

Pt/Ga₂O₃/Nb:SrTiO₃ 光电器件的自驱动光响应及阻变效应张 腾¹, 张 源¹, 任达华¹, 李 强¹, 余基映¹, 周金能², 易金桥¹

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摘 要: 为了构筑光传感和阻变一体化光电器件, 利用脉冲激光沉积法制备兼具稳定自驱动光响应和电致阻变特性的 Pt/Ga₂O₃/Nb:SrTiO₃ 光电器件, 研究了器件的光响应机制与阻变机理。在 0 V 偏压下, 器件具有快速的紫外光响应特性($\tau_r/\tau_d=60\text{ ms}/120\text{ ms}$), 峰值光响应度达 13.4 mA/W ($\lambda=250\text{ nm}$)。上述自驱动光响应被归因于 Pt/Ga₂O₃ 界面形成的 Schottky 结内建电场对光生载流子的高效分离作用。同时, 器件呈现稳定的双极性阻变行为, 高/低阻值变换比约为 10^4 , 通过施加不同的脉冲电压可实现多阻态间的快速切换, 且具有良好的抗疲劳和保持特性。器件的多级阻变效应主要来源于载流子注入和氧空位陷阱中心束缚/解束缚对 Schottky 势垒的调控作用。以上研究对于开发新型 Ga₂O₃ 基多功能光电器件具有指导意义。

关键词: 宽禁带半导体; 氧化镓薄膜; 紫外光响应; 电致阻变效应

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中国国民经济和社会发展第十四个五年规划和 2035 远景目标纲要将宽禁带半导体材料和先进存储技术列入了科技前沿攻关领域, 旨在实现高端芯片和高性能电子原材料领域关键核心技术的自主可控。Ga₂O₃ 是继 GaN 和 ZnO 之后的新一代超宽禁带半导体材料, 它具有约 4.9 eV 的直接带隙, 可应用于日盲紫外波段(200~280 nm), 同时它具有优异的热力学和化学稳定性, 故适于用作深紫外光电器件的开发^[1-5]。

自 2007 年日本石卷专修大学 Kokubun 等^[6]首次报道 Ga₂O₃ 多晶薄膜可作为日盲紫外光探测器以来, 国内外有关 Ga₂O₃ 基探测器的研究报道呈爆发式增长。中国科学院与科睿唯安联合发布的《2021 研究前沿》报告中, Ga₂O₃ 基日盲紫外探测器进入物理学研究领域 Top 10 热点前沿。当前, 对 Ga₂O₃ 紫外探测技术的研究工作尚处于初期阶段, 仍存在一系列关键科学和技术问题有待解决。光电导型探测器在器件制备上具有制作简单、易于集成等优点, 却存在响应速率慢、感光面积小和需外加偏压

等诸多劣势^[7]。基于光伏效应的自驱动型探测器利用能带势垒差形成的内建电场分离光生载流子, 无需外部供电装置就能实现对光信号的探测, 此类型器件通常表现出较快速的光响应^[8]。自驱动型光电探测器具有节能、便携、应用场景丰富等优点, 在物联网技术中的无线传感应用领域具有广阔前景。由于 Ga₂O₃ 宽禁带半导体本征的背景 n 型载流子浓度较高, 导致其 p 型掺杂难以实现^[9], 目前报道的 Ga₂O₃ 基光伏型探测器大多采用其它半导体材料(如 GaN^[10]、SiC^[11]、ZnO^[12]、Diamond^[13]和 SnO₂^[14]等)构建异质结, 这些 Ga₂O₃ 基异质结日盲紫外探测器具有响应度高、响应速率快等优点, 但由于异质外延的薄膜材料质量控制难度较大, 这些探测器仍未能充分发挥材料优势, 性能方面还有较大提升空间。因此, Ga₂O₃ 基自驱动型日盲紫外探测器从材料制备和器件结构等方面仍需要进一步深入研究。

此外, Ga₂O₃ 半导体具有丰富的物理性质, 其电致阻变效应也引起了学术界的研究兴趣。Gao 等^[15]报道了 Pt/Ga₂O₃/ITO 器件的双极性电致阻变特性,

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阻变机制被归结为氧空位在电极附近的迁移引起 Pt/Ga₂O₃ 界面 Schottky 势垒变化。他们还采用 Ti 电极与 Ga₂O₃ 形成欧姆接触,发现 Ti/Ga₂O₃/ITO 器件仍具有双极性阻变特性,认为该器件的阻变效应来源于 Ti/Ga₂O₃ 界面附近的氧化还原反应。基于相同的器件结构,Aoki 等^[16]利用扫描透射电镜观测到氧离子在 Pt/Ga₂O₃ 界面处可重复的聚集和驱散,引起了 Ga 离子价态的变化。因此,他们认为氧离子移动是电致阻变效应的起源。Wang 等^[17]发现 Au/Ga₂O₃/Nb:SrTiO₃/Au 器件由低阻态向高阻态转变时会出现微分负阻现象,指出器件的双极性阻变行为来源于氧空位陷阱对载流子的捕获/释放。此外,Guo 等^[18–19]研究了 Pt/Ga₂O₃/Pt 器件的电致阻变行为,由于 Ga₂O₃ 薄膜氧空位浓度不同,器件表现出不同的阻变行为。单极性阻变特性被解释为氧空位导电细丝的形成和断裂,而双极性阻变行为被认为是氧空位迁移引起 Pt/Ga₂O₃ 界面耗尽层变化。可见,受器件结构、电极材料和制备工艺等因素影响,电致阻变行为呈现多样性。人们对 Ga₂O₃ 阻变机制的认知尚未形成共识,具体微观机理有待进一步明晰。

综上所述,Ga₂O₃ 半导体材料兼具优异的光敏和阻变特性,有望应用于具有感存一体化特性的新型光电阻变器件。基于此考虑,本工作采用脉冲激光沉积法生长(400)晶面取向的 Ga₂O₃ 薄膜,表征薄膜的晶体结构、形貌特性,进而设计和制备 Pt/Ga₂O₃/Nb:SrTiO₃ 结构的光电器件;通过优化器件工艺,以期在同一器件实现高灵敏紫外光响应和稳定的阻变特性,深入研究器件的自驱动紫外光响应特性和电致阻变行为,并揭示器件光响应和阻变效应的物理机制,为发展新一代 Ga₂O₃ 基多功能光电器件提供理论指导和技术支撑。

1 实验

1.1 薄膜与器件制备

采用脉冲激光沉积(PLD)方法在(100)晶面取向的 0.7% Nd:SrTiO₃(NSTO)衬底上生长 Ga₂O₃ 薄膜,所用靶材为传统固相法自制的纯 Ga₂O₃ 陶瓷靶材,NSTO 基片由合肥科晶材料技术有限公司生产(尺寸:5.0 mm×5.0 mm×0.5 mm)。在薄膜沉积之前,先对陶瓷靶材进行预烧蚀约 3 min 以清除表面污染物。薄膜沉积条件:脉冲激光能量 300 mJ, O₂ 分压 3.0 Pa,衬底温度 650 °C,靶自转速率 5 r/min,衬底自转速率 10 r/min,脉冲激光频率 5 Hz,沉积

时间 30 min。在制备高质量 Ga₂O₃ 薄膜的基础之上,进一步构筑金属电极/Ga₂O₃/底电极三明治结构器件。室温下,利用直流磁控溅射法在 Ga₂O₃ 薄膜表面制作 Pt 金属点状电极作为器件的顶电极(金属掩模版的方形孔尺寸:200 μm×200 μm),随后将金属 In 直接焊接在 NSTO 衬底背面作为底部接触电极。上述 Pt 金属电极制备工艺条件为:直流源功率 100 W,工作气压 1.5 Pa,Ar 流量 10 mL/min,衬底自转 10 r/min,溅射时间 60 s。

1.2 性能表征及测试

利用德国 Bruker 公司生产的 D8 Discover 型高分辨四圆单晶 X 射线衍射仪(XRD)对 Ga₂O₃ 薄膜的进行结构表征,分别采取 2θ 扫描和 ω 扫描两种模式表征薄膜的晶体结构和结晶质量;采用美国 Thermo Fisher 公司生产的 Escalab 250Xi 型 X 射线光电子能谱仪(XPS)分析 Ga₂O₃ 薄膜材料的元素成分信息,此设备使用金属 Al 的 K_α 特征 X 射线(光子能量:1 486.6 eV),其中 X 射线的光斑直径约为 100 μm;利用德国 ZEISS 公司生产的 Sigma 500 型场发射扫描电子显微镜(FE-SEM)来表征薄膜的表面和截面形貌特征,此设备分辨率:0.8 nm@15 kV,放大倍数:10~100 万倍。采用美国吉时利公司生产的 Keithley 2635 型数字源表、深圳森东宝科技有限公司生产的探针台、电磁屏蔽暗箱等搭建半导体电学性能测试系统,测试器件的 I-V 扫描回线、多级阻态、保持和抗疲劳等特性。基于上述半导体电学性能测试系统,利用深圳市鼎阳科技股份有限公司生产的 SDG830 型数字信号发生器驱动 255 nm 深紫外发光二极管(LED)光源,测试器件的时间-电流关系曲线;利用北京卓立汉光公司的 Omni-λ3027 型单色仪、150 W 氙灯光源、斩波器、准直光转换器、锁相放大器等测试器件的暗电流、光谱响应、紫外-可见抑制比、探测率等特性。测量光谱响应之前,通过标准 Si 光电探测器校准入射光源光功率。

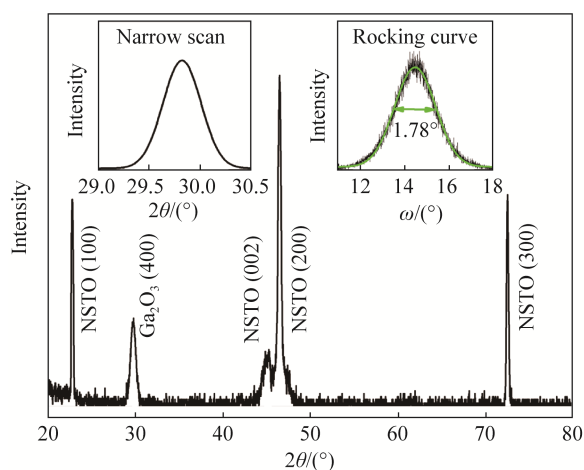
2 结果与讨论

2.1 Ga₂O₃ 薄膜的结构、成分及形貌

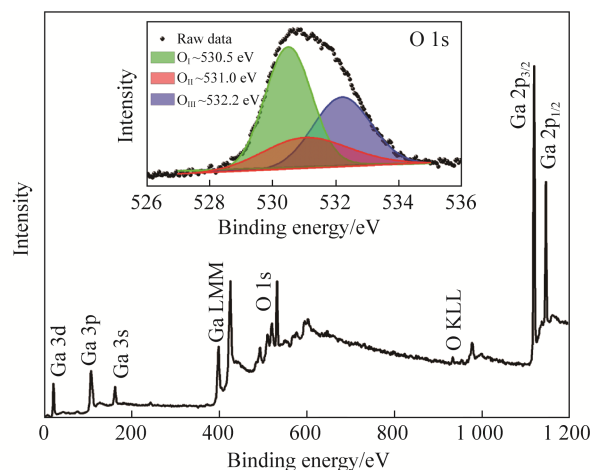
图 1a 所示为 Ga₂O₃ 薄膜样品的 XRD 测试结果。从 θ~2θ 扫描谱可以看到:除了衬底衍射峰,仅在 2θ 为 29.8°附近观察到 Ga₂O₃ (400)晶面衍射峰。通过 ω 扫描获得(400)晶面摇摆曲线半高宽(FWHM)约为 1.78°。对照标准 JCPDS 卡片(JCPDS 41-1103)可知,生长的 Ga₂O₃ 薄膜为 β 相。进一步测量薄膜的 XPS 谱以分析其表面元素成分,以 C 1s 峰(结合能~284.5 eV)

进行光谱校准后得到全谱扫描谱^[20]。如图 1b 所示, 谱图中除 Ga 和 O 样品元素以外无其它杂质元素峰出现, 表明生长的薄膜较为纯净。图 1b 内置插图给出了所制备 Ga₂O₃ 薄膜 O 1s 的高分辨 XPS 特征谱, 利用 Gauss 拟合可将上述光电子特征峰分解为独立的 3 个部分, 结合能位置分别位于: 1) ~530.5 eV (O_I), 由晶格中的 O²⁻ 贡献; 2) ~531.0 eV (O_{II}), 来源于

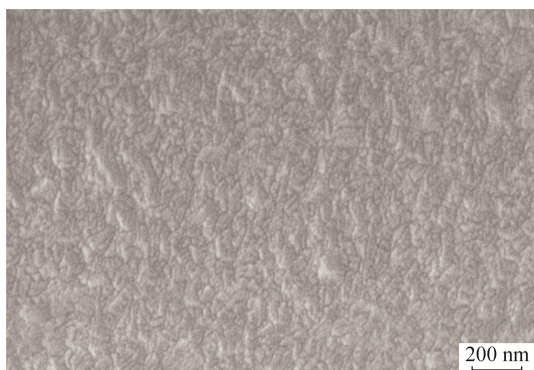
于氧空位缺陷; 3) ~532.2 eV (O_{III}), 主要与薄膜表面的—OH 吸附有关^[21]。通过以上结果分析, 暗示 Ga₂O₃ 薄膜生长过程中 O 原子缺失、形成 O 空位缺陷。通过电子显微镜进一步表征了薄膜的表面形貌特征及其厚度。由图 1c 和图 1d 可见, 生长的 Ga₂O₃ 薄膜由较小颗粒组成、表面平整致密, 薄膜厚度约为 174 nm。



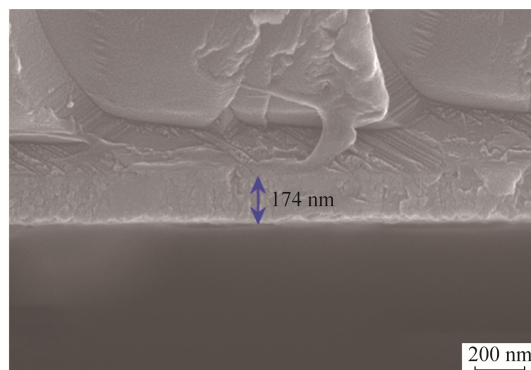
(a) XRD patterns



(b) XPS spectra



(c) Surface FE-SEM image



(d) Cross-sectional FE-SEM image

图 1 Ga₂O₃ 薄膜样品的 XRD 谱、XPS 谱及 FE-SEM 照片Fig. 1 X-ray diffraction (XRD) patterns, XPS spectra and FE-SEM images of samples Ga₂O₃ film sample

2.2 Ga₂O₃ 基器件的光响应特性

图 2a 为 Pt/Ga₂O₃/NSTO/In 器件在暗态和 255 nm 紫外光照下的 I - V 特性曲线, 规定 Pt 为正极、In 为负极, 即电流从上电极到下电极为正方向。可以看到, 器件表现出明显的二极管整流特性。为了确定金属 Pt 电极与 Ga₂O₃ 半导体薄膜的接触类型, 进一步测试 Pt/Ga₂O₃/Pt 器件的 I - V 特性。如图 2b 所示, Pt/Ga₂O₃ 界面形成 Schottky 接触。其中, 正、负偏压区间的曲线不对称, 这可能由于 Ga₂O₃ 薄膜表面存在局部的氧吸附或缺陷, 不同的表面态导致两处不同位置的 Pt/Ga₂O₃ 界面接触势垒产生差异。

光响应度是评估器件光敏特性的基本参数之一, 其物理含义为单位入射光功率产生的光电流输出。在特定入射波长下, 光响应度 R_λ 可描述为^[22]:

$$R_\lambda = (I_{\text{light}} - I_{\text{dark}}) / P_\lambda \cdot S \quad (1)$$

其中: P_λ 为入射光功率密度; S 为有效光照面积; I_{light} 和 I_{dark} 分别为器件的光电流和暗电流。在 0 V 偏压下, 测试获得 Pt/Ga₂O₃/NSTO/In 结构器件不同入射光波长的响应度光谱曲线如图 3a 所示。图中可以看到, 器件在紫外波段具有较高的响应度, 峰值光响应度达 13.4 mA/W ($\lambda=250$ nm)。从图 3a 中衬底的吸收光谱可以看到 NSTO 在紫外波段具有较强的

吸收, 根据 Tauc 法则对曲线进行线性外推^[23], 可知衬底吸收边位于约 360 nm 附近。因此, 光谱响应曲线中波长位于该区域附近的光响应主要来源于 NSTO 对紫外光的吸收作用。若仅考虑散粒噪声和热噪声的影响, 器件的探测率 D^* (单位: $\text{cm} \cdot \text{Hz}^{1/2} / \text{W}$, 也称为 Jones) 可表示为式(2)^[24–25]:

$$D^* = R_\lambda / (2eJ_d)^{1/2} \quad (2)$$

其中: J_d 为暗电流密度; e 为电子电荷。获得器件峰值响应波长对应的探测率为 1.49×10^{11} Jones。

进一步分析器件的光响应机制, 这里认为接触电极金属 In 与半金属态 NSTO 界面形成欧姆接触, 故不考虑 In/NSTO 界面的影响。Pt、 Ga_2O_3 和 NSTO 的功函数分别为 5.65、4.00 eV 和 4.00 eV^[26–27], 得到器件的能带结构示意图如图 3b 所示。金属 Pt 与

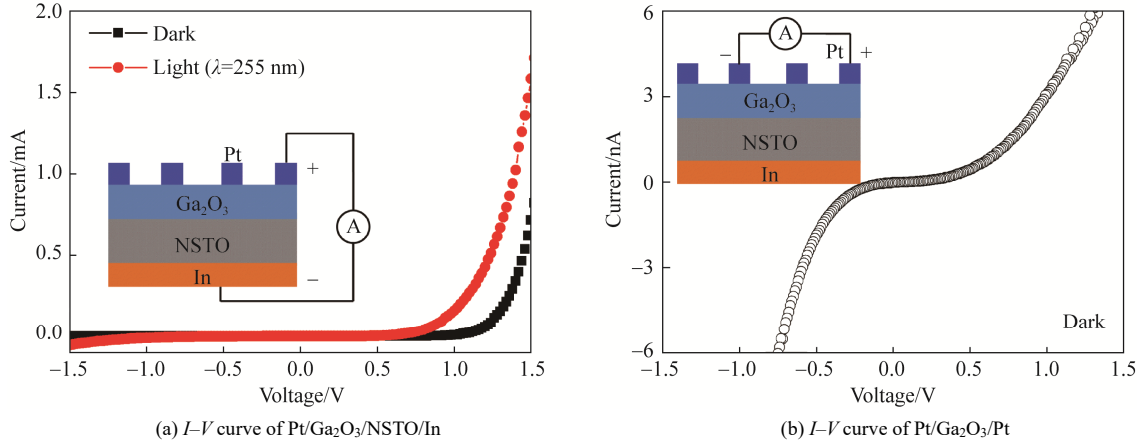


图2 不同结构器件的 I - V 特性曲线

Fig. 2 Current-voltage (I - V) curve of different devices

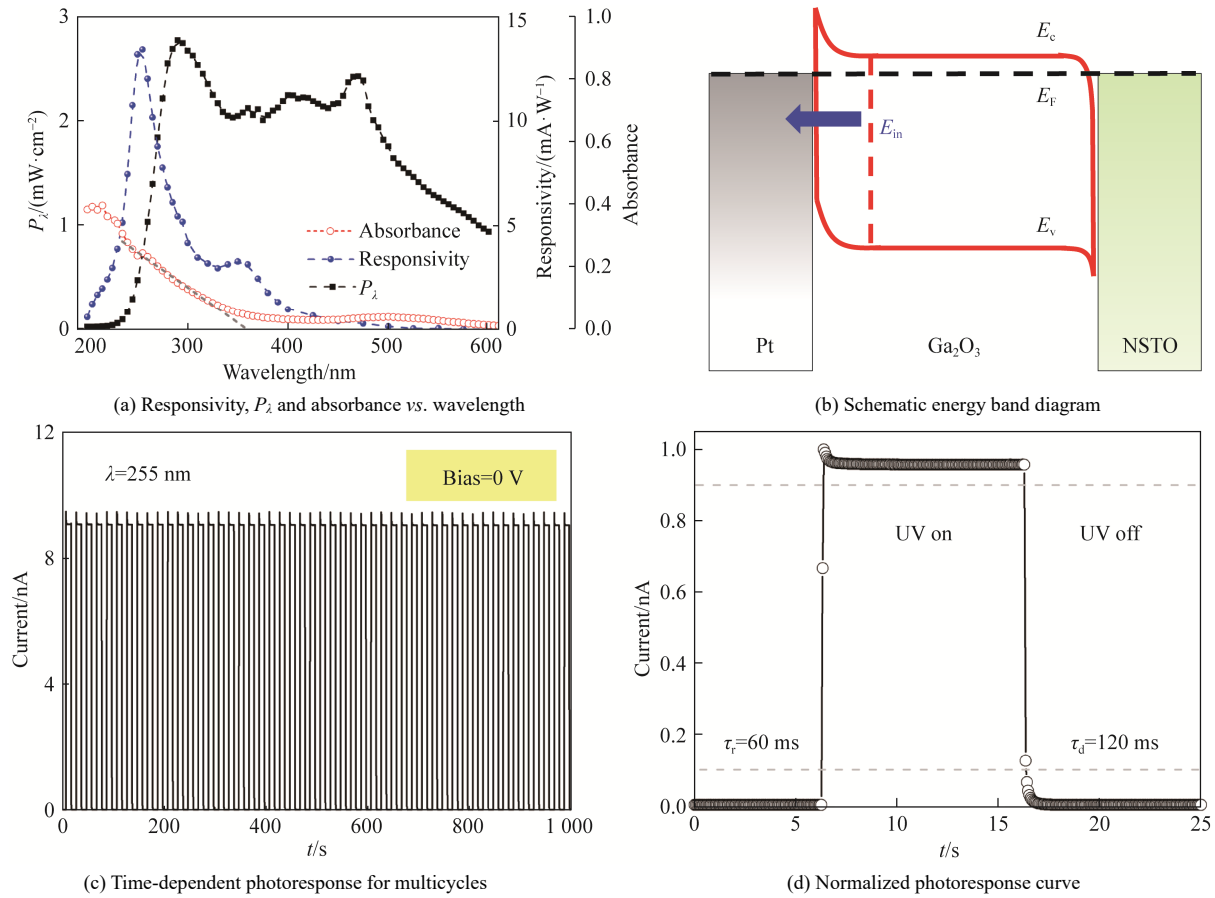


Fig. 3 Spectral response, energy band diagram and time-dependent photoresponse of the Pt/ Ga_2O_3 /NSTO/In device

Ga₂O₃ 半导体形成 Schottky 结(图 2 中实验结果也得到佐证), Pt/Ga₂O₃ 界面处形成内建电场 E_{in} 的方向由 Ga₂O₃ 指向 Pt。器件在无外部偏压条件下, 上述 Schottky 结内建电场 E_{in} 对光生载流子进行有效分离, 从而实现自驱动光响应。

以 255 nm 深紫外 LED 作为光源, 利用多功能数字信号源驱动 LED 产生不同频率的脉冲光信号来测试 Pt/Ga₂O₃/NSTO/In 器件的光响应速度, 获得器件多周期的时间响应特性曲线如图 3c 所示。在 0 V 偏压下, 随着紫外光的开/关切换, 器件的光/暗电流均能很快达到稳态, 呈现出快速和稳定的自驱动光响应。光响应速率反应了器件的瞬态响应过程, 响应时间分为上升时间(τ_r)和回复时间(τ_d)。一般而

言, τ_r 和 τ_d 分别被定义为光电流从暗态值增大至最大值的 90%和关闭光照时电流减小至最大值的 10% 所需时间^[28-29]。如图 3d 所示, 对单个周期的时间-电流曲线作归一化处理, 获得响应时间 τ_r 和 τ_d 分别为 60 ms 和 120 ms。上述时间-电流曲线中, 光照时光电流快速增大至最大值, 随后逐步下降至稳态, 这可能是由于光生载流子注入势垒区而引起内建电场变化所致。

将上述 Pt/Ga₂O₃/NSTO/In 结构光电器件的紫外光响应特性与文献中报道的同类型 Ga₂O₃ 基薄膜器件结果进行对比, 如表 1 所示。在 0 V 偏压下, 本工作制备的 Ga₂O₃ 基器件具有更高的光暗电流比和光响应度。

表 1 与文献中报道的 Ga₂O₃ 基 Schottky 结器件光响应性能的对比(0 V 偏压)

Table 1 Comparison with the photoresponse of Ga₂O₃-based Schottky junction devices reported in literature (measured at 0 V bias)

Device structure	I_{dark}/nA	I_{light}/nA	Responsivity/(mA·W ⁻¹)	Detectivity/(10 ¹⁰ Jones)	τ_r/τ_d	Reference
Au/Ga ₂ O ₃	0.18	2.700	1.28	17.70	0.03 s/0.08 s	[30]
Ti/Ga ₂ O ₃ /NSTO	0.42	8.600	2.60		0.21 s/0.07 s	[31]
Ni/Au/Ga ₂ O ₃ /Al ₂ O ₃			1.40		1.10 s/0.30 s	[32]
Ti/Ga ₂ O ₃ /Ni	1.32×10^{-2}		0.73	3.35	0.50 s/1.67 s	[33]
Ti/Ga ₂ O ₃ /Pt	1.00×10^{-4}	0.072	0.16		0.50 s/0.50 s	[34]
Pt/Ga ₂ O ₃ /NSTO	0.01	9.100	13.40	14.90	0.06 s/0.12 s	This work

I_{dark} is dark current; I_{light} is light current.

2.3 Ga₂O₃ 基器件的电致阻变行为

图 4a 为器件的 I - V 扫描回线, 其中阈值电流设置为 100 mA 以避免器件被击穿, 电压循环扫描顺序为: -5 V → 0 V → +3 V → 0 V → -5 V (如图中序号和箭头所示)。上述 I - V 扫描结果可以看到: 当电压从 -5 V 扫描至 +3 V (即 1 和 2 过程), 器件一直处于高阻态(HRS); 当电压从 +3 V 回扫至 -5 V (即 3 和 4 过程), 器件保持为低阻态(LRS)。当电压扫描至

-5 V, 器件的电阻从低阻态又重新回到高阻态。同时, 经 50 次循环扫描测试, 器件仍具有稳定的双极性电阻变换特性。电阻变换比通常被定义为^[35]: 高/低阻态的阻值比(R_{HRS}/R_{LRS}), 不同读取电压下 R_{HRS}/R_{LRS} 值的变化曲线如图 4b 所示。可见, 较低读出电压下可获得更高的电阻变换比。下面以 -0.5 V 的读取电压为例研究器件的阻态切换、多级阻变及保持特性。

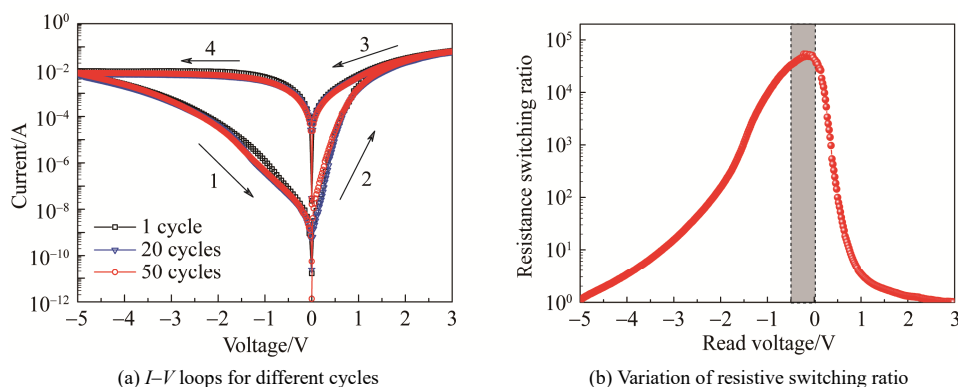


图 4 Pt/Ga₂O₃/NSTO/In 器件的 I - V 扫描回线和电阻变换比
Fig. 4 I - V loops and resistive switching ratio of the Pt/Ga₂O₃/NSTO/In device

通过交替施加 -5 V 和 $+3\text{ V}$ 脉冲电压(脉冲时间: 10 ms), 获得器件的阻态切换特性如图 5a 所示。图中可见, 施加不同方向脉冲电压可实现器件高低阻态的自由变换, HRS/LRS 比值近 10^4 。保持正向脉冲电压不变, 施加不同的反向偏压, 以获得器件的电阻值与反向脉冲电压的关系。如图 5b 所示, 施加的反向脉冲电压越大, 器件的电阻值则越高。进一步测试器件多级阻态间的切换特性, 发现不同的反向脉冲电压(-1.5 、 -3.0 V 和 -5.0 V pulse)可将器件从低阻态 LRS ($+3.0\text{ V pulse}$)变换成多个不同的阻态(中间阻态 IRS1、IRS2 和高阻态 HRS), 且多次重复测试后仍呈现稳定和快速的切换特性(如图 5c 所示)。以上结果表明: 器件具备稳定的多级阻变特性, 通过控制脉冲电压的大小可实现不同阻态的自由调控。图 5d 给出器件的 HRS 和 LRS 随时间变化关系曲线, 在测试时间 10^4 s 内, 器件高/低阻态的阻值未出现明显退化。由于撤销外电场后通常存在电阻弛豫现象, 电阻 R 与时间 t 满足 Curie-Von Schweidler 法则^[36]:

$$R = R_0 \cdot t^a \quad (3)$$

其中: 系数 $a < 1$ 。利用 Curie-Von Schweidler 法则对电阻-时间曲线进行线性外推, 可知器件阻态在 10^8 s 后仍可保持(电阻变换比超过 10^3), 展现出该器件在信息存储领域的应用潜力。

目前, 有关电致阻变效应微观机理解释主要分为导电细丝型^[16, 37–38]和界面型^[15, 17, 39]两大类。导电细丝机制认为金属离子或氧空位迁移在外电场作用下将形成低阻导电通道, 导电通道的形成和断裂是阻变行为的主要来源。此类阻变行为通常为突变型, 无法解释本文器件的缓变型 $I-V$ 特性。界面型阻变机制将阻变效应归结为载流子注入引起的界面势垒变化。经分析, 本工作器件呈现出较快速电阻变换特性, 考虑到电子迁移速率要快于氧空位, 故认为外部电场产生电子注入对 $\text{Pt}/\text{Ga}_2\text{O}_3/\text{Schottky}$ 势垒的调控作用是本器件产生电致阻变效应的主要成因, 而 Ga_2O_3 薄膜的本征氧空位缺陷作为陷阱中心主导了载流子的捕获/释放过程, 从而使得器件的阻态得以保持(即呈现不挥发特性)。同时, 改变脉冲电压的大小可以调控电子注入量, 进而调控界面势垒高度, 可解释上述 Ga_2O_3 基光电器件的多级阻变特性。

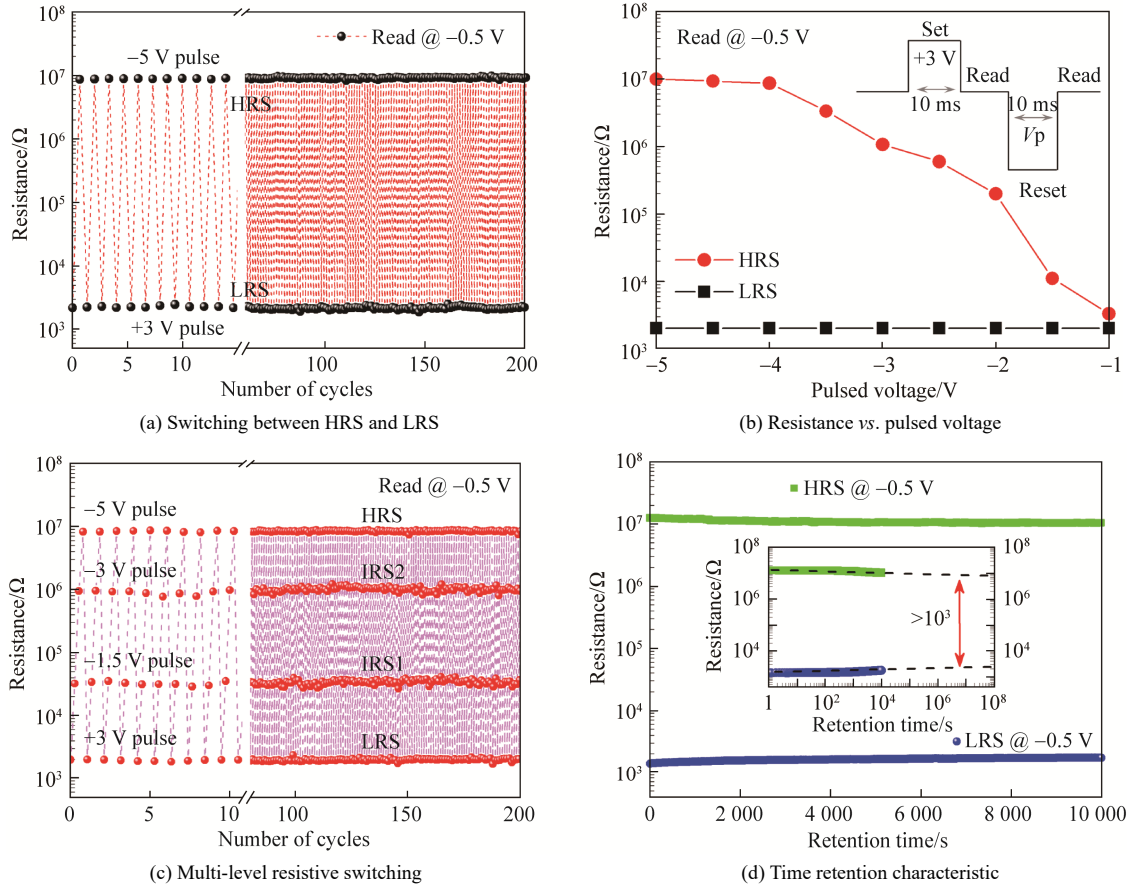


图 5 $\text{Pt}/\text{Ga}_2\text{O}_3/\text{NSTO}/\text{In}$ 器件的阻态切换、阻态随脉冲电压的变化、多级阻变特性及保持特性

Fig. 5 Resistive switching characteristic, variation of resistance with pulsed voltage, multi-level resistive switching and time retention characteristics of the $\text{Pt}/\text{Ga}_2\text{O}_3/\text{NSTO}/\text{In}$ device

3 结论

采用 PLD 技术在 NSTO 衬底上生长了晶面取向为(400)的 β 相 Ga₂O₃ 薄膜,制备了 Pt/Ga₂O₃/NSTO/In 结构的 Ga₂O₃ 基多功能光电器件,研究了器件的自驱动光响应和阻变行为。研究表明, Pt/Ga₂O₃ 界面形成 Schottky 接触,器件在 0 V 偏压下表现出较快的紫外光响应速度($\tau_r/\tau_d=60$ ms/120 ms),峰值光响应度和探测率分别为 13.4 mA/W 和 1.49×10^{11} Jones ($\lambda=250$ nm)。经分析,器件的自驱动光响应特性主要来源于 Pt/Ga₂O₃Schottky 结内建电场对光生载流子的高效分离。同时,器件表现出稳定的双极性电阻变换行为,交替施加 10 ms 脉宽的-5 V 和+3 V 脉冲电压,获得电阻变换比近似为 10^4 。通过施加不同方向和大小的脉冲电压,观察到器件多级阻态间的快速切换,且具有良好的抗疲劳特性。高/低阻态具有较好的保持性,在 10^4 s 测试时间内未出现明显退化,表现出不挥发特性。将器件阻变效应的内部机理归结为界面型阻变机制,电注入引起的 Schottky 势垒变化和氧空位缺陷陷阱中心引起的载流子束缚/解束缚过程共同决定了器件的阻变行为。以上研究结果为发展新型 Ga₂O₃ 基感存一体光电器件提供了前期基础,对于挖掘 Ga₂O₃ 半导体材料在图像识别和机器视觉等领域的应用潜力具有重要意义。

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Self-Driven Photoresponse and Resistive Switching Effects of Pt/Ga₂O₃/Nb:SrTiO₃ Optoelectronic Devices

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Extended Abstract

Introduction Ga₂O₃ is an ultra-wide bandgap semiconductor, which has a direct bandgap of 4.9 eV. Also, it has the superior thermodynamic and chemical stability, making it suitable for the development of deep ultraviolet optoelectronic devices. Ga₂O₃ exhibits the superior photosensitive and resistive properties, which has a promising application in sensor-memory integrated optoelectronic devices. In this paper, the crystal structure, composition, and morphology of the Ga₂O₃ thin film grown *via* pulsed laser deposition (PLD) was discussed, and then an optoelectronic device with Pt/Ga₂O₃/NSTO/In structure was designed and constructed. The physical mechanism of the Ga₂O₃-based device was investigated. The device process was optimized to achieve both high sensitivity ultraviolet photo-response and stable resistive switching characteristics. This work can provide theoretical guidance and technical support for the development of novel Ga₂O₃-based multifunctional optoelectronic devices.

Methods Ga₂O₃ thin films were grown on (100) Nd: SrTiO₃ (NSTO) substrates by the PLD method. The target material used was a pure Ga₂O₃ ceramic target prepared by a solid-state method. Before thin film deposition, the ceramic target was pre-ablated for 3 min to remove surface contaminants. The film deposition was performed at pulse laser energy of 300 mJ, O₂ partial pressure of 3.0 Pa, and substrate temperature of 650 °C. The target rotation speed was 5 r/min, the substrate rotation speed was 10 r/min, the pulse laser frequency was 5 Hz, and the deposition time was 30 min. Based on the deposited Ga₂O₃ thin films, a device with metal/Ga₂O₃/electrode sandwich structure was further constructed. At room temperature, Pt metal dot electrodes were fabricated on the surface of Ga₂O₃ thin films by a DC magnetron sputtering method as a top electrode of the device, and then weld the metal indium (In) directly onto the back of the NSTO substrate as a bottom contact electrode. The above Pt metal electrode preparation process was run at DC source power of 100 W, working pressure of 1.5 Pa, Ar flow rate of 10 mL/min, substrate rotation of 10 r/min, and sputtering time of 60 s.

The structure of Ga₂O₃ thin films was characterized by a model D8 Discover type high-resolution four circle single crystal X-ray diffractometer. The elemental composition of Ga₂O₃ thin film material was analyzed by a model Escalab 250Xi X-ray photoelectron spectroscopy. The surface and cross-sectional morphology of the films was characterized by a model Sigma 500 field emission scanning electron microscope. A semiconductor electrical performance testing system was constructed by a model Keithley 2635 digital source meter, probe station, and electromagnetic shielding dark box, to examine the *I-V* scanning loop, multi-level resistive

state, retention, and fatigue resistance characteristics of the device. A 255 nm LED light source was driven by a digital signal generator to test the time-dependent UV photoresponse characteristics. A Omni- λ 3027 setup consisting of monochromator, 150 W xenon lamp light source, chopper, collimating light converter, and phase-locked amplifier, was utilized to measure the dark current, spectral response, UV-visible suppression ratio, and detectivity of the photodetector.

Results and discussion The deposited β -Ga₂O₃ film with small particles and a flat and dense surface exhibits (004) plane preferential orientation. The Pt/Ga₂O₃/NSTO/In device with both fast self-driven ultraviolet photoresponse and stable resistive switching characteristics was fabricated. Under illumination, the photocurrent of the device rapidly increases to its maximum value and then gradually decreases to a steady state possibly due to the reduction in the Schottky junction built-in electric field caused by the injection of photogenerated carriers into the barrier region. The self-driven photoresponse is attributed to the efficient separation of photo-generated carriers by a built-in electric field formed at the Pt/Ga₂O₃ interface. On the other side, the device exhibits a stable bipolar resistive switching behavior. Alternating -5 V and $+3$ V pulse voltages with a 10 ms pulse width results in a resistive switching ratio of nearly 10^4 . A rapid switching between multi-level resistance states occurs at different pulse voltages. The intrinsic oxygen vacancy defect in Ga₂O₃ thin film as the trap center dominates the capture/release process of charge carriers, thereby maintaining the resistance state. Changing the pulse voltage can control the amount of electron injection, thus affecting the height of the interface barrier, which can explain the multi-level resistive characteristics of the device. The resistance state shows a good retention, and there is no significant degradation within 10^4 s, showing the nonvolatile characteristics. In addition, the device also exhibits stable and fast switching characteristics after multiple repeats, indicating potential applications in memory devices. The mechanism of resistive switching effect can be attributed to the interface type resistance mechanism. The variation of the Schottky barrier caused by external electrical injection and the carrier trapping/detrapping process caused by the oxygen vacancy defect trap center jointly determine the resistive switching effect.

Conclusions The fabricated device had a fast UV photoresponse ($\tau_r/\tau_d=60$ ms/120 ms) with a peak responsivity of 13.4 mA/W and 1.49×10^{11} Jones ($\lambda=250$ nm) at 0 V bias. According to the analysis, the Schottky contact formed at the Pt/Ga₂O₃ interface resulted in a fast self-driven photoresponse at 0 V bias. In addition, the fabricated device also exhibited a stable bipolar resistive switching behavior with a high/low resistance ratio of 10^4 . The fast switching between multiple resistance state was achieved with the superior anti-fatigue and retention characteristics at different pulse voltages. The external electric field and oxygen-vacancy trap centers was considered as the main origin of resistive switching effect in Ga₂O₃-based optoelectronic device.

Keywords wide-bandgap semiconductors; gallium oxide thin film; ultra-violet photoresponse; resistive switching effect