AlGaN/GaN HEMT材料. 而经过3 min H_2热处理的模板表面由于受到刻蚀程度严重，生长的AlGaN/GaN HEMT材料表面粗糙不平，如图4(f)所示.

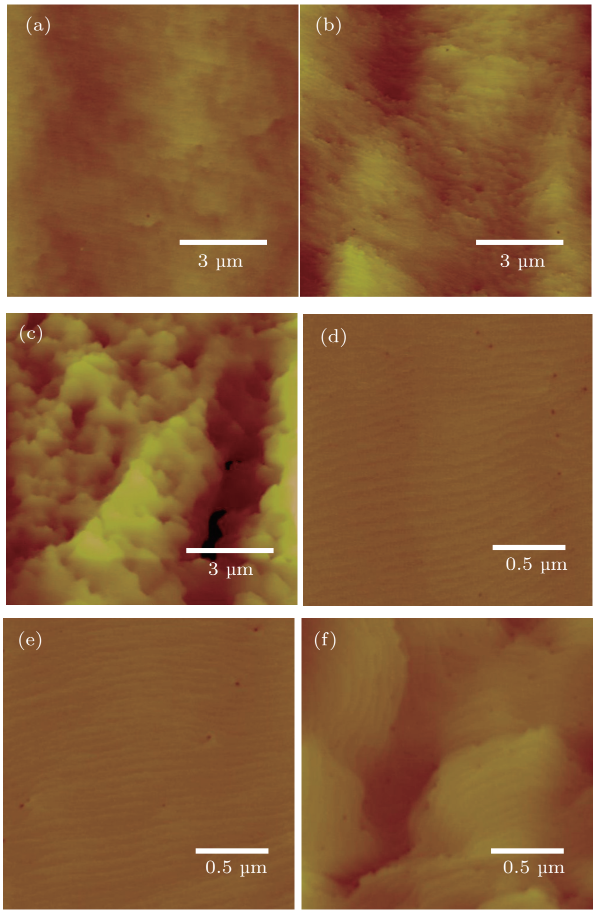

图4 AlGaN/GaN HEMT表面AFM (a)—(c)分别为热处理过程中H_2处理0，1和3 min 10 μm × 10 μm图; (d)—(f)为对应2 μm × 2 μm图

Fig. 4. AFM morphologies of AlGaN/GaN HEMT surfaces: (a)–(c) are the 10 μm × 10 μm morphologies with H_2 treatment time are 0 minute, 1 minute and 3 minutes in thermal treatment process, respectively, as (d)–(f) are corresponding 2 μm × 2 μm morphologies.

使用霍尔测试仪测试了AlGaN/GaN HEMT 2DEG迁移率. 采用交替气氛模式处理GaN模板表面，H_2时间为1 min时生长的AlGaN/GaN HEMT迁移率明显高于H_2时间为0 min和3 min时的迁移率，如图5所示. 根据文献[8, 10]报道，GaN表面极易吸附空气中的C，O等杂质，影响材料及器件性能. 高温下H_2刻蚀GaN，表面杂质发生解吸附，有利于提升材料质量，改善迁移率; 但是长时间H_2热处理会加剧GaN分解，GaN表面粗化使得界面散射加剧，2DEG迁移率急剧降低[19]. 经过1 min的H_2热处理，GaN模板表面的杂质浓度降低，获得清洁表面; 同时H_2刻蚀GaN表面时间较短，避免形成粗糙表面，生长AlGaN/GaN HEMT后表面平整，材料性能提高，2DEG迁移率大于2100 cm^2/V·s，如表1所列.

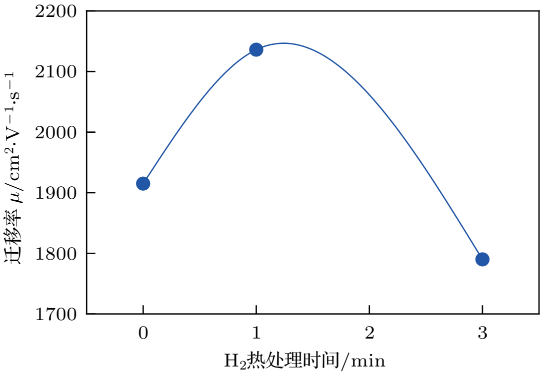

图5 GaN同质外延AlGaN/GaN HEMT 2DEG迁移率

Fig. 5. 2DEG mobility of AlGaN/GaN HEMT on a GaN homogeneous substrate.

测试了AlGaN/GaN HEMT的室温(300 K) PL谱. 图6所示为以GaN近带边峰(361 nm附近)强度($I_{\rm b}$)归一化的PL图谱，560 nm附近的峰为黄光峰. 一般认为黄光峰的产生机理及黄光峰强度(I_y)与材料中的C，O等杂质及相关缺陷有关[20–22]. 样品A和C对应的AlGaN/GaN HEMT黄光峰相对强度($I_y/I_{\rm b}$)远高于样品B对

应的AlGaN/GaN HEMT黄光峰相对强度; 样品C中GaN带边峰基本不可见(如表1所列). 推测认为: 1) NH_3抑制了GaN表面分解, 使表面吸附的C, O杂质没有脱附或脱附不完全, 导致GaN外延时材料黄光峰相对强度较高, 因此样品A对应的AlGaN/GaN HEMT材料的黄光峰相对强度较高[20,21]; 2) 高温下H_2促进GaN分解, 模板表面吸附的杂质脱附比较完全, 因此, 样品B对应的AlGaN/GaN HEMT材料的黄光峰相对强度较低; 3) 长时间的H_2刻蚀导致粗糙的生长界面, 影响GaN的生长机理及晶体质量, 样品C对应的AlGaN/GaN HEMT材料的GaN近带边峰强度降低, 黄光峰相对强度增高[22].

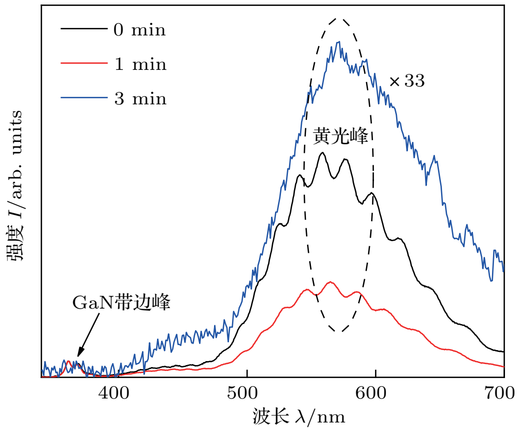

图6 GaN同质外延AlGaN/GaN HEMT结构PL图谱
Fig. 6. PL spectra of AlGaN/GaN HEMT on a GaN homogeneous substrate.

表2 已有报道的GaN衬底同质外延AlGaN/GaN HEMT电学性能及本文数据
Table 2. Statistical electrical properties data of AlGaN/GaN HEMT on a GaN homogeneous substrate.

研究人员	迁移率/$cm^2{\cdot}V^{-1}{\cdot}s^{-1}$	面电子密度/cm^{-2}
Khan et al.[23]	1650	1.4×10^{13}
Tomás et al.[24]	2110	1.1×10^{13}
Chen et al.[17]	2068	8.2×10^{12}
Piotrowska et al.[25]	1210	1.64×10^{13}
本文	2113	9.6×10^{12}

在2 inch GaN衬底上外延AlGaN/GaN HEMT材料, 采用交替气氛模式处理GaN衬底表面, H_2时间为1 min, GaN厚度约1.4 μm. 图7为GaN衬底生长的AlGaN/GaN HEMT表面AFM (2 μm × 2 μm)图片, 可以看到规则有序且平直排列的原子台阶, 表面粗糙度为0.126 nm, 表面质量较高. 图8为GaN同质外延材料(002)面和(102)面摇摆曲线, 半高宽分别为65 arcsec和62 arcsec, 晶体质量高. 室温Hall测试结果中, 2DEG迁移率和浓度分别为2113 $cm^2/V{\cdot}s$和9.6×10^{12} cm^{-2}, 电学性能良好, 迁移率在已有报道中最高, 如表2所列. SIMS谱显示生长界面处C, O杂质浓度分别为4×10^{16} cm^{-3}和9×10^{16} cm^{-3}, 杂质浓度低,

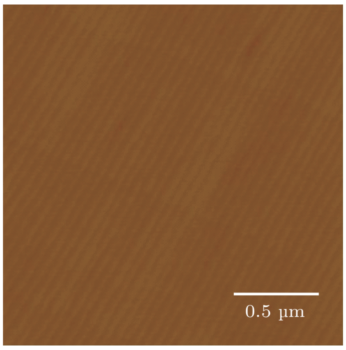

图7 GaN同质外延AlGaN/GaN HEMT表面AFM(2 μm × 2 μm)
Fig. 7. AFM morphology (2 μm × 2 μm) of AlGaN/GaN HEMT surface on a GaN homogeneous substrate.

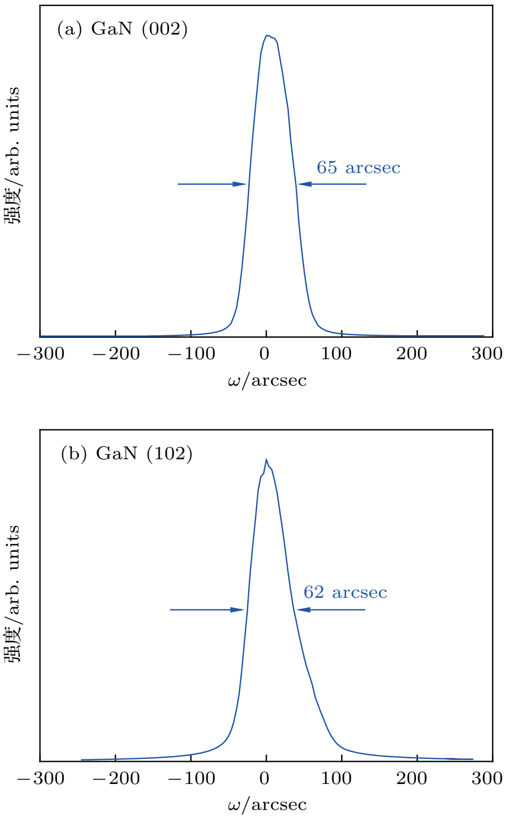

图8 GaN同质外延材料XRD (002)面(a)和(102)面(b)摇摆曲线
Fig. 8. XRD rocking curves of (002) (a) and (102) (b) peaks of the AlGaN/GaN heterostructure grown on a GaN homogeneous substrate.

如图9所示. 说明NH_3/H_2混合气体和H_2交替气氛热处理可以有效清洁GaN衬底表面, 获得高迁移率AlGaN/GaN HEMT材料.

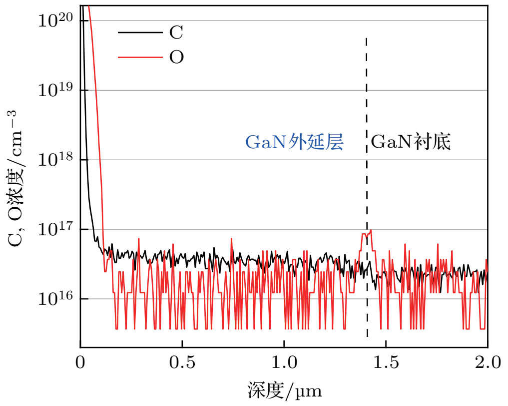

图9 GaN衬底同质外延AlGaN/GaN HEMT中C, O杂质SIMS谱, 0 μm为材料表面

Fig. 9. SIMS impurity profiles of C, O in the epi-wafer of an AlGaN/GaN HEMT on a GaN homogeneous substrate. The surface is located at 0 μm.

4 结 论

采用NH_3/H_2混合气体和H_2交替气氛热处理的方式, 分别在GaN模板和半绝缘GaN衬底上外延AlGaN/GaN HEMT材料. 结果表明, H_2能够去除GaN表面C, O杂质, 降低杂质浓度, 获得清洁表面; NH_3/H_2混合气体可以抑制高温刻蚀GaN, 获得平滑的材料表面; 采用NH_3/H_2混合气体和H_2交替气氛热处理衬底有利于生长表面光滑、黄光峰相对强度较小、2DEG迁移率高的AlGaN/GaN HEMT材料. 在采用该方式处理的GaN衬底上同质外延AlGaN/GaN HEMT材料, 表面平整, 晶体质量高, 2DEG迁移率达到2113 $cm^2/V{\cdot}s$, 具有良好的电学性能.

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Highmobility AlGaN/GaN high electronic mobility transistors on GaN homo-substrates*

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(Received 4 December 2017; revised manuscript received 1 February 2018)

Abstract

Gallium nitride (GaN) has great potential applications in high-power and high-frequency electrical devices due to its superior physical properties. High dislocation density of GaN grown on a foreign substrate leads to poor crystal quality and device reliability. The homo-epitaxial growth of GaN material has low dislocation density, which is the foundation of high performance of AlGaN/GaN highelectronic mobility transistor. However, it is difficult to prepare flat surface of GaN template or GaN substrate in thermal treatment process under the metal-organic chemical vapor deposition (MOCVD) ambient condition in which hydrogen (H_2) is commonly used to clean the substrate surface, i.e., to remove impurities from the substrate surface, since H_2 would greatly enhance GaN decomposition in MOCVD high-temperature condition and etch GaN into roughness surface

In this work, an alternation gas model of ammonia/hydrogen (NH_3/H_2) mixed gas and H_2 gas is designed. This technique is used in a thermal treatment process of GaN template and substrate by MOCVD. Then, we *in-situ* grow AlGaN/GaN HEMTs (high electron mobility transistors) on GaN template and GaN substrate, respectively. A series of alternation gas samples with various H_2 treatment times is investigated. Optical microscope and atomic force microscope are used to observe the morphologies of GaN template and AlGaN/GaN HEMTs and two-dimensional electron gas (2DEG) mobility and density of AlGaN/GaN HEMTs are measured by contactless Hall measurement. Optical properties of AlGaN/GaN HEMTs are analyzed by photoluminescence at room temperature. The residual impurities of C and O in the GaN epilayer and the interfacial region between GaN epilayer and GaN substrate are analyzed by secondary ion mass spectrometry.

The study results show that H_2 enhances GaN decomposition in MOCVD at high temperature, and GaN decomposition greatly strengthens with H_2 treatment time increasing leading to rough surface and the decrease of 2DEG mobility. The NH_3/H_2 mixed gas could suppress GaN decomposition and avoid roughn surface, but go against cleaning out the purity from GaN surface, and the relativive intensity of the yellow band is higher. The NH_3/H_2 mixed gas and H_2 gas alternate thermal treatment model with proper H_2 treatment time on GaN template or GaN substrate, not only obtains atomically flat surface of GaN template and HEMT structure, but also cleans out the purity from GaN surface, which is conducive to the increase of the electric properties of HEMT material. The highest 2DEG mobility reaches to 2136 $cm^2/V{\cdot}s$ with 1 min H_2 treatment in the alternate gas thermal treatment process grown on GaN templates and the electrical properties of HEMT material turn excellent.

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* Project supported by the National Key Research and Development Program of China (Grant No. 2017YFB0404100).

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Finally, an alternate model with 5 min NH_3/H_2 mixed gas followed by 1 min H_2 and then 4 min mixed gas of thermal treatment process is used, the surface morphology of HEMT grown on GaN substrate shows highly uniform atomically steps and the root-mean-square value is 0.126 nm for 2 μm × 2 μm scan area; the HEMT 2DEG mobility 2113 $cm^2/V{\cdot}s$ grown on GaN substrate shows good electric properties, the residual impurities of C and O in the interfacial region between GaN epilayer and GaN substrates are below 1×10^{17} cm^{-3}, showing clean interfacial.

Keywords: metal-organic chemical vapor deposition, GaN, thermal treatment, homo-epitaxial

PACS: 68.55.–a, 73.40.Kp, 78.55.Cr **DOI:** 10.7498/aps.67.20172581