

晶格匹配 InAlN/GaN 异质结 Ti/Al/Ni/Au 欧姆接触的 温度依赖特性

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摘要 在硅衬底晶格匹配 $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ 异质结外延片上制备了Ti/Al/Ni/Au欧姆接触传输线模型测试结构, 通过测试变温电流-电压特性研究方块电阻(R_{sh})和比接触电阻率(ρ_{sc})的温度依赖特性. 结果表明: (1) 沟道层的 R_{sh} 对温度呈指数依赖关系, 幂指数约-2.61, 主要由高温下半导体的晶格散射机制决定; (2) 300~523 K的变温范围内, ρ_{sc} 随温度上升呈先增大后减小的趋势; 当温度低于350 K时, ρ_{sc} 的温度依赖关系主要由TiN合金的类金属特性决定; 而在更高的温度下, 热场发射机制将逐渐占主导. 基于以上2种模型的并联形式对实验数据进行了拟合, 并分析了提取的重要物理参数.

关键词 晶格匹配, InAlN/GaN 异质结, 欧姆接触, 温度依赖特性, 类金属特性, 热场发射

GaN基半导体材料优越的物理特性, 如高电子迁移率、高电子漂移速率、强击穿电场和良好的热稳定性等, 使AlGaIn/GaN异质结特别适合制备在微波功率领域具有巨大应用前景的高电子迁移率晶体管(HEMT)^[1]. 然而, 势垒层显著的逆压电效应严重限制了器件在长时间大信号工作模式下的可靠性^[2]. 目前最有效的一种解决方法是用晶格匹配无应力的 $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ 异质结代替传统的AlGaIn/GaN异质结^[3]. 另一方面, 为了获得尽可能大的输出电流, HEMT的源极和漏极通常采用欧姆接触结构, 其质量好坏直接影响器件的整体电学性能. 因此, 研究InAlN/GaN异质结欧姆接触的电学特性及电流输运机制具有重要的应用价值. 2002年, Qiao等人^[4]提出电子主要以隧穿方式通过AlGaIn势垒层, 这些电子

主要源于AlGaIn/GaN异质结界面的二维电子气(2DEG); 2009年, Liu等人^[5]认为AlGaIn势垒层应采用串联双势垒描述, 载流子主要以热场发射(TFE)方式透过有效势垒层; 2013年, Kim等人^[6]则提出, 快速热退火过程会在金-半界面形成TiN合金钉状物, 从而有效促进电子在该处的隧穿; 同年, Lucolano等人^[7]提出了类金属输运机制, 认为载流子可在贯穿势垒层的TiN合金中直接输运.

为了进一步揭示InAlN/GaN异质结的欧姆接触特性, 本文在硅衬底的晶格匹配 $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ 异质结外延片上制备了Ti/Al/Ni/Au欧姆接触的传输线模型(TLM)测试结构, 通过测量具有不同电极间距样品的变温电流-电压(T - I - V)特性, 研究了方块电阻(R_{sh})和比接触电阻率(ρ_{sc})的温度依赖特性, 并且提出

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了并联比接触电阻率模型. 利用该模型解释了异质结欧姆接触的载流子输运, 认为异质结欧姆接触的载流子输运由传统的TFE机制和TiN的类金属特性共同决定.

1 实验

利用金属有机化合物气相沉积法在(111)面硅衬底上生长了晶格匹配无应力的 $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ 异质结, 外延结构主要包括 $1.6\text{ }\mu\text{m}$ 的非故意掺杂GaN层, 1 nm 的AlN插入层, 18 nm 的非掺杂 $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$ 势垒层和 2 nm 的非掺杂GaN帽层(有效提高沟道迁移率和极化势垒高度). 利用水银探针台测试了外延层的高频电容-电压曲线, 确定了界面的2DEG体浓度约为 $9.11\times 10^{19}\text{ cm}^{-3}$. 沉积金属电极之前, 在材料表面刻蚀形成台面, 再在台面上利用标准的光刻和剥离技术定义了一系列线性排列的长 $\times$ 宽($L\times W$)为 $80\text{ }\mu\text{m}\times 100\text{ }\mu\text{m}$ 的矩形TLM结构. 为了形成良好的欧姆接触, 在电子束蒸发Ti/Al/Ni/Au金属层后, 立即将外延片在 N_2 氛围 870°C 下快速热退火 30 s ; 同时, 为减少电极之间半导体表面可能存在的横向漏电流分量, 利用等离子增强化学气相沉积技术在裸露的半导体表面生长 150 nm 厚的氮化硅钝化层; 最后, 为了方便探针测试, 在欧姆接触表面电镀 $2\text{ }\mu\text{m}$ 的Au层进行电极加厚. 图1(a)和(b)分别为制备的器件结构截面示意图和TLM测试结构平面照片, 相邻电极之间的距离 d 依次为 $3, 4, 8, 16$ 和 $90\text{ }\mu\text{m}$. 利用Keithley 4200半导体参数分析仪和MAC3C变温测试仪进行 T - I - V 测试, 变

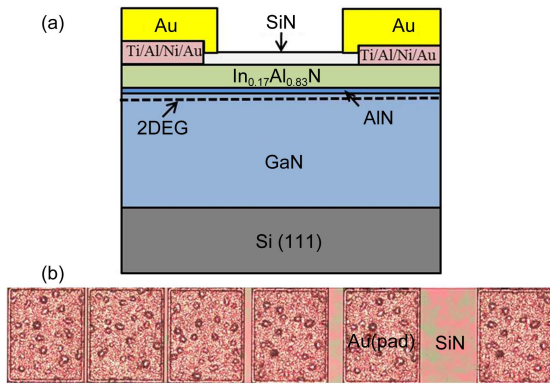


图1 (网络版彩色)(a) InAlN/GaN异质结Ti/Al/Ni/Au欧姆接触的截面示意图; (b) TLM测试结构的平面照片

Figure 1 (Color online) (a) Schematic cross section of InAlN/GaN heterostructure with Ti/Al/Ni/Au ohmic contact; (b) planar image of TLM measurement structure

温范围为 $300\sim 523\text{ K}$.

2 结果与讨论

图2(a)为TLM测试结构的室温 I - V 特性曲线, 不同电极间距样品均表现出良好的欧姆特性, 并且间距越大, 对应的斜率越小, 即电阻越大. 一般情况下, 相邻电极间的总电阻 R_T 由金-半界面的接触电阻 R_C 和材料的体电阻 R_B 两部分组成,

$$R_T = 2R_C + R_B = \frac{2R_{sh}}{W}L_T + \frac{R_{sh}}{W}d, \quad (1)$$

式中, $L_T = \sqrt{\rho_{cs}/R_{sh}}$ 为传输长度. 在均匀掺杂情况下作 R_T - d 图应得到1条直线, 通过斜率可求得 R_{sh} , $d=0$ 时的截距可求得 ρ_{cs} . 图2(b)为不同温度下 R_T 随 d 的变化情况, 呈现明显的线性关系, 且斜率(即 R_{sh}/W)随温度升高而增加.

图3(a)显示了通过线性拟合获得的 R_{sh} 随温度的变化关系. 对于异质结半导体, $R_{sh}=1/q\mu_n n_{2DEG}$, 其中, μ_n 为2DEG迁移率, n_{2DEG} 为2DEG面密度. 因此, In-AlN/GaN异质结 R_{sh} 的温度依赖特性可能由 μ_n 和 n_{2DEG} 2

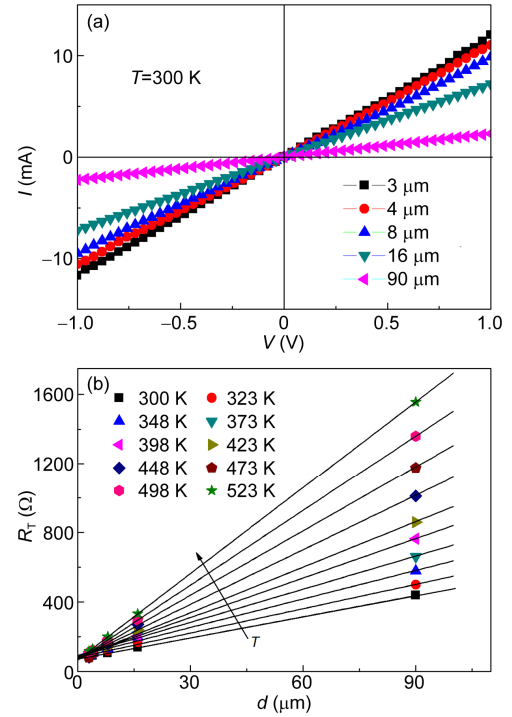


图2 (网络版彩色)(a) TLM测试结构的室温 I - V 特性曲线; (b) 不同温度下 R_T 与 d 的关系

Figure 2 (Color online) (a) I - V characteristics of TLM measurement structures at room temperature; (b) R_T as a function of d at different temperatures

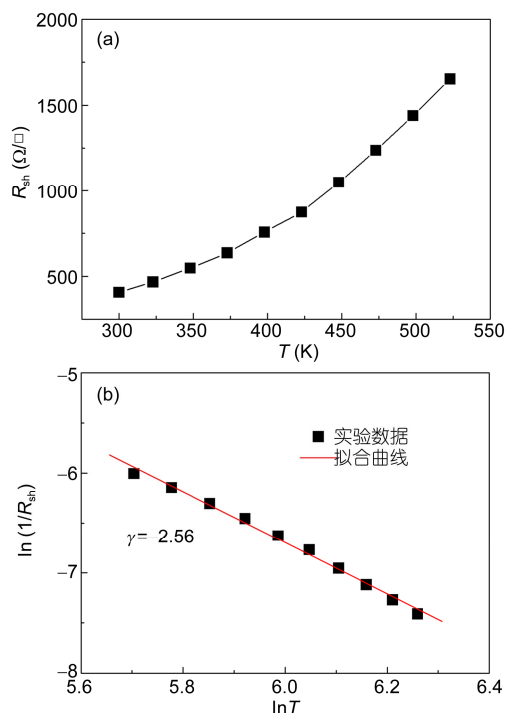


图3 (网络版彩色)(a) R_{sh} 随温度的变化关系; (b) $\ln(1/R_{sh})$ - $\ln T$ 的线性拟合结果

Figure 3 (Color online) (a) R_{sh} as a function of temperature; (b) the linear fitting results of $\ln(1/R_{sh})$ and $\ln T$

个因素决定. 值得指出的是, 2DEG的形成主要与势垒层内的强极化效应相关, 面密度是温度的弱函数, 所以 μ_n 对 R_{sh} 应有较大影响. 经典理论表明, 影响 μ_n 的主要散射机制包括晶格散射和杂质散射. 对于电离杂质较多的半导体, 低温时晶格原子的热振动能较低, 对载流子的散射作用较弱, 杂质散射(库伦力作用)效应起主要作用; 而在高温时, 载流子热运动速度加快, 在杂质原子附近停留时间变短, 杂质散射作用减弱, 而晶格原子的热振动剧烈, 因此晶格散射作用更显著. 在本文的温度范围内, 影响 μ_n 的主要散射机构应为晶格散射, R_{sh} 满足以下关系^[8]:

$$R_{sh} = R_{sh0} \left(\frac{T_0}{T} \right)^\gamma, \quad (2)$$

式中, R_{sh0} 是 R_{sh} 在 $T_0=300$ K下的值(406 $\Omega/\square$), γ 是幂指数. 式(2)可变换为

$$\ln(1/R_{sh}) = \beta + \gamma \ln T, \quad (3)$$

式中, β 为常数. 晶格散射机制占主导时, $\ln(1/R_{sh})$ 与 $\ln T$ 应呈线性关系, 斜率为 γ . 图3(b)给出了实验获得的 $\ln(1/R_{sh})$ - $\ln T$ 关系及其拟合结果, 可以看出, 它们遵循很好的线性关系. 拟合得到 $\gamma=-2.56$, 明显小于

已报道的蓝宝石衬底器件的 -1.57 ^[6], 表明硅衬底上的 R_{sh} 有更强的温度依赖性. 相对于蓝宝石衬底, 硅衬底上的GaN外延层具有较大的位错密度^[9], 对沟道电子迁移率的温度效应有更显著的影响.

图4为比接触电阻率 ρ_{sc} 随温度的变化关系. 其中, 常温300 K下的 $\rho_{sc}=3.40 \times 10^{-4} \Omega \text{ cm}^2$, 接近于Kim等人^[6]在InAlN/GaN体系中的最低 $\rho_{sc}(5.28 \times 10^{-4} \Omega \text{ cm}^2)$. 结果表明, 温度从300 K升至523 K的过程中, ρ_{sc} 呈现先增大后减小的趋势, 在350 K左右达到最大值. 考虑到异质结界面2DEG的存在和势垒层厚度仅18 nm, ρ_{sc} 的温度依赖特性可以由TFE机制决定, 对应的比接触电阻率 ρ_{TFE} 可表示为^[10]

$$\rho_{TFE} = \frac{dV}{dJ} \bigg|_{V=0} = \left(\frac{1}{qA^*} \right) \frac{k_B^2}{\sqrt{\pi(\Phi_B + E_n)E_{00}}} \times \cosh \left(\frac{E_{00}}{k_B T} \right) \sqrt{\coth \left(\frac{E_{00}}{k_B T} \right)} \exp \left(\frac{\Phi_B + E_n}{E_0} - \frac{E_n}{k_B T} \right), \quad (4)$$

式中, Φ_B 为有效隧穿势垒高度, E_n 为费米能级与导带底的能量差, $E_{00}=qh/4\pi(N_D/\text{cm}^2)^{1/2}$ 为特征隧穿能量, N_D 为2DEG体浓度, $E_0=E_{00}\coth(E_{00}/k_B T)$, $A^*=4\pi m^* q k_B^2/h^3$ 是理查德森常数, $m^*=0.2m_e$ 是电子有效质量. 利用式(4)对实验数据进行拟合, 发现TFE模型仅与高温部分(>400 K)的数据点吻合, 在较低温度段则出现相反的变化趋势.

相关研究表明^[6,7], InAlN/GaN异质结和Ti/Al/Ni/Au金属层在快速热退火形成欧姆接触的过程中, 会产生贯穿整个势垒层的TiN合金钉状物, 对电流输运有直接影响. TiN是一种类金属化合物, 存在显著的

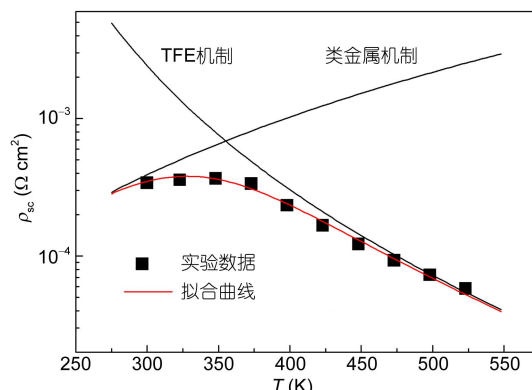


图4 (网络版彩色)比接触电阻率的实验数据及拟合结果

Figure 4 (Color online) Experimental data of specific contact resistance and the fitting results based on the parallel model

温度效应, 所以 ρ_{sc} 随温度升高而增大的行为可能与该合金的类金属特性有关, 对应的比接触电阻率 ρ_{metal} 可描述为^[11]

$$\rho_{metal} = b \left(\frac{T}{T_0} \right)^{\alpha}, \quad (5)$$

式中, b 为 $T_0=300$ K时的比接触电阻率, α 为幂指数, 表示电阻率随温度变化的快慢。

整个测试温度范围内的 ρ_{sc} 可写为TFE机制和类金属特性的并联形式:

$$\frac{1}{\rho_{sc}} = \frac{1}{\rho_{TFE}} + \frac{1}{\rho_{metal}}, \quad (6)$$

低温时, 类金属机制占主导, $\rho_{sc} \sim \rho_{metal}$; 高温时, TFE机制占主导, $\rho_{sc} \sim \rho_{TFE}$. 图4中的拟合曲线与实验数据非常吻合, 证明了式(6)的并联模型的正确性. 基于TFE机制的拟合可得: $N_D=3.72 \times 10^{19} \text{ cm}^{-3}$, $E_n=0.122 \text{ eV}$, $\Phi_B=0.86 \text{ eV}$. 对于异质结界面的2DEG, 应采用简并半导体的载流子浓度关系式描述^[12]:

$$N_D = N_C \frac{2}{\sqrt{\pi}} F_{1/2} \left(\frac{E_n}{k_B T} \right), \quad (7)$$

$$F_{1/2}(\xi) = \int_0^{\infty} \frac{x^{1/2}}{1 + e^{x-\xi}} dx, \quad (8)$$

式中, $N_C=2.3 \times 10^{18} \text{ cm}^{-3}$, 为GaN导带底的有效态密度; $F_{1/2}$ 为费米积分. 将 $E_n=0.122 \text{ eV}$ 代入上式, 得 $N_D=2.34 \times 10^{19} \text{ cm}^{-3}$, 该值与拟合的结果很接近. 值得注意的是, 拟合获得的 N_D 值仍小于未处理的InAlN/GaN异质结外延片中的 $N_D(\sim 9.11 \times 10^{19} \text{ cm}^{-3})$, 这可能是退火过程减弱了势垒层的极化效应所导致^[13]. 有效隧穿势垒高度 $\Phi_B=0.86 \text{ eV}$ 比之前报道的 $\Phi_B=0.48 \text{ eV}$ ^[14]高, 但仍明显小于理论的肖特基势垒高度. 根据双势垒模型, 可能是退火过程在势垒层表面层内部形成的大量氮空位所导致, 电子很容易透过较高势垒的表面层, 有效势垒主要由剩余的隧穿区域的势垒决定^[5]. 通过类金属机制的拟合可得 $\alpha=3.8$, 拟合值在金属电阻率与温度关系的指数范围($1 < \alpha < 5$)^[11]内, 表明类金属机制的可靠性.

3 结论

首先在硅衬底晶格匹配的 $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ 异质结外延片上制备了一系列Ti/Al/Ni/Au欧姆接触TLM测试结构, 然后通过变温 I - V 特性测量研究了 R_{sh} 和 ρ_{sc} 的温度依赖特性, 结果显示 R_{sh} 随温度升高发生退化主要由晶格散射决定, 而 ρ_{sc} 随温度升高先增大后减小的趋势由TFE机制和类金属输运机制共同决定.

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Temperature dependent characteristics of Ti/Al/Ni/Au ohmic contact on lattice-matched InAlN/GaN heterostructures

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Due to the excellent physical properties, such as high breakdown field, high electron drift velocity, and good thermal stability, GaN-based high electron mobility transistors (HEMTs) have emerged as the most promising candidates for the high power and high frequency application. However, for conventional AlGaIn/GaN devices, significant inverse piezoelectric effect within the barrier layer severely limits the reliability of devices, which could induce rather larger gate leakage current especially when operating in a long-term large signal mode. Recently, one of the most effective solutions is to replace the traditional AlGaIn/GaN structure with a lattice matched $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ heterojunction, which has a larger two-dimensional electron gas (2DEG) density without piezoelectric effect inside the barrier layer. Besides, in order to obtain high output current density in GaN-based HEMTs, fabricating high-quality ohmic contact as the source and drain electrodes is essential, which can directly affect the overall electrical performance of the device. However, so far the carrier transport mechanisms of the ohmic contact on InAlN/GaN heterostructure remain unclear and should be well understood in physics. In terms of that, in this work, the transmission line model measurement structure of Ti/Al/Ni/Au ohmic contact was fabricated on the lattice-matched $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ heterostructure grown on a Si substrate, and the temperature dependent characteristics of the sheet resistance (R_{sh}) and the specific contact resistivity (ρ_{sc}) are investigated by using temperature-variable current-voltage measurements from 300 to 523 K. The lattice-matched $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ epi-layers are grown by metal-organic chemical vapor deposition on c-plane sapphire substrates. The epi-structure includes a 3 μm i-GaN layer, a 2 nm AlN spacer layer, an 18 nm $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$ barrier layer, and a 2 nm GaN cap layer. Standard lithography and lift-off techniques are used to define the electrode patterns. The ohmic contact is formed by annealing a Ti/Al/Ni/Au metal stack in N_2 environment at 870°C for about 30 s. The results show that, (1) $1/R_{\text{sh}}$ follows a power law dependence on temperature with a coefficient of about 2.56, which can be attributed to the lattice scattering of the semiconductor at high temperatures; (2) ρ_{sc} exhibits a roll-over behavior in the measured temperature range from 300 to 523 K. At temperatures lower than 350 K, the temperature dependence of ρ_{sc} can be mainly explained by the metal-like effect of the TiN alloy, while at higher temperatures the thermionic field emission mechanism dominates gradually. The experimental data points can be well fitted with a parallel combination of the above two models. It turns out that, the effect electron density N_{D} is about $3.27 \times 10^{19} \text{ cm}^{-3}$, which is lower than the result of $9.11 \times 10^{19} \text{ cm}^{-3}$ obtained by C-V measurements, due to a weakened polarization effect after the rapid thermal annealing (RTA) process, and the effective tunneling barrier height is about 0.86 eV, which is much smaller than the theoretical prediction result, probably due to the generation and accumulation of negatively charged N vacancy near the barrier surface layer during the RTA process.

lattice-matched, InAlN/GaN heterostructure, ohmic contact, temperature-dependent characteristics, metal-like effect, thermionic field emission

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