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1000 V p-GaN混合阳极AlGaN/GaN二极管*

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GaN 材料具有优异的电学特性, 如大的禁带宽度 (3.4 eV)、高击穿场强 (3.3 MV/cm) 和高电子迁移率 (600 $cm^2/(V{\cdot}s)$). AlGaN/GaN 异质结由于压电极化和自发极化效应, 产生高密度 (1×10^{13} cm^{-2}) 和高迁移率 (2000 $cm^2/(V{\cdot}s)$) 的二维电子气 (2DEG), 在未来的功率系统中, AlGaN/GaN 二极管具有极大的应用前景. 二极管的开启电压和击穿电压是影响其损耗和功率处理能力的关键参数, 本文提出了一种新型的具有高阻盖帽层 (high-resistance-cap-layer, HRCL) 的 p-GaN 混合阳极 AlGaN/GaN 二极管来优化其开启电压和击穿特性. 在 p-GaN/AlGaN/GaN 材料结构基础上, 通过自对准的氢等离子体处理技术, 在沟道区域形成高阻盖帽层改善电场分布, 提高击穿电压, 同时在阳极区域保留 p-GaN 结构, 用于耗尽下方的二维电子气, 调控开启电压. 制备的 p-GaN 混合阳极 (p-GaN HRCL) 二极管在阴阳极间距 L_{ac} 为 10 μm 时, 击穿电压大于 1 kV, 开启电压 +1.2 V. 实验结果表明, p-GaN 混合阳极和高阻 GaN 盖帽层的引入, 有效改善 AlGaN/GaN 肖特基势垒二极管电学性能.

关键词: AlGaN/GaN, 二极管, p-GaN

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1 引 言

1986 年, Amano 等[1] 用金属有机化学气相沉积法成功外延出表面光滑无裂纹的 GaN 单晶层, 引发了 GaN 材料的研究热潮. Si 基 AlGaN/GaN 肖特基势垒二极管 (AlGaN/GaN SBD) 具有高工作频率、低开态电阻和高击穿场强等优异的电学性能[2−4], 在功率转换装置, 如升压转换器、半桥逆变器、降压-升压转换器[5−7] 和功率因数校正电路中发挥着重要的作用. AlGaN/GaN SBD 拥有优异性能的主要原因是 AlGaN/GaN 异质结构中压电极化和自发极化效应能够产生高浓度和高电子迁移率的二维电子气 (2DEG)[8].

传统的 AlGaN/GaN SBD 面临着击穿电压小、热稳定性差、电流密度低[9]、正向电流和反向击穿电压相互制衡等不足. 为了改善 AlGaN/GaN SBD 的击穿特性, 大量研究工作已经展开. 2016 年, Hu 等[10] 研究了结终端 AlGaN/GaN SBD, 在凹槽与阳极连接凹槽边缘处淀积一层 Si_3N_4 栅介质, 击穿电压为 600 V (V_{BD}@1 μA/mm); 2017 年, Bai 和 Du[11] 设计了一种钝化层由高介电常数 La_2O_3 和低介电常数 SiO_2 混合材料制备的 AlGaN/GaN SBD, 击穿电压可达 902 V (V_{BD}@1 mA/mm); 2017 年, Ma 和 Zanuz 等[12] 人研究的场板结合三维晶体管结构的 AlGaN/GaN SBD, 击穿电压可达 500 V (V_{BD}@10 nA/mm). 2018 年, Lei 等[13] 研究了双沟道双凹槽阳极结构 AIGaN/GaN SBD, 将金属氧化物半导体场板设置在浅凹陷区域上夹断下面的沟道, 抑制器件截止状态时的泄漏电流, 击穿电压可达 704 V (V_{BD}@1 μ A/mm). 然而, 现有 GaN 基肖

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特基势垒二极管的击穿电压一般只能达到理论值的50%左右[14], 进一步提升击穿电压成为了研究的焦点.

本文提出了一种新型p-GaN混合阳极高阻盖帽层(p-GaN HRCL) AlGaN/GaN二极管, 在传统AlGaN/GaN SBD的基础上进行两方面结构改进: 一是p-GaN混合阳极结构, 在阳极区域引入Mg掺杂的p-GaN, 通过p-GaN的掺杂浓度对器件的开启电压实现调控; 二是高阻GaN盖帽层结构, 在阴阳极之间利用自对准氢等离子体技术钝化非电极区域获得, 改善电极之间的电场分布, 有效提高器件击穿电压.

2 器件结构与制备

p-GaN HRCL二极管结构原理图如图1所示, Ni/Au接触p-GaN区域向阴极延伸1.5 μm, 阳极阴极间距 L_{ac} = 10 μm, 台面宽度150 μm. 本文使用的p-GaN/AlGaN/GaN异质结是在2英寸Si (111)衬底上通过金属有机化学气相沉积外延结得到的, 器件外延结构自下而上分别为: 4.8 μm C掺杂高阻GaN缓冲层, 150 nm GaN沟道层, 1 nm AlN空间层, 18 nm未掺杂的 $Al_{0.2}Ga_{0.8}N$ 势垒层和70 nm Mg掺杂浓度为2—3 × 10^{19} cm^{-3} 的p-GaN结构.

器件隔离采用F离子注入, 注入能量分别为: 140, 80, 40 keV, 注入剂量分别为: 1.2 × 10^{14}, 6 × 10^{13}, 4 × 10^{13} cm^{-2}. 欧姆接触采用氯基感应耦合等离子体刻蚀技术(ICP)将表面p-GaN层刻掉. 接着, 使用光刻胶做掩膜, 电子束蒸发设备蒸发Ti/Al/Ni/Au (20 nm/130 nm/50 nm/100 nm)多层金属, 剥离后在氮气氛围下890 °C 30 s的快速热退火形成欧姆接触. 在阳极蒸发Ni/Au (50 nm/ 150 nm)金属层, 与覆盖的p-GaN形成欧姆接触. 最后, 对器件进行氢等离子体处理, 以钝化非电极区域p-GaN, 在氮气氛围下进行350 °C 5 min的快速退火, 修复氢离子注入时产生的损伤. 氢等离子体处理采用Oxford Plasmalab System 100 ICP 180, RF功率2 W, ICP功率300 W和压强8 mTorr. 注入的氢与p-GaN中的Mg施主形成络合物, 将p-GaN形成高阻GaN (HR-GaN)[15]. 图2为器件能带示意图, 可以看到, HR-GaN下方能带压低, AlGaN/GaN界面处的2DEG重新感生, 传输线方法测试了钝化之后的材料, 其方块电阻570 Ω/□, 接触电阻0.7 Ω·mm; p-GaN下方的导带被抬高[16], 对应沟道下方二维电子气被耗尽.

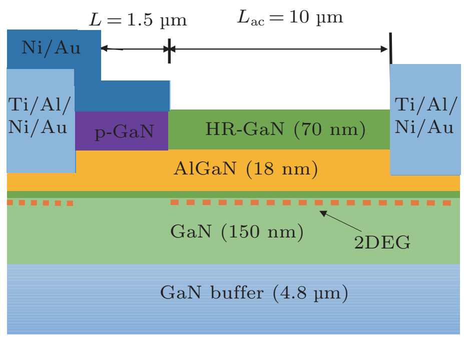

图1　p-GaN HRCL二极管结构剖面图

Fig. 1. Schematic cross-sectional structure of p-GaN HRCL diode.

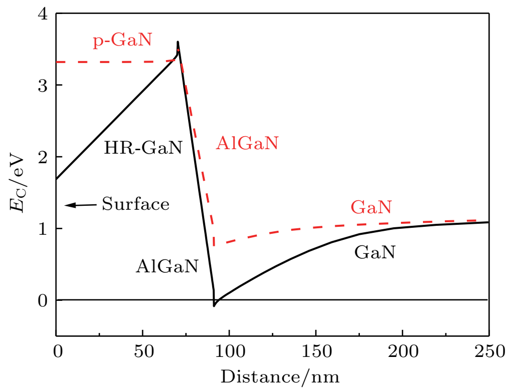

图2　二极管中HR-GaN区域(实线)和p-GaN区域(虚线)能带结构

Fig. 2. Band diagram of HR-GaN region (solid line) and p-GaN region (dotted line) in the diode.

3 结果与讨论

对器件进行正向偏压测试, 获得的正反向扫描(第一次方形, 第二次圆形) p-GaN HRCL二极管 *I*-*V* 特性及其对数图像如图3所示. 器件阴阳极间距 L_{ac} = 10 μm, 开启电压 V_{on} 为+1.2 V (本文中定义 V_{on}@1 mA/mm), 最大正向电压10 V时, 电流密度可达533 mA/mm. 器件在100 mA/mm下的比导通电阻 $R_{on,sp}$ 为3.75 mΩ/cm^2, 从图4击穿电压对应比导通电阻的值中可以看出, p-GaN HRCL二极管相较于其他类型的GaN SBD而言处于国际水平.

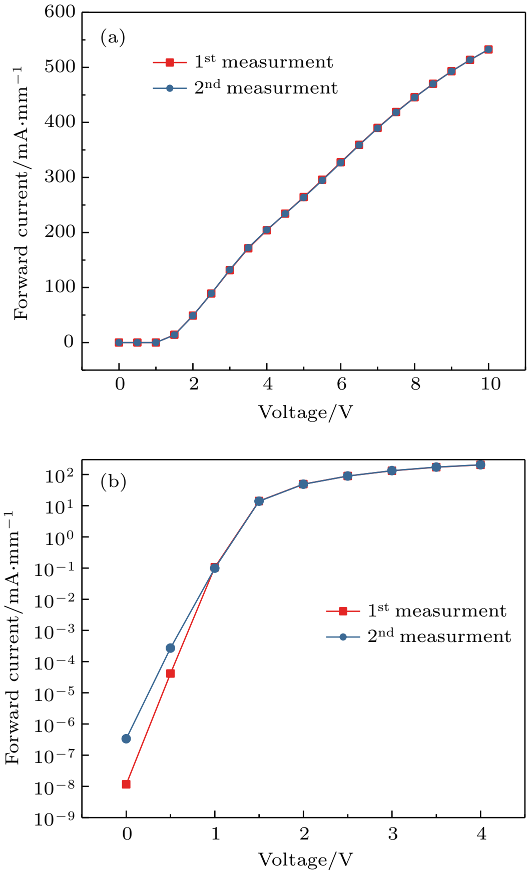

图3　(a) 线性坐标和 (b) 半对数坐标下的 p-GaN HRCL 二极管正向 I-V 特性

Fig. 3. p-GaN HRCL diode forward I-V characteristics in linear coordinates (a) and semi-logarithmic coordinates (b).

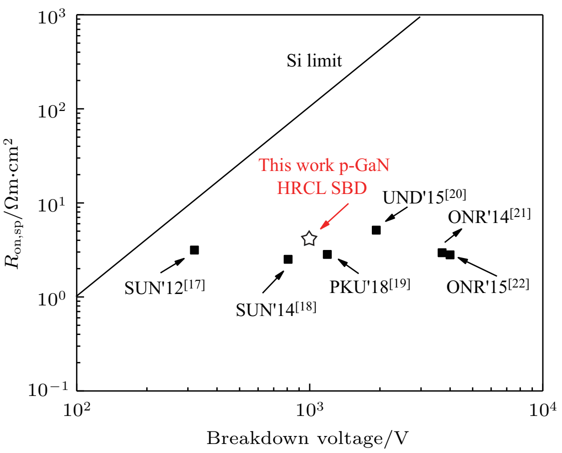

图4　GaN 二极管击穿电压对应比导通电阻, 红色五角星为 p-GaN HRCL 二极管

Fig. 4. Breakdown voltage versus $R_{\mathrm{on,sp}}$ for GaN SBD. The red star represents the p-GaN HRCL diode.

反向偏压0到1 kV 测试范围内, 器件耐压特性如图5所示, 在 $L_{\mathrm{ac}} = 10$ μm的条件下, 耐压高达1 kV (文中定义击穿电压 V_{BD} @1×10^{-4} A/mm), 在漏电流小于 1×10^{-5} A/mm条件下, 器件获得了大于875 V的击穿电压. 器件的高耐压是由于图6所示的极化效应[7], 图6 (b) 器件中HR-GaN/AlGaN界面处出现负电荷, 相对于图6 (a) 器件中没有HR-GaN高阻盖帽层的结果而言, 图6 (b) 器件表面的高阻盖帽层能够增加AlGaN中的垂直电场, 减少肖特基接触附近的横向电场集中, 降低器件峰值电场强度, 提高击穿电压.

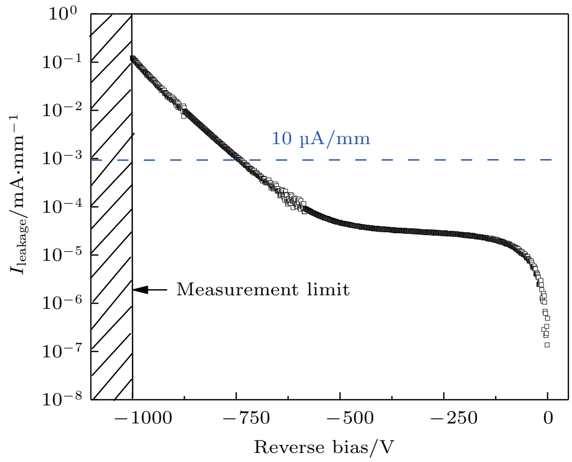

图5　p-GaN HRCL 二极管反向击穿特性

Fig. 5. Reverse breakdown characteristic of p-GaN HRCL diode.

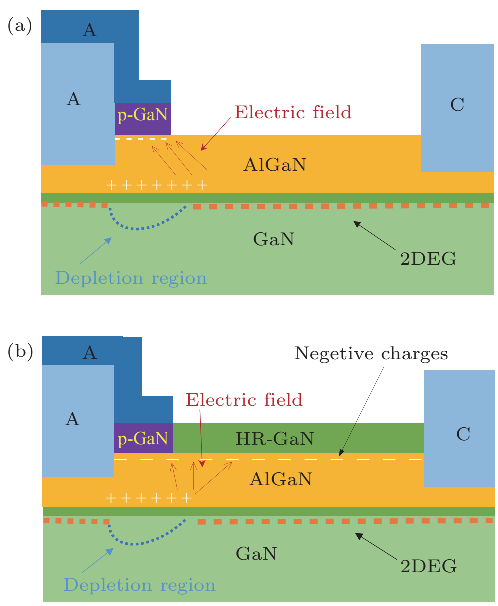

图6　(a) 无 HRCL p-GaN 二极管和 (b) HRCL p-GaN 二极管垂直电场分布

Fig. 6. Vertical electric field distribution of p-GaN diode without HRCL (a) and with HRCL (b).

4 总　结

在传统Si基AlGaN/GaN肖特基势垒二极管结构上, 本文提出了一种新型p-GaN混合阳极

HRCL AlGaN/GaN二极管. 器件通过阴阳极之间的高阻GaN盖帽层结构, 改善电极之间的电场分布, 提高击穿电压; 同时在阳极区域引入Mg掺杂的p-GaN, 耗尽沟道下方二维电子气, 通过掺杂浓度调控开启电压. 实验结果表明, p-GaN HRCL二极管阴阳极间距L_{ac}为10 μm, 器件击穿电压大于1 kV, 开启电压+1.2 V, 有效提高AlGaN/GaN势垒二极管电学性能. 我们将进一步研究p-GaN中Mg^{2+}掺杂浓度对开启电压的调控作用, 实现p-GaN HRCL二极管更低的正向开启电压.

参考文献

[1] Amano H, Sawaki N, Akasaki I 1986 *Appl. Phys. Lett.* **48** 255

[2] Chen K J, Häberlen O, Lidow A 2017 *IEEE. Trans. Electron Dev.* **64** 779

[3] Li W Y, Zhang Z L, Fu K 2017 *J. Semi-cond.* **38** 074001

[4] Dora Y, Chakraborty A, McCarthy L 2006 *IEEE Electron Dev. Lett.* **27** 713

[5] Kim J, Kim C 2013 *IEEE Trans. Power Electron.* **28** 3827

[6] Ma F, Luo A, Xu X, Xiao H 2013 *IEEE Trans. Ind. Electron.* **60** 728

[7] Ishida H, Shibata D, Yanagihara M 2008 *IEEE Electron Dev. Lett.* **29** 1567

[8] Ma L, Wang Y, Yu Z P 2004 *Chin. J. Semi-cond.* **25** 1285 (in Chinese) [祃龙, 王燕, 余志平 2004 半导体学报 **25** 1285]

[9] Lee J G, Park B R 2013 *IEEE Trans. Power Electron.* **34** 214

[10] Hu J, Stoffels S, Lenci S 2016 *IEEE Trans. Electron Dev.* **63** 997

[11] Bai Z Y, Du J F 2017 *Superlattices Microstruct.* **111** 1000

[12] Ma J, Zanuz D C 2017 *IEEE Electron Dev. Lett.* **39** 260

[13] Lei J C, Jin W, Tang G F 2018 *Electron. Lett.* **51** 1889

[14] Wu Y F, Guo W L, Cheng Y F 2017 *Chin. J. Lumin.* **38** 477 (in Chinese) [吴月芳, 郭伟玲, 陈艳芳 2017 发光学报 **38** 477]

[15] Hao R H, Fu K, Yu G H 2016 *Appl. Phys. Lett.* **109** 152106

[16] Hao R H, Li W Y, Fu K, Yu G H 2017 *IEEE Electron Dev. Lett.* **38** 1087

[17] Ha M W, Lee J H, Han M K 2013 *Solid-State Electron.* **73** 1

[18] O Seok, Han M K, Byun Y C 2015 *Solid-State Electron.* **103** 49

[19] Gao J N, Jin Y F, Xie B 2018 *IEEE Electron Dev. Lett.* **38** 859

[20] Cooke M 2015 *Semicond. Today* **10** 98

[21] Kizilyalli I C, Edwards A P, Nie H 2014 *IEEE Electron Dev. Lett.* **35** 247

[22] Kizilyalli I C, Prunty T, Aktas O 2015 *IEEE Electron Dev. Lett.* **36** 1073

p-GaN hybrid anode AlGaN/GaN diode with 1000 V operation*

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Abstract

GaN plays an important role in compound semiconductor, which exhibits excellent electrical properties such as wide band gap (3.4 eV), high breakdown field strength (3.3 MV/cm), and high electron mobility (600 $cm^2/(V·s)$). AlGaN/GaN heterojunction produces two-dimensional electron gas (2DEG) with high density (1×10^{13} cm^{-2}) and high electron mobility (2000 $cm^2/(V·s)$) which are caused by strong piezoelectric and spontaneous polarization. The Si-based AlGaN/GaN devices emerge as a promising candidate for the nextgeneration switching application in power system due to 2DEG of AlGaN/GaN heterojunction. Turn-on and breakdown voltage are key parameters for diodes and they have a tradeoff between each other. These two parameters affect diode loss and power handling capability. For better properties, we propose a novel p-GaN hybrid anode AlGaN/GaN diode with high-resistance-cap-layer (HRCL) to optimize turn-on voltage and breakdown characteristics. Based on the p-GaN/AlGaN/GaN material structure, an HRCL is fabricated in the channel region by self-aligned hydrogen plasma treatment to improve the breakdown voltage. Hydrogen plasma is adopted to compensate for holes in the p-GaN to release electrons from the 2DEG channel, forming a high-resistivity area. The transmission line method tests the material after passivation, showing that its sheet resistance is 570 Ω/□ and a contact resistance is 0.7 Ω·mm. In the HRCL p-GaN diode, negative charges can appear at the interface of HR-GaN/AlGaN due to polarization effect, which increases the vertical electric field in AlGaN and reduces the lateral electric field near the cathode in the p-GaN, compared with in the p-GaN diode without HRCL. The p-GaN in the anode region is reserved to regulate the turn-on voltage by depleting the underlying 2DEG. The p-GaN structure raises conduction band beyond the Fermi level, ensuring the reduction of 2DEG. The fabricated HRCL p-GaN diode exhibits a high breakdown voltage over 1000 V at $I_{leakage} = 1\times10^{-4}$ A/mm with a cathode-anode distance L_{ac} of 10 μm and a turn-on voltage of +1.2 V when forward current is 1 mA/mm. These results indicate that the introduction of p-GaN hybrid anode and HRCL can enhance the electrical properties of AlGaN/GaN diode effectively. However, little attention has been paid to doping concentration in p-GaN. Study of the regulation of Mg^{2+} doping concentration on the turn-on voltage in p-GaN will be investigated in future to achieve a low forward turn-on voltage of the p-GaN HRCL diode.

Keywords: AlGaN/GaN, diode, p-GaN

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