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基于钙钛矿材料的高性能光电探测器研究进展

张 姝¹, 黄育杰², 郝亚峰², 马富鹏², 武慧嘉², 朱 璞², 李子唯²,
牛文宇², 李腾腾^{2*}, 刘美宏², 雷 程², 梁 庭²

(1. 天津航技术物理研究所, 天津 300308;

2. 中北大学 宽禁带半导体超越照明材料与技术全国重点实验室, 山西 太原 030051)

摘要: 钙钛矿光电探测器因钙钛矿材料的高光吸收系数、高载流子迁移率、高缺陷容忍、可调带隙等优异光电特性及低成本溶液制备法而备受关注, 在通信、传感、医疗等多个领域展现出广阔应用前景。系统论述了钙钛矿光电探测器最新研究进展, 详细剖析了二极管型、光电导型和晶体管型钙钛矿光电探测器典型结构、工作原理、器件优势及最新研究成果与发展现状。并结合当前研究趋势, 客观分析了钙钛矿光电探测器发展所面临的挑战及限制因素, 并对基于钙钛矿材料的高性能光电探测器领域未来发展做出展望, 旨在推动该领域进一步发展, 并为后期实践提供方向性参考与建议。

关键词: 钙钛矿; 光电探测器; 光电二极管; 光电导; 光电晶体管

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Advances in High-Performance Photodetectors Based on Perovskite Materials

ZHANG Shu¹, HUANG Yujie², HAO Yafeng², MA Fupeng², WU Huijia², ZHU Pu², LI Ziwei²,
NIU Wenyu², LI Tengting^{2*}, LIU Meihong², LEI Cheng², LIANG Ting²

(1. Tianjin Jinhang Institute of Technical Physics, Tianjin 300308, China;

2. State Key Laboratory of Widegap Semiconductor Optoelectronic Materials and Technologies,
North University of China, Taiyuan 030051, China)

Abstract: Perovskite photodetectors have attracted much attention due to their excellent optoelectronic properties such as high light absorption coefficients, high carrier mobility, high defect tolerance, tunable band gap and low-cost solution preparation method of perovskite materials, and have shown broad application prospects in many fields such as communication, sensing, and medical treatment. In this paper, the latest research progress of perovskite photodetectors is systematically reviewed, and the typical structures,

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【作者简介】张 姝(1986—), 女, 工程师, 硕士, 主要从事光电子与交叉领域研究。E-mail: zhangshu8358@163.com。

*【通信作者】李腾腾(1993—), 男, 副教授, 博士, 主要从事太赫兹功能器件、微纳光电材料与器件(探测传感方向)及基于第三代半导体材料的功率半导体器件研究。E-mail: litengteng@nuc.edu.cn。

working principles, device advantages, latest research results and development status of diode-type, photoconductive and transistor perovskite photodetectors are analyzed in detail. Finally, combined with the current research trends, the challenges and constraints of the development of perovskite photodetectors are objectively analyzed, and the future development of high-performance photodetectors based on perovskite materials is prospected, aiming to promote the further development of this field and provide directional reference and suggestions for later practice.

Key words: perovskite; photodetectors; photodiode; photoconductor; phototransistor

0 引言

光电探测器作为将光信号转换为电信号的核心器件,广泛应用于通信传感、医疗诊断、环境监测、军事国防等重要领域^[1-5]。光电探测器的高性能主要取决于半导体材料的选择,传统硅基光电探测器因具有对可见光及近红外波段响应良好、工艺成熟、低功耗等优点而广受青睐,但随着新型半导体材料研究的不断深入,硅基及 III-V 族半导体材料在响应波长范围、光电转换效率、灵敏度、制造成本等方面的局限性日益凸显。为了突破传统材料限制,研究人员不断探索新的半导体材料及制备技术,如图 1 所示,以钙钛矿为代表的新型半导体材料凭借其高吸收效率^[6]、长载流子扩散长度^[7]、带隙可调^[8]等卓越光电特性而备受关注,已成为当前光电探测领域的重要研究方向。

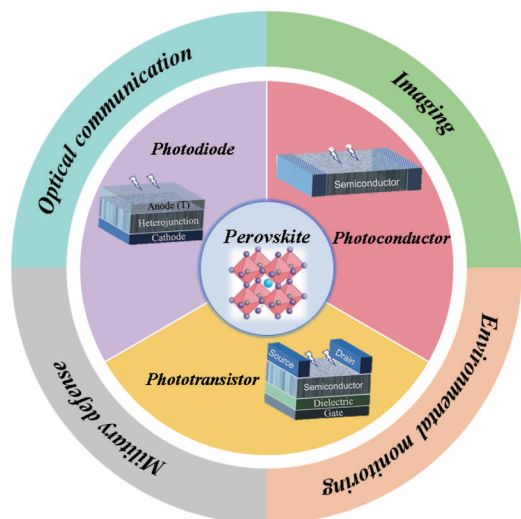


图 1 钙钛矿光电探测器的结构与应用

Fig. 1 Structure and application of perovskite photodetectors

钙钛矿光电探测器的工作原理是基于钙钛矿材料的内光电效应。根据钙钛矿光电探测器的不同结构,又可划分为光电导效应^[9]、光伏效应^[10]或光倍增效应^[11],当钙钛矿吸收的入射光子能量大于禁带宽度时,价带电子被激发到导带,同时在

价带上产生一个空穴。电子和空穴作为带电载流子,能够分别在导带和价带自由运动,从而改变钙钛矿材料的导电特性。钙钛矿光电探测器的快速发展得益于钙钛矿材料独特的结构特性^[12],并且钙钛矿材料可以通过溶液法^[13]、蒸发法^[14]等低成本工艺进行大规模制备,为其实际应用提供了巨大的成本优势。

本综述聚焦钙钛矿光电探测器的研究历程及发展现状,系统阐述了钙钛矿材料的晶体结构及光电特性,详细剖析不同工作原理下钙钛矿光电探测器的性能特征以及最新研究进展,并总结了基于钙钛矿材料的光电探测器技术领域面临的挑战,最后对未来研究方向做出展望,以期高性能光电探测器相关研究提供参考和启示。

1 钙钛矿材料

1.1 晶体结构

钙钛矿原本是用来描述一种名为钛酸钙(CaTiO_3)的矿物,后来通过俄罗斯矿物学家 Lev A. Perovski 的分析研究,确认了这种材料的结构特性,并将所有具有 ABX_3 型化学结构的材料统称为钙钛矿。其中, A 和 B 代表阳离子, A 的离子半径远大于 B, A 可以是有机离子或金属离子($\text{CH}_3\text{NH}_3^+ = \text{MA}^+$ 、 $\text{HC}(\text{NH}_2)_2^+ = \text{FA}^+$ 、 Cs^+ 或 Rb^+), B 为二价过渡金属离子(Pb^{2+} , Sn^{2+}), X 为阴离子,一般适用于器件的是卤素离子(I^- , Br^- , Cl^-)。

钙钛矿的晶体结构如图 2 所示,其基本单元为由二价金属阳离子 B 和负一价卤素离子 X 通过强配位键结合而成的八面体。这些八面体通过顶角相连,形成独特的空间框架结构^[8]。钙钛矿形成的两个关键因素分别是阳离子 A 的尺寸和八面体因子,即 B 与 X 离子半径的比值,只有当这两个条件满足特定范围时,才可稳定形成严格的钙钛矿结构。基于这两个标准,可以精确预测、设计并合成各种化学组成的钙钛矿材料。

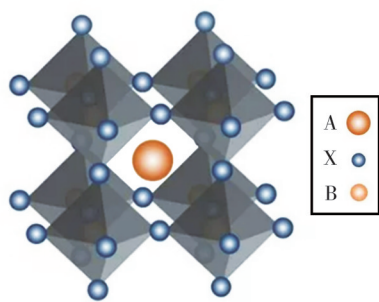


图2 钙钛矿晶体结构

Fig. 2 Perovskite crystal structure

对于钙钛矿材料带隙的调节,则是由于其B位金属阳离子位于八面体的中心,而框架结构的空余部分由A位的有机基团或无机阳离子分布在三维网络的空隙中来填充的^[12],因此,可以通过离子替换的方式实现带隙直接调节。

1.2 光电特性

钙钛矿材料,尤其是铅钙钛矿和铯钙钛矿材料,在可见光范围内展现出卓越的光吸收能力,其光吸收系数可达 10^4 cm^{-1} ,远高于传统硅材料^[13]。此外,这类材料还具备高效的载流子迁移率特性,单晶 MAPbI_3 钙钛矿载流子迁移率可高达 $(164 \pm 25) \text{ cm}^2 \text{ V}^{-1} \text{ S}^{-1}$,而多晶钙钛矿薄膜的载流子迁移率也普遍位于 $1 \sim 24 \text{ cm}^2 \text{ V}^{-1} \text{ S}^{-1}$ 之间^[14-15],这一特性使得光生载流子能够高效输送至电极,显著降低能量损失。同时,钙钛矿材料较长的载流子扩散长度进一步增强了光电器件的转换效率^[16-18]。更令人瞩目的是,作为直接带隙半导体,钙钛矿材料的带隙还具有可调性,能够灵活适应多样化的光电应用需求^[19-20],为器件性能优化提供更多可能。综上所述,钙钛矿材料凭借其高光吸收系数、优异载流子迁移率、长扩散长度、直接带隙特性及带隙可调性,已成为高效光电器件的理想材料选择,极大推动了相关技术与研究的快速发展。

2 钙钛矿光电探测器研究进展

光电探测器的性能评估依赖于一套统一的参数体系,鉴于其光敏材料、结构设计和工作机制的不同,目前广泛采纳的性能指标涵盖响应度(R)、归一化探测度(D^*)、外量子效率(EQE)以及线性动态范围(LDR)等。其中,响应度是衡量光电探测器对光信号响应能力的重要指标,其定义为器件产生的光电流与入射光功率之比,可表示为^[21-22]

$$R = \frac{I_{\text{ill}} - I_{\text{dark}}}{A E_e}, \quad (1)$$

式中: I_{ill} 和 I_{dark} 分别为光电流与暗电流; A 为有效光照面积; E_e 为入射光功率密度。

归一化探测率是衡量光电探测器在极限弱光条件下探测能力的关键参数,可表示为^[23]

$$D^* = R \cdot \frac{\sqrt{A \Delta f}}{i_n}, \quad (2)$$

式中: Δf 为频率带宽; i_n 为噪声电流。

外量子效率用于衡量光电探测器将吸收到的入射光子能量转化为自由载流子的能力,其数值与响应度成正比,可表示为^[24-26]

$$\text{EQE} = R \times \frac{hc}{e\lambda} \times 100\%, \quad (3)$$

式中: h 为普朗克常量; c 为光速; λ 为入射光波长。

线性动态范围用于衡量光电探测器的有效探测范围,在该范围内,光电流会随着入射光强的增加而呈线性增长,可表示为^[27-28]

$$\text{LDR} = 20 \lg \frac{I_{\text{upper}} - I_{\text{dark}}}{I_{\text{lower}} - I_{\text{dark}}}, \quad (4)$$

式中: I_{upper} 和 I_{lower} 分别为光电流偏离线性响应时的高光电流值和低光电流值。光电探测器的线性动态范围越大,同时探测弱光和强光的能力就越强。

关于钙钛矿光电探测器的分类可以从两个维度进行阐述。首先,根据探测的波长范围不同,可分为紫外探测器、可见光探测器、近红外探测器、X射线探测器以及 γ 射线探测器^[29],这一分类方式直接关联到探测器在不同光谱区域内的应用需求。其次,从光敏材料与电极的空间配置角度,钙钛矿光电探测器又可分为垂直结构和横向结构^[30],如图3所示。垂直结构探测器进一步可分为二极管型和垂直光电导型,横向结构探测器则包括横向光电导型和晶体管型^[31-32],这种分类方式有助于理解探测器内部结构与性能特点之间的关系,从而为设计和优化探测器提供指导。

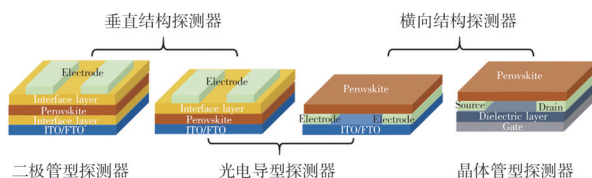


图3 钙钛矿光电探测器结构分类

Fig. 3 Structural classification of perovskite photodetectors

2.1 二极管型钙钛矿光电探测器

二极管型钙钛矿光电探测器作为一类先进的光电探测器件,融合了钙钛矿材料独特的光电特性与二极管的结构优势^[33]。从结构设计上看,这

类探测器主要分为p-n结和肖特基结两种典型构型^[34-37]。在p-n结型钙钛矿光电探测器中,通过对钙钛矿材料进行精准的p型与n型掺杂处理,于结区构建起内建电场。当外部光子入射至钙钛矿活性层时,若光子能量超越钙钛矿材料的禁带宽度,价带电子将受激发跃迁至导带,从而生成电子-空穴对^[34]。这些光生载流子在结区内部电场的强力牵引下,电子迅速向n型区域定向迁移,空穴则向p型区域移动,最终形成可被检测的光电流^[35]。肖特基结型钙钛矿光电探测器则是借助金属与钙钛矿半导体之间的界面接触形成肖特基势垒。在光照条件下,钙钛矿吸收光子产生电子-空穴对后,肖特基势垒所产生的电场促使光生载流子发生分离。其中,电子在电场作用下向金属一侧运动,空穴则向钙钛矿内部移动,进而产生光电流信号^[37]。在器件工作过程中,钙钛矿材料的适宜禁带宽度起到了关键作用,其禁带宽度一般在1.5~2.3 eV区间内,这使得它能够对特定波长范围的光子产生高响应,并在光生载流子产生环节扮演核心角色^[38]。同时,二极管结构所提供的内建电场有效地降低了光生载流子的复合几率,从而极大地提高了器件光电转换效率。

2014年,Dou等^[39]开创性地开展了基于前驱体溶液的反应熔液法(Reactive Melt Processing, RMP)工艺制备高性能混合钙钛矿光电探测器的研究工作,其结构如图4(a)所示。图4(b)显示

了当器件中插入空穴阻挡层时,可呈现出最小的暗电流密度,在-0.1 V偏压下,该器件的探测率高达 10^{14} Jones,外部量子效率(External Quantum Efficiency, EQE)达80%(见图4(c)),相较于同波段的硅基探测器,其探测率提升了一个数量级。自从首次报道基于MAPbI₃光吸收剂的钙钛矿太阳能电池以来,有机-无机杂化钙钛矿材料的应用引起了很大的关注^[40-43]。2020年,Tao等^[44]开展了基于MAPbI₃单晶前驱体(Single Crystal Precursor, SCP)制备钙钛矿薄膜的研究,旨在提升基于钙钛矿薄膜的光电探测器性能。与传统的RMP制备方案相比,基于SCP的光电探测器的性能更加优异,在可见光波段的优势显著,展现了在光电探测应用中的巨大潜力。他们采用MAPbI₃单晶作为前驱体,通过热浇铸法成功制备了晶粒尺寸较大的高质量钙钛矿薄膜。实验结果表明,基于单晶前驱体钙钛矿薄膜的光电探测器(见图4(d))在660 nm波长、 $1.25 \text{ mW} \cdot \text{cm}^{-2}$ 光强、-0.4 V偏压下实现了 $0.633 \text{ A} \cdot \text{W}^{-1}$ 的响应度,同时,器件的EQE超过了100%(见图4(e), (f))。此外,空穴选择层在影响二极管型钙钛矿光电探测器的暗电流与噪声电流特性方面起到了关键作用^[45]。2024年,Lucía-Martínez等^[46]通过优化器件的空穴传输层,在可见光范围内实现了低暗电流、高外量子效率、低噪声电流,且获得了高达 10^{12} Jones的探测率。

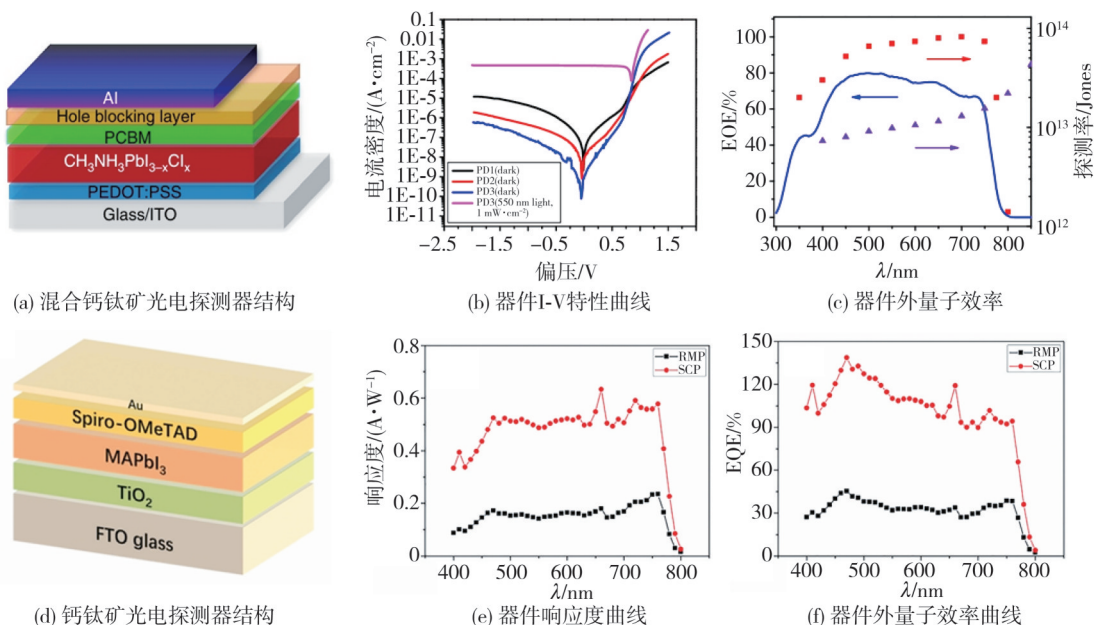


图4 钙钛矿光电探测器结构及性能^[39,44]

Fig. 4 Structure and performance of perovskite photodetectors^[39,44]

近年来,在钙钛矿薄膜制备技术的持续创新推动下,通过维度调控与化学掺杂优化钙钛矿光电性能的研究已取得了显著进展^[47-52]。为获得高探测率光电二极管,需结合低噪声电流与高光敏度,以往虽可通过降低3D光电二极管的暗电流密度提升探测率,但3D钙钛矿在能级调控方面存在局限^[53-55]。鉴于此,2022年,Ollearto等^[56]提出了多维钙钛矿材料用于高灵敏度光电二极管,如图5(a)所示。该器件将低维、垂直方向的钙钛矿相定位在与电子阻挡层相邻的界面上,增加产生热电荷的活化能,从而在不影响响应度的前提下,有效地将暗电流密度降低至创纪录的 $5 \times 10^{-9} \text{ mA} \cdot \text{cm}^{-2}$,在600 nm处产生

了超过 7×10^{12} Jones的基于噪声电流的特异性探测率,如图5(b),(c)所示。

2024年,Nam等^[57]在器件中引入了锗(Ge)元素,用以制备 $\text{EDA}_{0.01}\text{FA}_{0.98}\text{SnI}_3$:Ge型无铅锡基二极管型钙钛矿光电探测器,结构如图5(d)所示。Ge的引入产生了键结合力更强的Ge-I键,能够填补 Sn^{2+} 和 I^- 空位,还能有效钝化晶界缺陷,显著降低陷阱态密度和抑制离子迁移,从而减少暗电流和噪声。在660 nm波长、-0.1 V偏压下,该器件的暗电流密度仅为 $1.39 \times 10^{-7} \text{ A} \cdot \text{cm}^{-2}$,探测率为 1.61×10^{12} Jones(见图5(e)),相较于对照组提升显著。

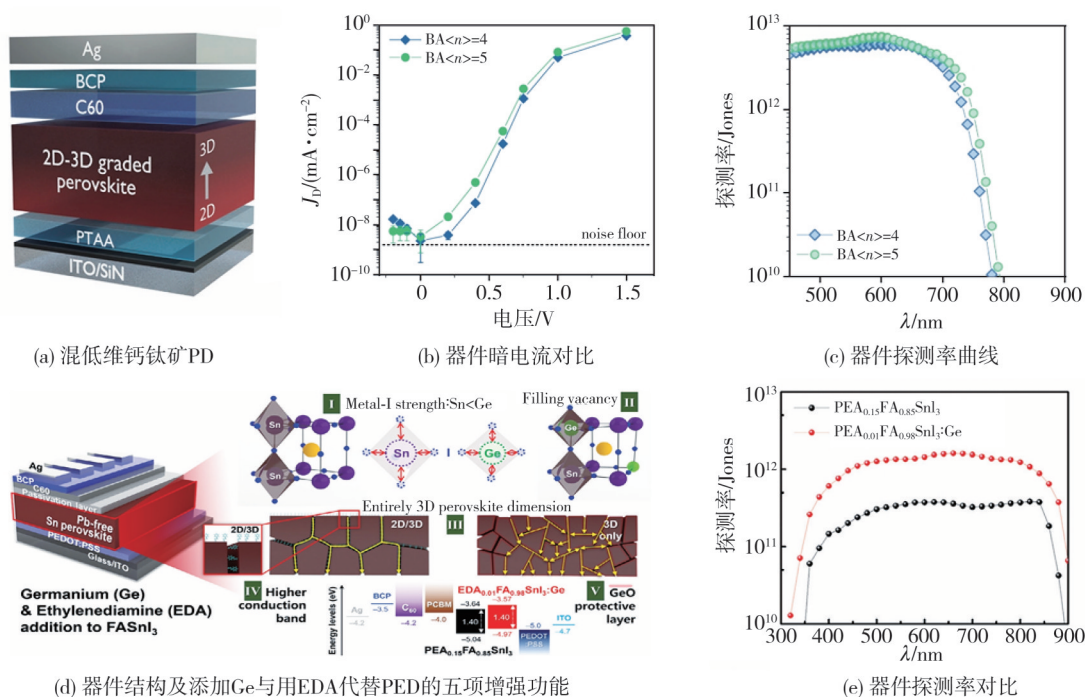


图5 光电二极管结构及性能^[56-57]

Fig. 5 Photodiode structure and performance^[56-57]

2.2 光电导型钙钛矿光电探测器

光电导型钙钛矿光电探测器基于光电导效应工作,通过半导体材料吸收光子能量产生非平衡载流子,进而增加材料的电导率^[58-60]。通常,光电导型探测器采用共面结构,在半导体材料两端设计叉指或条状电极,形成光敏电阻,当施加适当偏置电压时,回路中便产生光电流^[61-62],其大小正比于器件的有效光照面积,同时与电极间距成正比。与其他两种常见类型的钙钛矿光电探测器相比,光电导型钙钛矿光电探测器制作工艺简单,具有较大的应用潜力。

横向结构钙钛矿光电探测器电极间的跨度相

对偏大,导致钙钛矿材料中的载流子在传输路途上极易被各类陷阱捕获,由此产生光电流的无端损耗。为了提升钙钛矿光电探测器的性能,通常可以在制备时使用钙钛矿单晶与不同形状的钙钛矿纳米材料^[63-66]。2019年,Chen等^[67]提出了一种基于全无机钙钛矿 α - CsPbI_3 纳米线阵列的高性能钙钛矿光电探测器,在-5 V偏压下,器件暗电流低至 $2.1 \times 10^{-11} \text{ A}$ (见图6(a)),还实现了 $1294 \text{ A} \cdot \text{W}^{-1}$ 的响应度以及 2.6×10^{14} Jones的探测率(见图6(b))。2020年,Jing等^[68]制备了一种基于超薄单晶钙钛矿薄膜的高性能柔性光电探测器,结构如图6(c)所示。该器件的活性层厚度仅为20 nm,达到了 $5600 \text{ A} \cdot \text{W}^{-1}$ 的超高响应度(见

图 6(d)), 此外, 该探测器具有极短的开关时间, 3 dB 带宽为 0.2 MHz, 且在数千次弯曲后光电特性可恢复。无机-无机杂交钙钛矿纳米线(NW) $\text{CH}_3\text{NH}_3\text{PbI}_3$ 有着出色的光响应。然而, 一维纳米线与金属电极之间低效的载流子收集, 以及钙钛矿的降解问题, 限制了 $\text{CH}_3\text{NH}_3\text{PbI}_3$ 纳米线在商业

生产中的应用^[69]。2022 年, Wang 等^[70]将六方氮化硼(hBN)、石墨烯以及 $\text{CH}_3\text{NH}_3\text{PbI}_3$ 结合, 制造了一种混合范德瓦耳兹异质结构光电探测器(见图 6(e)), 该探测器展现出卓越的响应度和比探测率, 分别高达 $558 \text{ A} \cdot \text{W}^{-1}$ 和 $2.3 \times 10^{12} \text{ Jones}$ (见图 6(f))。

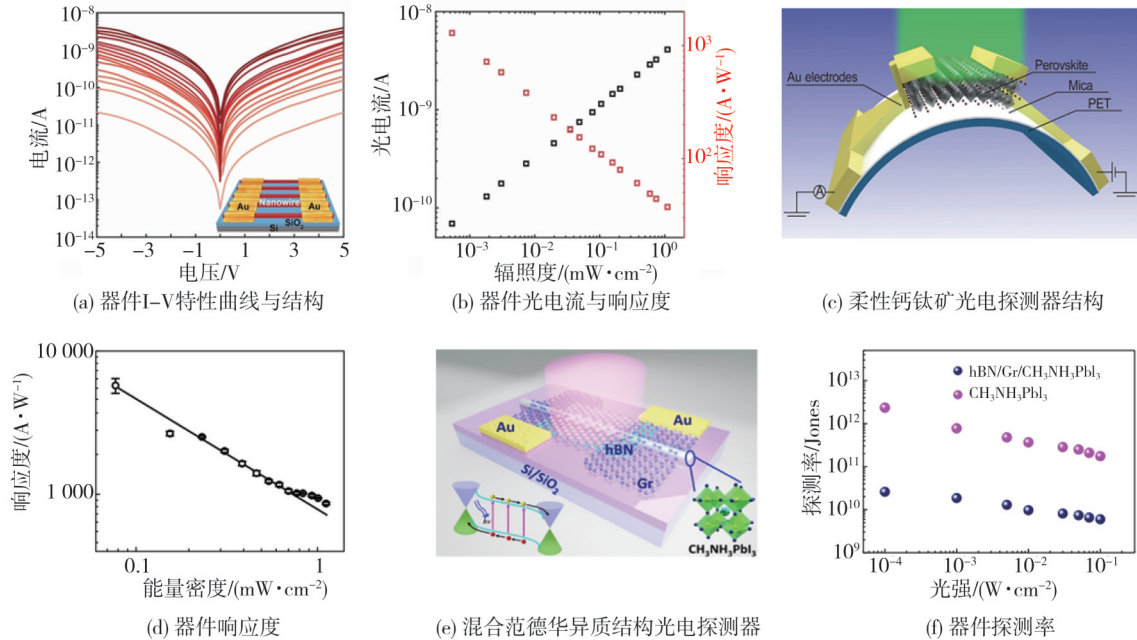


图 6 横向光电导型钙钛矿光电探测器结构及性能^[67-68,70]

Fig. 6 Structure and performance of transverse photoconducting perovskite photodetectors^[67-68,70]

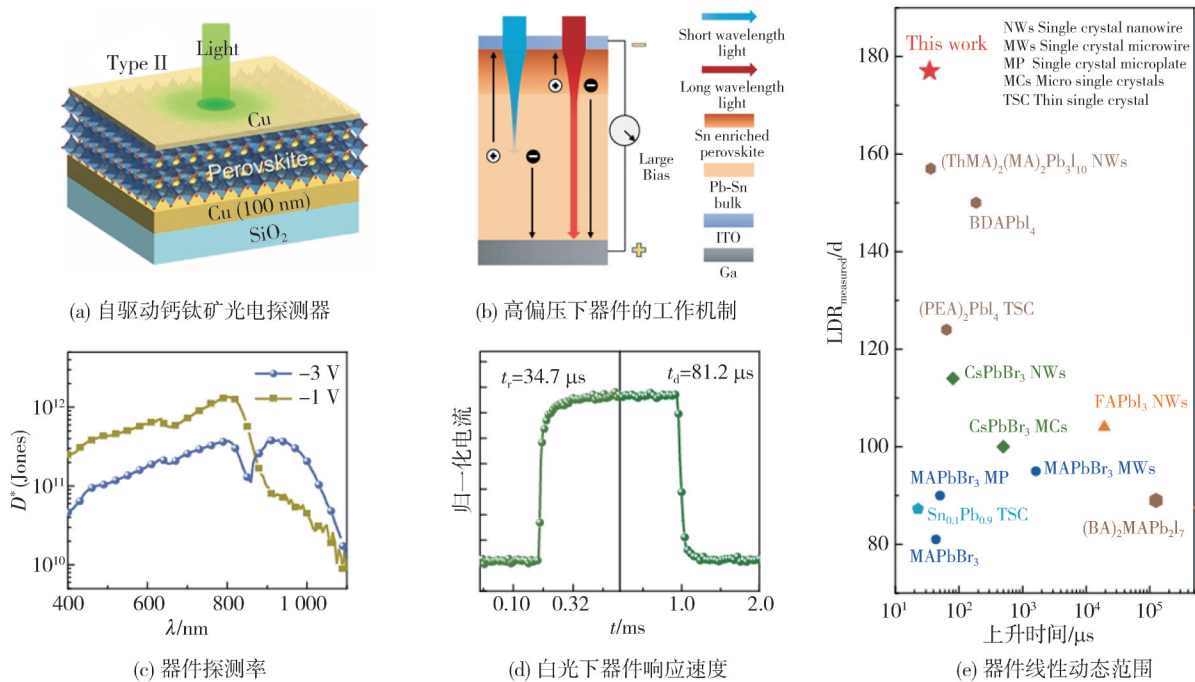


图 7 垂直光电导型钙钛矿光电探测器结构及性能^[72,75]

Fig. 7 Structure and performance of perovskite photodetector with vertical photoconductivity^[72,75]

与横向光电导型相比, 垂直光电导型钙钛矿光电探测器优势显著。垂直结构分离载流子高效、复

合率低、对微光敏感、响应速度快, 横向则易复合、灵敏度较差^[71]。2022 年, Cao 等^[72]设计了一种基于

Dember效应的自驱动钙钛矿光电探测器(见图 7(a)), 探测率与上升(衰减)时间分别为 1.3×10^9 Jones 与 $2.6(3.5) \mu\text{s}$ 。获取全彩和红外图像的昼夜成像技术在安防监控和自动驾驶领域有着巨大的市场需求^[73-74], 目前主流的解决方案依赖于宽光谱硅光电探测器结合红外滤光片, 这种方法导致复杂性和故障率提升, 为了应对这一挑战, 2024 年, Mao 等^[75]提出了一种基于 Pb-Sn 合金化单晶的垂直带隙梯度型钙钛矿光电探测器, 器件结构与高偏压下的工作机制如图 7(b) 所示。在 -1 V 偏压下, 800 nm 处探测率可达 1.3×10^{12} Jones(见图 7(c)), 具有高响应速度(见图 7(d)), 线性动态范围为 177 dB (见图 7(e)), -3 dB 截止频率为 46.4 kHz 。此外, 基于此探测器制作的无红外截止滤光片的成像模型具有优异的性能, 与商业硅光电探测器相对比, 在红外干扰下, 该探测器的色彩还原能力较强。

2.3 晶体管型钙钛矿光电探测器

光电导型钙钛矿光电探测器的 EQE 可远超 100% , 但较大的暗电流在一定程度上限制了它的实际应用范围^[76-78]。相比之下, 二极管型钙钛矿光电探测器通过引入载流子阻挡机制, 可有效降

低暗电流。大多数二极管型钙钛矿光电探测器采用垂直结构, 其载流子传输距离由半导体膜厚决定, 最小可达纳米尺度, 这显著缩短了载流子渡越时间, 从而极大地提高了器件的响应速度。但由于二极管型钙钛矿光电探测器依赖于光伏效应, 导致 EQE 通常低于 100% ^[45, 79-81]。

晶体管型钙钛矿光电探测器是一种结合了多种器件优点的先进结构, 其核心部分是由钙钛矿材料构成的导电沟道以及 3 个电极(分别为源极、漏极和栅极)^[82-84]。根据电极与钙钛矿薄膜之间的相对位置, 该探测器的设计可以分为两类: 顶部接触设计和底部接触设计。在晶体管型钙钛矿光电探测器的工作过程中, 源极和漏极之间的电压保持恒定, 而源漏电流则受到栅极电压和光照强度的共同影响^[85]。这种结构实现了超过 100% 的 EQE, 使得探测器展现出较高的光电流和响应度。

全无机钙钛矿量子点(Inorganic Perovskite Quantum Dots, IPQD)有着优异的光电性能与环境稳定性, 可用于各种光电器件^[86-88]。2018 年, Zou 等^[89]将 CsPbI_3 QDs 和窄带隙共轭聚合物 DPP-DTT 相结合, 制备了一种层状异质结高性能光电晶体管(见图 8(a))。

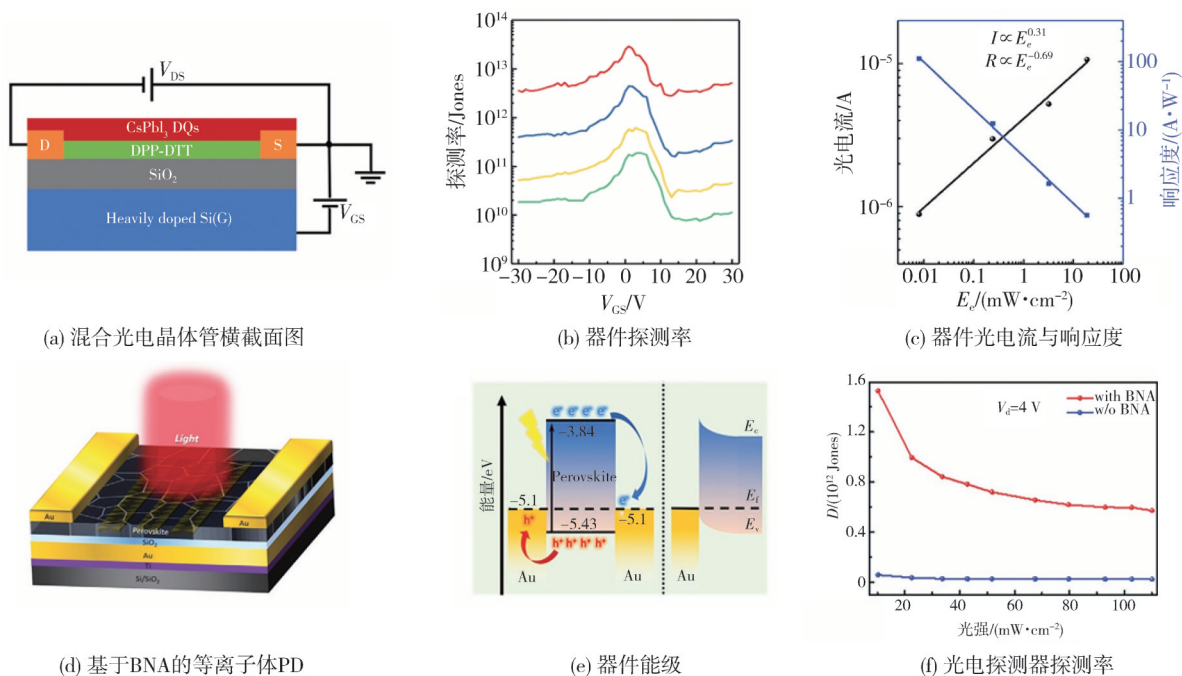


图 8 光电晶体管结构与性能^[89, 93]

Fig. 8 Phototransistor structure and performance^[89, 93]

其探测率可达 2.9×10^{13} Jones, 响应度为 $110 \text{ A} \cdot \text{W}^{-1}$ (见图 8(b), (c)), 还克服了由于 QD 之间的电荷传输不佳而导致的 IPQD 光电探测器灵

敏度的现有限制。钙钛矿在近红外波段具有较低的光电转换效率, 而利用领结纳米天线(Bowtie Nano-Antenna, BNA)与表面等离子体共振耦合

可以增强光电器件的性能^[90-92], 2020 年, Wang 等^[93]设计了一种基于金领结 BNA 阵列的等离子体功能化晶体管型钙钛矿光电探测器, 其结构与能级如图 8(d), (e)所示。在 785 nm 激光照射下, 该探测器的探测率高达 1.5×10^{12} Jones, 且具有强近红外选择性光响应。

近年来, 混合系统一直被大家所关注, 它结合了混合材料的特殊属性, 并通过多个不同接口的交互创建了多样的功能^[94-96]。2017 年, Chen 等^[97]将有机半导体与全无机卤化铅钙钛矿量子点相互混合, 获得了 $1.7 \times 10^4 \text{ A} \cdot \text{W}^{-1}$ 的响应度, 2×10^{14} Jones 的探测率, 以及高达 67 000% 的 EQE。2020 年, Hou 等^[98]将 CsPbBr₃ 薄膜和氧化铟锡纳米线(ITO NWs)集成到 InGaZnO 沟道中, 制备了一种混合光电晶体

管(见图 9(a))。该器件展现出了高达 $4.9 \times 10^6 \text{ A} \cdot \text{W}^{-1}$ 的卓越响应度(见图 9(b)), 同时, 具有极短的响应时间与出色的机械柔韧性。2022 年, Tong 等^[99]提出了一种二维混合钙钛矿光电探测器, 如图 9(c)所示。该器件有着超灵敏的弱光检测性能, 即使在低至 $1.6 \text{ nW} \cdot \text{cm}^{-2}$ 的创纪录低光强度下也能捕捉到可区分的光开关信号, 此外, 该器件的响应度与探测率分别达到了 $2.3 \times 10^5 \text{ A} \cdot \text{W}^{-1}$ 与 4.1×10^{14} Jones(见图 9(d))。2024 年, Yun 等^[100]将 ZnON 通道层与多阳离子钙钛矿相结合, 并引入胍盐碘化(GuI)作为界面钝化层, 设计了一种基于 ZnON/钙钛矿异质结的高性能混合光电晶体管(见图 9(e))。该器件的响应速度为 0.1 s, 响应度为 $5.97 \times 10^6 \text{ A} \cdot \text{W}^{-1}$, 还有着超高的特异性探测率。

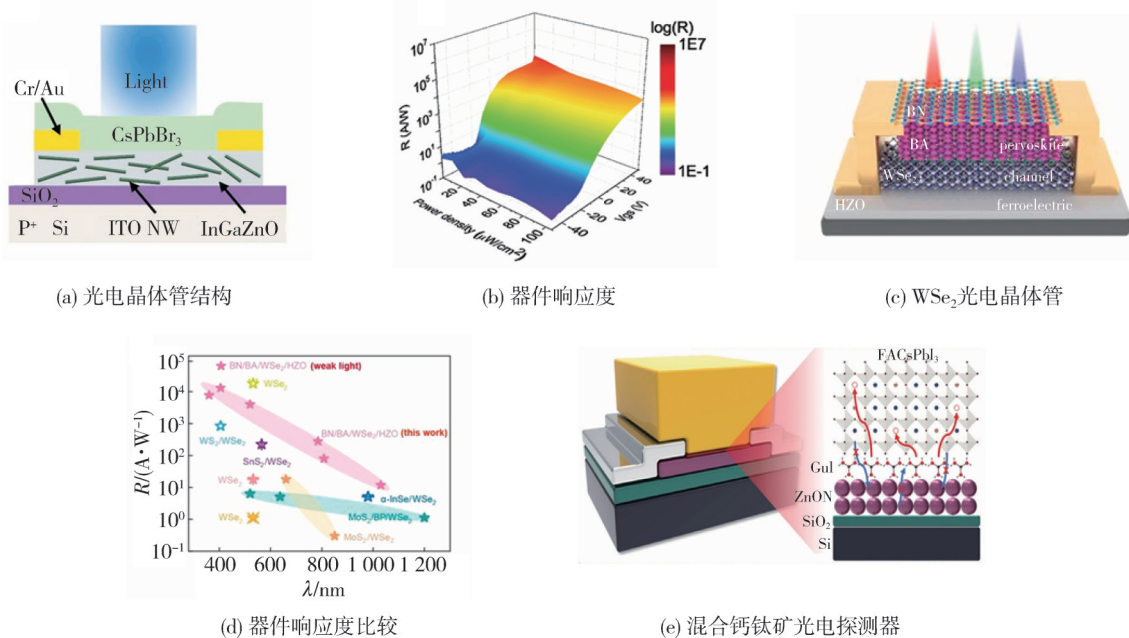


图 9 混合光电晶体管结构与性能^[98-100]

Fig. 9 Hybrid phototransistor structure and performance^[98-100]

3 总结与展望

随着信息技术和智能化产业的快速发展, 高性能光电探测器在各种领域的需求不断增加, 钙钛矿光电探测器凭借其优异的光电性能、低成本和柔性可调性, 已成为新一代光电探测技术的热门选择。然而, 尽管其潜力巨大, 但在实际应用中仍面临一些挑战, 包括材料稳定性差、环境敏感性高、铅等有毒物质的使用以及制备工艺的可重复性等问题^[101-105]。这在一定程度上限制了其大规模商业化应用, 为了克服这些问题, 未来需持续深入地研究钙钛矿材料的特性并优化钙钛矿薄

膜制备工艺, 探索新的器件结构设计与复合体系构建将是推动该领域发展的关键路径。相信在不远的将来, 稳定可靠的钙钛矿光电探测器就会问世, 并在 6G 及未来通信拓展、智能传感、环境监测等众多领域中发挥愈发关键的作用。

利益冲突声明/Conflict of Interests

所有作者声明不存在利益冲突。

All authors declare no relevant conflict of interests.

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