

基于光电上转换的红外可视化探测研究进展

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摘要 基于光电上转换的红外可视化探测技术兼具无创成像、原位检测、微型化及拓展人眼可视范围等优势, 已在生物医疗、公共安全及工业检测等领域展现出广阔的应用前景。本文系统梳理了红外上转换探测器的材料体系、器件结构及其工作机理, 并按材料类别与结构特征归纳了近年来的研究进展与应用场景。在研究进展方面, 有机材料凭借低成本、可柔性及大面积加工特性, 在光电性能方面取得持续突破; 而量子点材料因带隙可调、可溶液加工, 有效拓展了短波红外波段的探测能力。此外, 多子单元串联结构显著提升载流子利用率, 使上转换效率与工作电压突破传统瓶颈。在应用层面, 该技术已成功用于生物医疗成像、可穿戴电子、交互式彩色显示及多功能光通信系统, 表现出低功耗、高分辨率与大面积集成的突出优势。最后, 本文对当前红外可视化探测器面临的关键科学问题与技术挑战进行了总结与展望, 旨在为高性能红外可视化器件的设计优化与工程化应用提供理论依据与实践参考。

关键词 红外成像, 上转换, 光电探测器, 发光二极管, 可视化

智能交互显示技术已成为信息化与互联网时代不可或缺的信息接口。图像作为人类获取外界信息的最直接途径, 约80%以上的环境信息依赖视觉系统获得^[1]。然而, 受限于视锥细胞的光谱响应范围(380~780 nm), 人眼仅能感知电磁波谱的极窄片段, 大量蕴含于紫外、红外乃至太赫兹波段的关键信息长期处于视觉盲区^[2]。因此, 构建可交互的智能光电显示器件, 突破人眼感知极限, 实现多维度信息可视, 对医疗诊断及工业检测均具有重要意义。

传统红外成像技术(如InGaAs焦平面阵列)因复杂的读出电路、高精度倒装键合工艺及高昂的像素化成本, 难以兼顾柔性、低成本及实时可视化等发展需求^[3-6]。近年来, 基于光电上转换的红外可视化成像技术凭借颠覆性器件结构, 有效突破了上述瓶颈。其核心创新在于利用磁控溅射、热蒸发或溶液法等简易薄膜

工艺, 将红外探测器(photodetector, PD)与发光二极管(light-emitting diode, LED)单片异质集成于同一衬底, 通过载流子注入式线性上转换机制, 实现“红外光子-电子-可见光子”的直接转换^[7-11]。值得注意的是, 基于光电上转换的线性策略与基于双光子吸收的非线性策略(如三重态-三重态湮灭^[12-14]和稀土离子掺杂^[15-19])在实现路径上各具特色。前者通过“光-电-光”的转换方式, 避免了传统红外成像中复杂的读出电路与数字处理系统, 易于实现低成本、轻量柔性、高集成度的大面积成像, 适用于对功率和成本敏感的可视化场景。而后者作为“光-光”的直接转换过程, 在材料设计与光谱调控方面具有独特的灵活性, 适用于超分辨率成像与多光谱探测等前沿领域^[20], 但其效率通常依赖于特定波长的高功率激发光源。鉴于此, 上转换光电探测器(upconversion device, UCD)凭借其独特的器件架构与制备优

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Hu Y, Liang J, Chen L, et al. Advances in infrared visualization via photoelectric upconversion (in Chinese). Chin Sci Bull, 2026, 71: 1240-1254, doi: 10.1360/CSB-2025-5519

势,已在生物医疗^[21,22]、无创检测^[23]、信息通讯^[24,25]以及军事夜视^[26,27]等领域展现出革命性应用潜力,是下一代多功能光电显示器件的有力候选。

本文围绕红外可视化成像技术的最新研究进展展开系统综述(如图1所示)。首先,归纳UCD的材料体系、器件结构及工作机理;其次,以PD与LED单元所用材料为主线,结合多子单元串联集成策略,梳理研究现状;最后,深入探讨红外可视化成像的典型应用场景,并对其未来发展趋势与关键挑战进行展望。本文旨在为高性能红外可视化器件的设计与应用提供理论依据与实践参考,并期望激发更多学者投身该领域研究,共同推动其跨越式发展。

1 红外可视化探测器的基础

1.1 材料体系

材料是器件的基础。目前,用于红外可视化探测的

半导体材料大体可分为四类:有机半导体、量子点(quantum dots, QDs)、钙钛矿及二维材料,如图2(a)所示。

有机半导体以碳基共轭分子为主体,具备低成本、可溶液法大面积成膜及良好环境稳定性等优势^[28,29],因此成为最早被系统研究的UCD功能层材料。然而,有机半导体材料吸收边多局限在近红外(near infrared, NIR)区域,对短波红外(short-wave infrared, SWIR)乃至中红外波段的响应仍显不足^[7]。QDs材料的出现有效拓宽了光谱窗口。作为尺寸2~20 nm的核/壳型零维纳米晶,QDs兼具带隙可调、色纯度高、溶液加工及低成本等特性,可同时承担UCD中的光敏单元(如PbS、PbSe QDs用于SWIR探测)与发光单元(CdSe、InP基QLED)^[4,30-34]。前者可将检测波长扩展至SWIR以上,从而在环境监测与夜视应用中具有应用潜力^[35-37];后者则凭借卓越的色彩饱和度和发光稳定性,适用于高保真成像^[30,38]。需要指出的是,QDs在溶液成膜过程中

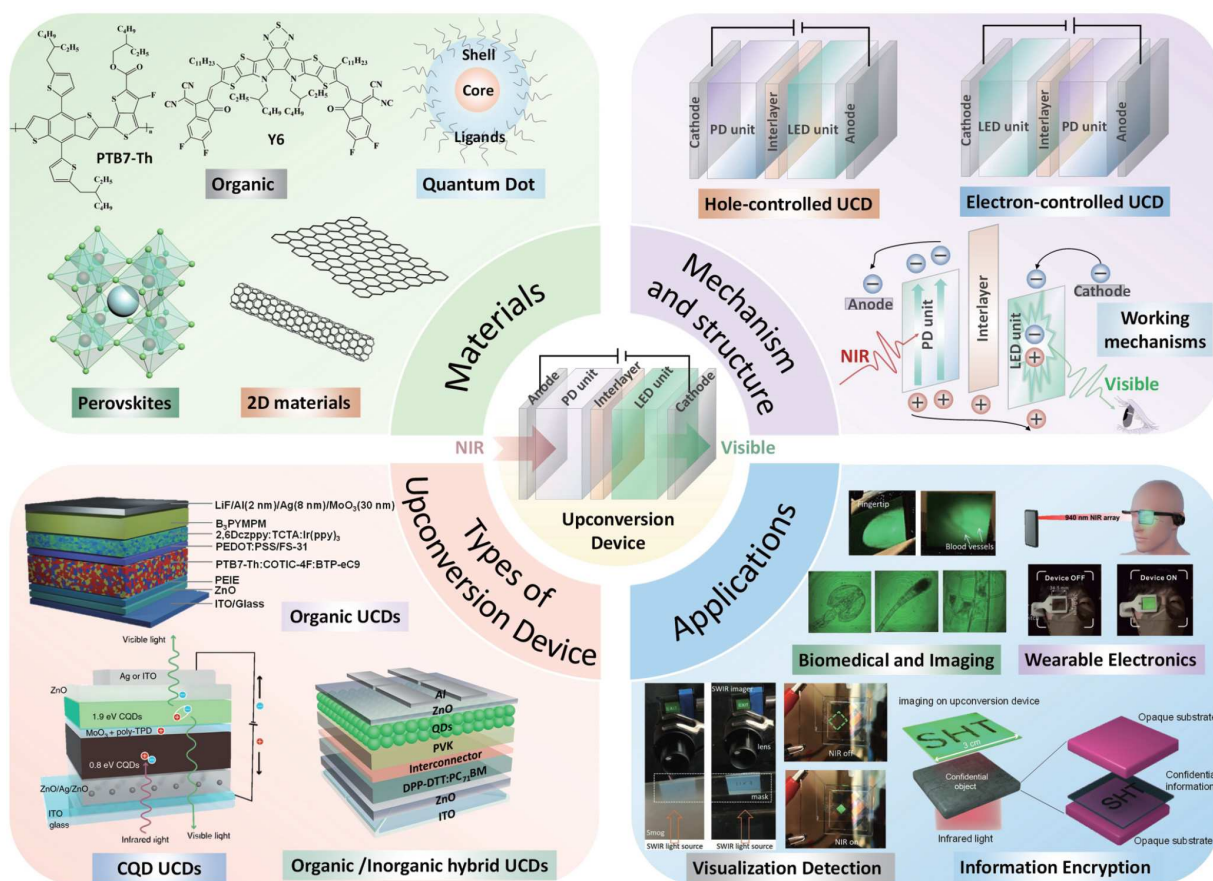


图1 (网络版彩色)基于光电上转换的红外可视化成像技术的研究进展总览,包括材料、结构和机理、种类以及应用

Figure 1 (Color online) Overview of advances in infrared visualization imaging techniques based on photoelectric upconversion, encompassing materials, structures and mechanisms, types, and applications

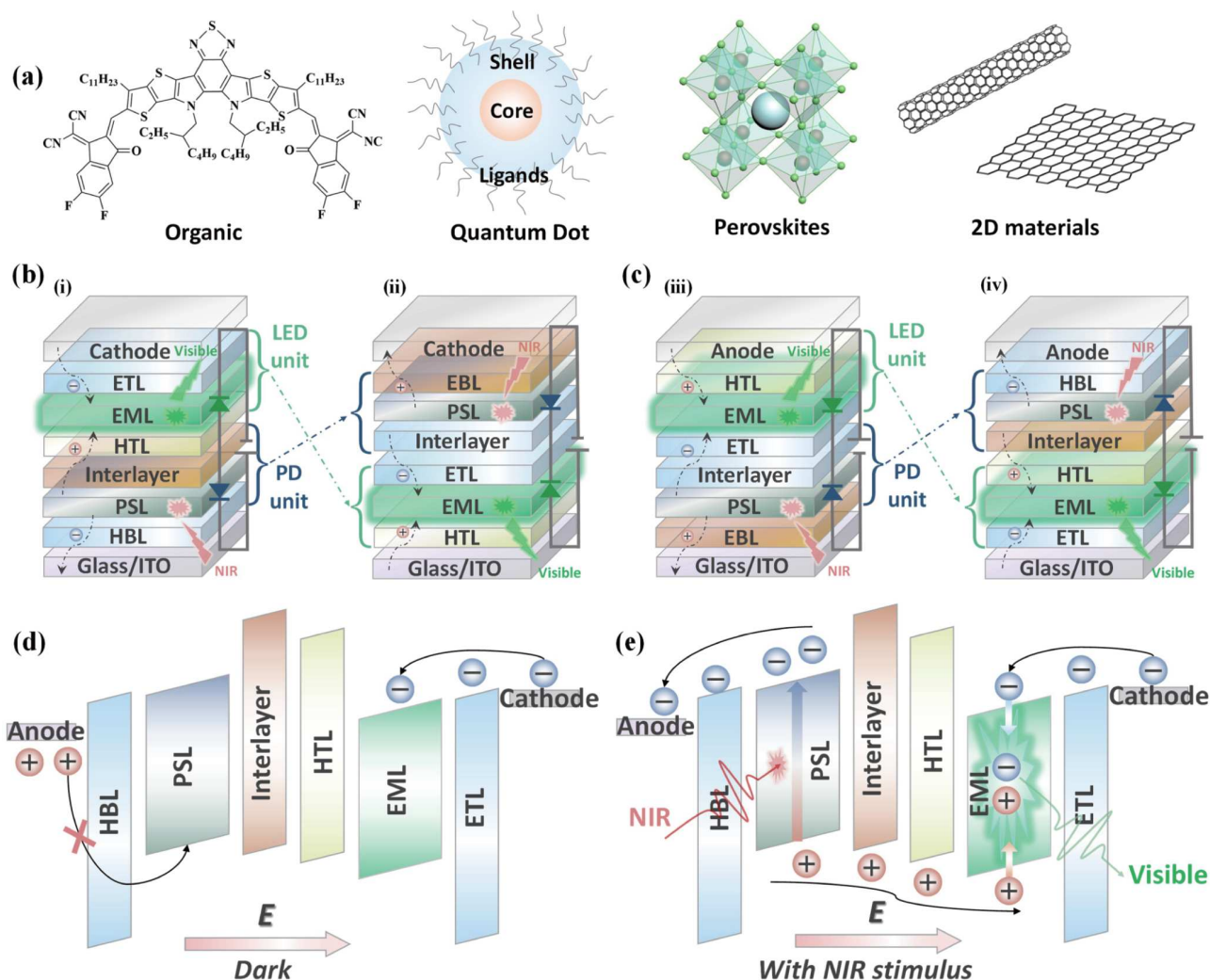


图 2 (网络版彩色)红外可视化探测器的材料种类、器件结构以及工作原理。(a) 有机材料、QDs、钙钛矿和二维材料结构示意图; (b) (i)空穴和(ii)电子控制型正置结构; (c) (iii)电子和(iv)空穴控制型倒置结构; (d) 黑暗条件和(e) NIR光刺激下红外可视化探测器的工作机制

Figure 2 (Color online) Infrared visualization detectors, detailing material types, device structures, and operational principles. (a) Schematic representations of organic, quantum dot, perovskite, and two-dimensional materials; (b) (i) hole- and (ii) electron-controlled conventional structures; (c) (iii) electron- and (iv) hole-controlled inverted structures; operational mechanisms of infrared visualization detectors, illustrated under (d) dark conditions and (e) NIR light stimulation

的界面侵蚀及重金属毒性仍是制约其规模化的瓶颈, 相关研究尚处起步阶段。

为进一步提升器件性能并拓展工作波段, 钙钛矿与二维材料等新兴体系正受到广泛关注。钙钛矿材料(ABX_3 结构)因高吸收系数、优异的载流子输运特性、宽光谱响应及低成本溶液制备潜力^[39], 已在太阳能电池、LED以及PD领域大放异彩^[40-43]。将其引入UCD, 可望实现SWIR高效探测与发光, 但其对水氧敏感、易分解的化学本性仍是稳定性难题。二维材料则凭借原子级厚度、高载流子迁移率、优异光学透过性及机械柔性^[44], 被视为电荷传输层与透明电极的理想备选^[45],

为大面积、半透明乃至柔性可视化成像技术提供了新的材料平台与思路。

1.2 结构构型

根据PD与LED单元对载流子的提取/注入方式, 可将UCD归纳为四种典型架构, 如图2(b)和(c)所示: (i) 空穴控制正置结构; (ii) 电子控制正置结构; (iii) 电子控制倒置结构; (iv) 空穴控制倒置结构。其中, “正置”与“倒置”的区别主要源于LED单元中电荷传输层的堆叠顺序。正置结构以空穴传输层靠近阳极、电子传输层靠近阴极为特征, 与常规光电二极管结构一致, 而倒置结

构则相反。“空穴控制”与“电子控制”则指在上转换过程中被有效利用的光生载流子类型,前者依赖光生空穴注入发光层,后者则依赖光生电子。目前,绝大多数报道采用的是空穴控制型^[23,46~51]。该结构将LED单元堆叠于PD单元之上,工艺兼容性好。同时,对于非透明设备,入射红外光必须穿过玻璃/ITO基板,以最大化光敏层中的光子吸收,从而提高光生载流子产率。对于透射模式UCD,入射路径与电极无关,可通过优化光敏区域减小角度畸变,显著提高成像分辨率。

相比之下,电子控制构型的研究仍显稀缺^[52,53],其光电性能显著落后于空穴主导结构。研究表明,该差异主要源于传统电子传输层与光敏受体之间存在较高的注入势垒及不利的界面接触。因此,开展能带对准工程与界面工艺优化是推动电子控制型UCD发展的关键,亟待深入探索。

1.3 工作机理

以空穴控制正置结构为例(图2(d)),器件纵向结构依次为:阳极/空穴阻挡层/光敏层/连接层/空穴传输层/发光层/电子传输层/阴极。

在黑暗环境下,光敏层无红外激发,无法产生光生载流子,加上空穴阻挡层的深能级势垒有效阻断空穴自阳极向发光层的注入,抑制其与阴极电子的辐射复合,因此,器件处于“关断”状态。该阻挡层是降低暗噪声、提升对比度的核心。

当器件受红外辐照时,光敏单元吸收光子并产生激子,在外电场作用下,激子解离为自由载流子。其中,电子经电子传输层向阳极迁移并被收集,空穴则通过连接层与空穴传输层注入发光单元,与阴极注入的电子复合辐射可见光,如图2(e)所示。

该过程表明,UCD的激活由“红外刺激+外偏置”协同调控。值得注意的是,这里需要突出UCD对红外光的快速响应,而非电场依赖。因此,通过能垒工程严格抑制暗态发射,并在光照条件下高效提取/注入光生载流子,是实现低功耗、高灵敏度UCD的核心策略^[49]。

2 红外可视化探测器的研究进展

2.1 无机结构

1967年,Kruse等人^[54]首次提出并验证了UCD的概念,实现了1.5~0.9 μm 的上转换发射,但受限GaAs的低电致发光量子效率,内部转换效率仅为 2.8×10^{-5} 。随

后,无机UCD逐步发展^[55,56]。2009年,Yang等人^[57]将高内部效率的GaAs/AlGaAs LED与雪崩增益的Ga-NAsSb/GaAs PD单片集成,将上转换效率提升至4.8%,为高效率红外可视化器件的直接外延生长奠定了实验基础。然而,无机材料需严格晶格匹配,工艺温度高,与柔性衬底不兼容,且设备成本昂贵。另外,LED与探测单元之间的能级失配导致器件通常只能将中波红外或SWIR上转换至NIR而非可见光,显著制约了其在可视化场景中的应用。

2.2 有机结构

有机光电子学的蓬勃发展为有机UCD提供了契机。早期研究在荧光有机发光二极管(organic light-emitting diode, OLED)中引入NIR敏化层(TiOPc),利用红光增强空穴注入以提升效率^[58],但器件无法抑制暗态噪声,难以实现成像功能。随后,凭借可低温成膜、柔性及大面积加工等优势,有机UCD得到快速发展^[52,59~63]。

2021年,Tao等人^[23]利用三元混合的NIR光敏单元与OLED耦合(器件和能级结构见图3(a)),将上转换效率提高至12.92%,弱光响应低至 $3.2 \mu\text{W}/\text{cm}^2$ 。然而,界面激基复合物及复杂三元体系增加了工艺难度。同年,Liu等人^[46]以单一活性材料C1AIPc搭配磷光LED(BCzPh:CN-T2T)(图3(b)),实现25.52%的上转换效率与1588 dpi超高分辨率,并在 12×12 微阵列上完成字母动态成像,验证了可穿戴红外视觉应用的可行性。最近,Li等人^[24]基于有机本体异质结的特征吸收,设计了波长选择性UCD,有效抑制环境杂散光,为目标识别与光通信提供了新思路。

尽管热蒸发工艺已推动有机UCD不断突破,但兼具成本效益的溶液法仍面临严峻挑战。Dong等人^[48]通过分子设计与界面工程,成功制备了溶液加工快速响应UCD(图3(c)),开启电压1.5 V、明暗对比度 1.1×10^5 、上转换效率10.68%,性能可媲美热蒸发器件。作者指出,正交溶剂选择与界面修饰是抑制溶液渗透、实现多层结构的关键。该工作为大规模溶液法制备高性能UCD提供了范例。

虽然有机UCD具备成熟的工艺稳定性、优异的光电性能、可柔性大面积加工等优势。然而,有机材料在红外吸收边与载流子迁移率方面仍逊于无机体系,限制了其在SWIR乃至中波红外场景的拓展,特别是在热成像等高要求领域^[7]。

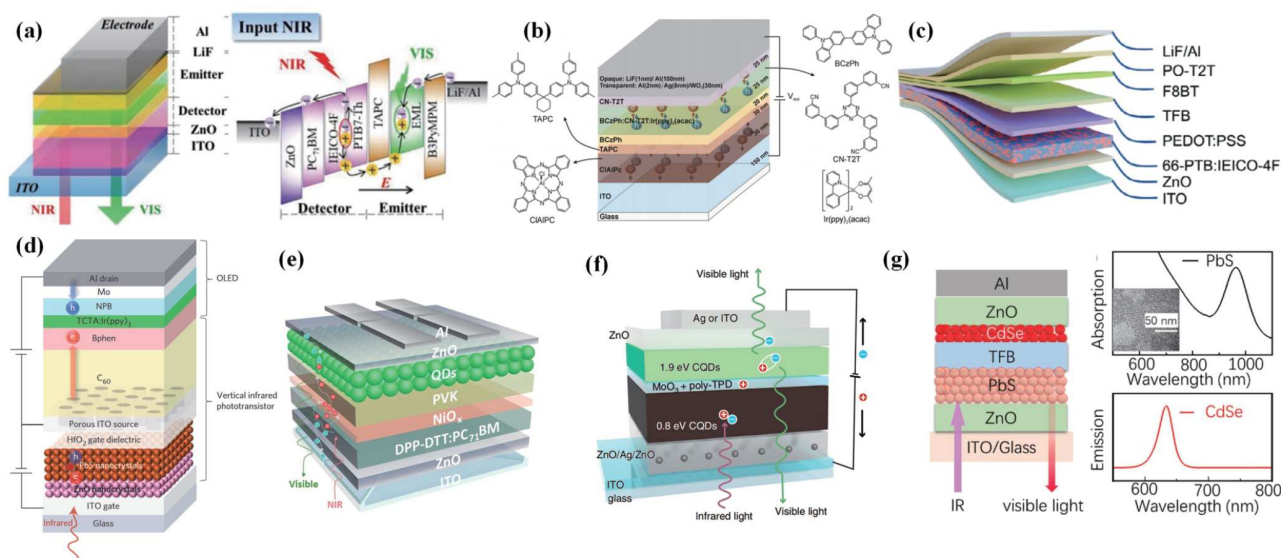


图 3 (网络版彩色)UCD的不同结构类型. (a) 基于三元混合体异质结光敏单元的UCD结构示意图和器件的运行机制(Copyright © 2021, Wiley-VCH GmbH)^[23]; (b) 基于单组分的有机UCD结构示意图及其对应的分子结构(Copyright © 2021, Elsevier)^[46]; (c) 溶液处理的有机UCD的示意图(Copyright © 2024, Wiley-VCH GmbH)^[48]; (d) 由磷光OLED和垂直光电晶体管组成的器件结构(Copyright © 2016, Springer Nature)^[67]; (e) 有机探测与QLED杂化的可视化探测器(Copyright © 2024, Wiley-VCH GmbH)^[49]; (f) 掺杂银纳米粒子的QDs-UCD结构示意图(Copyright © 2020, Springer Nature)^[50]; (g) 典型的基于QDs的红外上转换光电探测器的器件结构, 以及对应PbS CQDs的吸收光谱和CdSe CQDs的光致发光光谱(Copyright © 2023, Royal Society of Chemistry)^[75]

Figure 3 (Color online) Different structural types of UCD. (a) Schematic structure of a UCD utilizing a ternary hybrid heterojunction photosensitive unit, along with the device operation mechanics (Copyright © 2021, Wiley-VCH GmbH)^[23]; (b) schematic representation of a single-component-based organic UCD and its associated molecular structure (Copyright © 2021, Elsevier)^[46]; (c) diagram of a solution-processed organic UCD (Copyright © 2024, Wiley-VCH GmbH)^[48]; (d) device structure, consisting of a phosphorescent OLED and a vertical phototransistor (Copyright © 2016, Springer Nature)^[67]; (e) visualization detector hybridized with organic detection and QLED (Copyright © 2024, Wiley-VCH GmbH)^[49]; (f) schematic structure of QDs-UCD doped with silver nanoparticles (Copyright © 2020, Springer Nature)^[50]; (g) device structure of a typical QDs-based infrared upconversion photodetector, and the absorption spectrum of PbS CQDs and photoluminescence spectrum of CdSe CQDs (Copyright © 2023, Royal Society of Chemistry)^[75]

2.3 有机/无机杂化结构

有机/无机杂化器件可协同发挥两类材料优势, 兼顾性能与工艺灵活性^[3,8,10,64,65]. Ban等人^[66]最早将OLED与InGaAs/InP PD集成, 实现1.5 μm 到520 nm绿光上转换, 但效率仅0.7%. 2016年, Frank. So团队^[67]开发了高增益发光光电晶体管(light-emitting phototransistor, LEPT), 如图3(d)所示, 首次在同一芯片上集成传感、放大与发光功能, 然而复杂工艺阻碍其进一步发展. 最近, Lei等人^[49]通过溶液处理将有机PD单元与QLED集成(图3(e)), 系统研究了互连层能级与迁移率对性能的影响, 为界面工程提供了普适指导. 随后, 该团队以单组分非富勒烯受体Y6简化异质结, 避免可见光重吸收, 获得高效单组分UCD^[68], 但受QLED外量子效率限制, 器件效率仅1.3%. Liu等人^[69]将 Zn^{2+} 掺杂CsPbBr₃钙钛矿QDs作为LED单元, 结合PM6:Y6光敏单元, 采用全溶液工艺制备杂化UCD, 将上转换效率提高

到5.68%, 成像分辨率大于508 dpi.

2.4 量子点结构

相比于有机材料, QDs的响应波长可覆盖到中红外甚至远红外, 且兼具溶液法处理的优势, 使其逐渐在红外可视化探测中崭露头角^[70~72]. Sun等人^[73]首次以窄带隙PbS QDs耦合红光QLED, 构建了电子控制型QDs-UCD, 上转换效率为3.35%. 2020年, Ning等人^[50]利用PbS与绿光CdSe/ZnS QD结合, 成功实现了1.5 μm 到525 nm的上转换发射(图3(f)). 为了保证PD单元能够提供足够的光电流来驱动可见光发射, 他们在光敏层中掺入了银纳米颗粒来优化载流子的注入, 最终实现了6.5%的上转换效率. 2022年, Tang等人^[74]构建了一种基于HgTe PD单元与QLED集成的QDs-UCD, 实现了2.5 μm 到绿光的上转换发射, 效率高达30%, 弱光响应低至20 $\mu\text{W}/\text{cm}^2$, 为拓展中红外可视化提供了可行路径.

最近, Wu等人^[75]系统分析了QDs-UCD中PD与QLED的耦合机制及效率损失来源(图3(g)), 为后续优化奠定了理论基础。

尽管如此, 高性能QDs通常含Pb、Hg等重金属, 环境与健康风险不容忽视。此外, QDs对可见光的显著吸收会导致发射光子二次损耗, 降低出光效率。未来需从无毒QDs合成与透明器件结构设计两方面入手, 以推动QDs-UCD的可持续发展。

2.5 多单元串联结构

为进一步提升上转换效率, 研究者提出多LED或多个PD单元串联策略, 实现对光生电子-空穴的充分利用。相比传统单通道器件, 串联结构可成倍提高激子利用率与发光效率。2018年, Lu等人^[76]首次在两个OLED之间加入一个有机NIR敏化层, 验证了串联UCD的可行性。随后, Yang等人^[77]将NIR PD与绿色串联OLED集成(图4(a)), 上转换效率达到了29.6%, 但该构型仅利用光生空穴, 光生电子仍被浪费。2023年, Liu等人^[78]利用

热蒸发工艺开发半透明大面积有机红外传感器, 通过调节单组分CIAIPc双极传输特性, 实现双端载流子全被利用, 上转换效率突破30%。

然而, 上述高性能器件均依赖热蒸发, 溶液法仍面临层间互溶与界面粗糙等技术壁垒。幸运的是, 2024年, Kang等人^[79]以化学交联功能层实现溶液法串联(图4(b)), 将QDs吸收单元与双QLED集成, 分别利用电子与空穴, 获得3.2%的上转换效率, 为半透明、大面积柔性UCD提供了可行路线。最近, Han等人^[80]将两个有机PD单元与OLED集成(图4(c)), 利用PD的光生伏特效应产生1.70 V开路电压, 使器件在0.64 V超低偏压下即可工作, 效率达10.64%, 为低功耗生物成像开辟了新思路。

3 红外可视化探测器的应用

3.1 医疗监测与生物成像

光电容积脉搏波(photoplethysmography, PPG)检测是最成熟的应用之一^[81-85]。当NIR光穿透指尖并被光

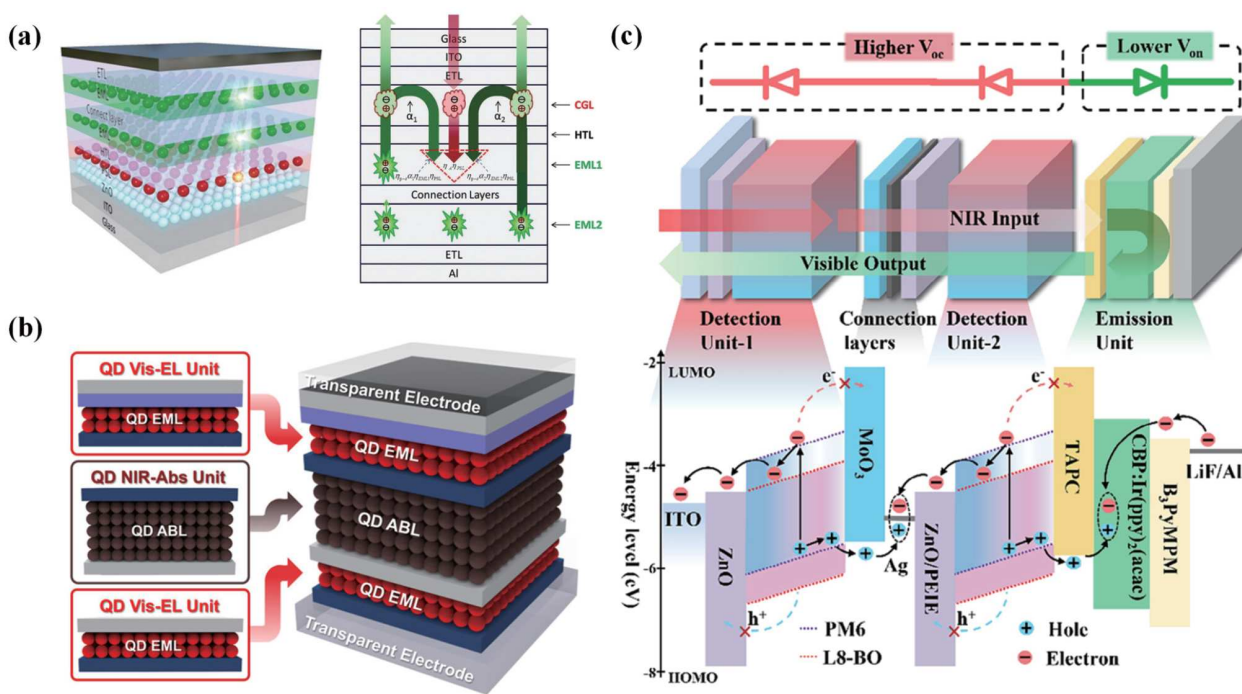


图 4 (网络版彩色)多单元串联UCD. (a) NIR UCD集成器件示意图, 以及对应的工作原理(Copyright © 2018, Royal Society of Chemistry)^[77]; (b) 一个吸光层与两个发光单元串联的半透明QDs-UCD示意图(Copyright © 2024, American Chemical Society)^[79]; (c) 两个PD单元与一个LED单元串联的结构示意图, 以及在红外光输入下的能带图(Copyright © 2025, Wiley-VCH GmbH)^[80]

Figure 4 (Color online) Multi-unit tandem UCD. (a) Schematic diagram of the NIR UCD integrated device, and the corresponding operating principle (Copyright © 2018, Royal Society of Chemistry)^[77]; (b) schematic diagram of a semi-transparent QDs-UCD with one light-absorbing layer and two light-emitting units in tandem (Copyright © 2024, American Chemical Society)^[79]; (c) schematic diagram of the structure of two PD units in tandem with a single LED unit, and the energy-band diagrams under infrared light input (Copyright © 2025, Wiley-VCH GmbH)^[80]

电探测器接收时, 血液内血红蛋白与氧合血红蛋白对 NIR 光吸收的差异可实时转换为周期性光电流信号(图 5(a)). 通过解析单个脉搏波的收缩期与舒张期特征, 可进一步计算血氧饱和度等生理指标, 为临床诊断提供关键依据^[86].

Tao 等人^[21]将高性能 NIR-OPD 集成于动脉监测与病理成像系统(图 5(b)), 实现了手臂不同部位 PPG 信号的实时采集与心动周期特征分析. Liu 等人^[87]则利用生物组织在 NIR 波段的透明性及静脉血管的高吸收特性, 借助大面积透明 UCD 完成手臂局部血管成像(图 5(c)). 与可见光成像相比, NIR 图像可呈现更为清晰的静脉拓扑结构. Li 等人^[88]进一步采用反射式 UCD 对手掌血管分布及血流脉动进行同步监测(图 5(d)), 为临床提供了

直观、无创的诊断手段.

此外, 生物微结构的非侵入式无创检测也是可视化探测发展重要趋势^[23,48,89,90]. 基于电荷耦合器件(charge coupled device, CCD)的红外可视化平台已被用于生物标本的无损检测^[23], 与可见光图像相比, 红外可视化图像可分辨高密度、复杂组织结构, 呈现更丰富的细节特征(图 5(e)). 因此, 高质量红外生物成像在不破坏样品完整性的前提下, 为医疗诊断与生命科学研究提供了新的技术路径.

3.2 可穿戴电子与交互式彩色显示

将红外可视化成像与可穿戴电子深度融合, 是面向智能时代的重要发展方向. Liu 等人^[78]提出一种双视

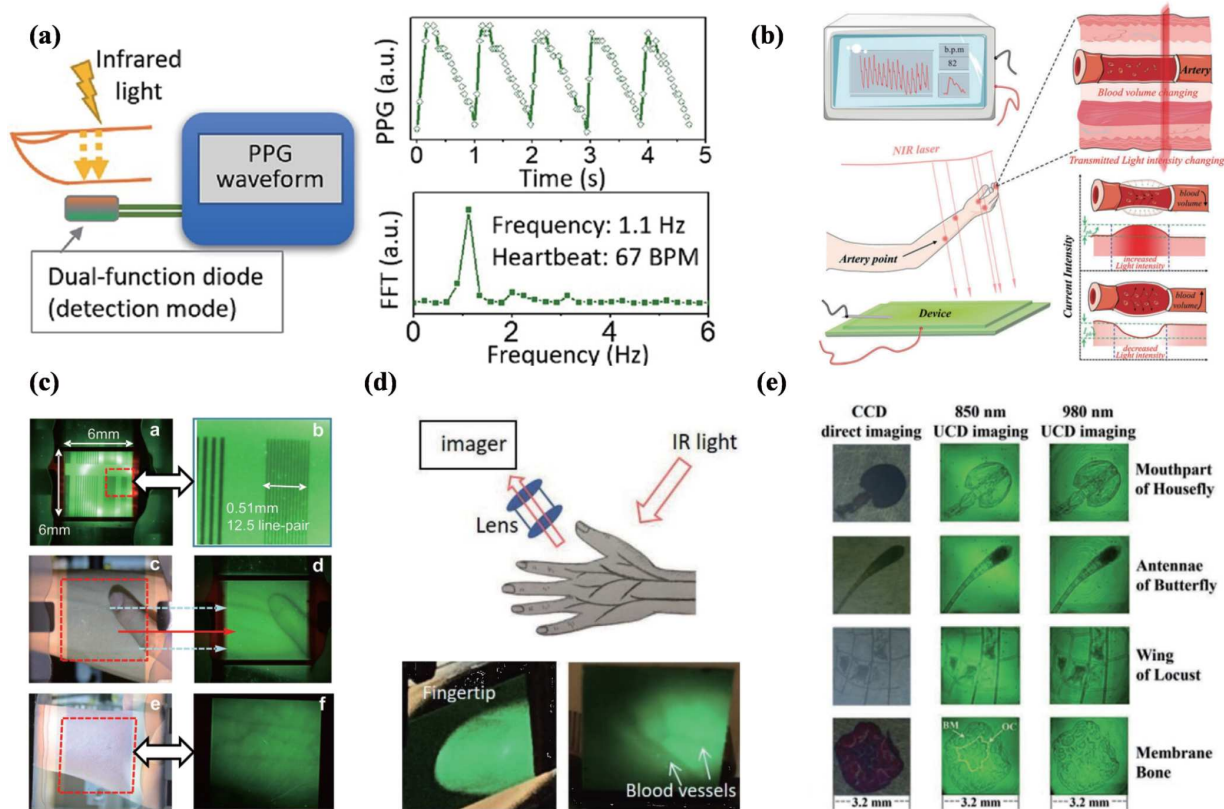


图 5 (网络版彩色)医疗监测与生物成像. (a) PPG监测系统原理图. 利用双功能检测器监测到的PPG波形, 以及经傅里叶变换处理的频域信号(Copyright © 2024, Elsevier)^[86]; (b) 透射式动脉脉搏实时监测的测试原理图(左侧代表测试方法, 实时显示测试结果, 右侧代表测试原理)^[21]; (c) 用于局部血管绘图NIR上变频器^[87]; (d) 成像仪对手反射的红外光进行可视化成像, 显示指尖和血管特征(Copyright © 2021, Wiley-VCH GmbH)^[88]; (e) 850和980 nm波长照射下, 利用UCD对生物样本进行的可视化成像(Copyright © 2021, Wiley-VCH GmbH)^[23]

Figure 5 (Color online) Health monitoring and bioimaging. (a) Schematic diagram of the PPG monitoring system, illustrating the monitored PPG waveform obtained using a dual-function detector and the processed frequency-domain signal by Fourier transform (Copyright © 2024, Elsevier)^[86]; (b) schematic diagram depicting the method for real-time transmissive arterial pulse monitoring, with the left side illustrating the test method and real-time display of results, while the right side outlines the test principle^[21]; (c) NIR up-converters for localized vascular mapping^[87]; (d) imager visualization of infrared light reflected from the human hand, showing fingertip and vascular features (Copyright © 2021, Wiley-VCH GmbH)^[88]; (e) visualization of biological samples using UCD under 850 and 980 nm wavelengths (Copyright © 2021, Wiley-VCH GmbH)^[23]

听协同的上转换护目镜(图6(a)). 通过大面积半透明UCD与护目镜集成, 利用不同图案及对应音频信号的同步输出, 显著增强了信息交互能力. 该团队进一步开发出半透明、大面积、高分辨率、单像素、低功耗的“反偷拍”检测仪(图6(b)), 在弱光环境下实现面部识别与红外信号原位监测^[47]. 最近, Jiang等人^[22]在此基础上, 采用大面积主动光源辅助, 构建响应波长1200 nm、响应功率低至微瓦级的可穿戴红外成像仪(图6(c,d)), 可在1~2 m范围内, 内实时捕获激光雷达940 nm信号, 显著提升了反监控应用的灵活性. 这种简单、轻便、可穿戴的防探测面板代表了红外可穿戴显示电子的重

大进步, 有望激发新颖的立体视觉应用, 并加速UCD的商业化进程. 多色显示能够传递更丰富的信息, 并增强人机交互体验. 这对于人机交互的智能显示和可穿戴电子领域具有重要的应用前景. Tang等人^[91]利用多刺激响应硅传感器与颜色可调的OLED集成, 首次实现了红外光、温度与多颜色输出的智能交互器件(图6(e)). 通过引入激子阻挡层精确调控OLED发射光谱, 器件可在不同激励下呈现宽色域变化, 实现直观反馈. 然而, 多颜色发光单元不仅增加了制备工艺的复杂性, 激子阻挡层材料的选择与优化也需要严格控制. 因此, Lei等人^[92]提出溶液法集成有机红外传感器与彩色QLED

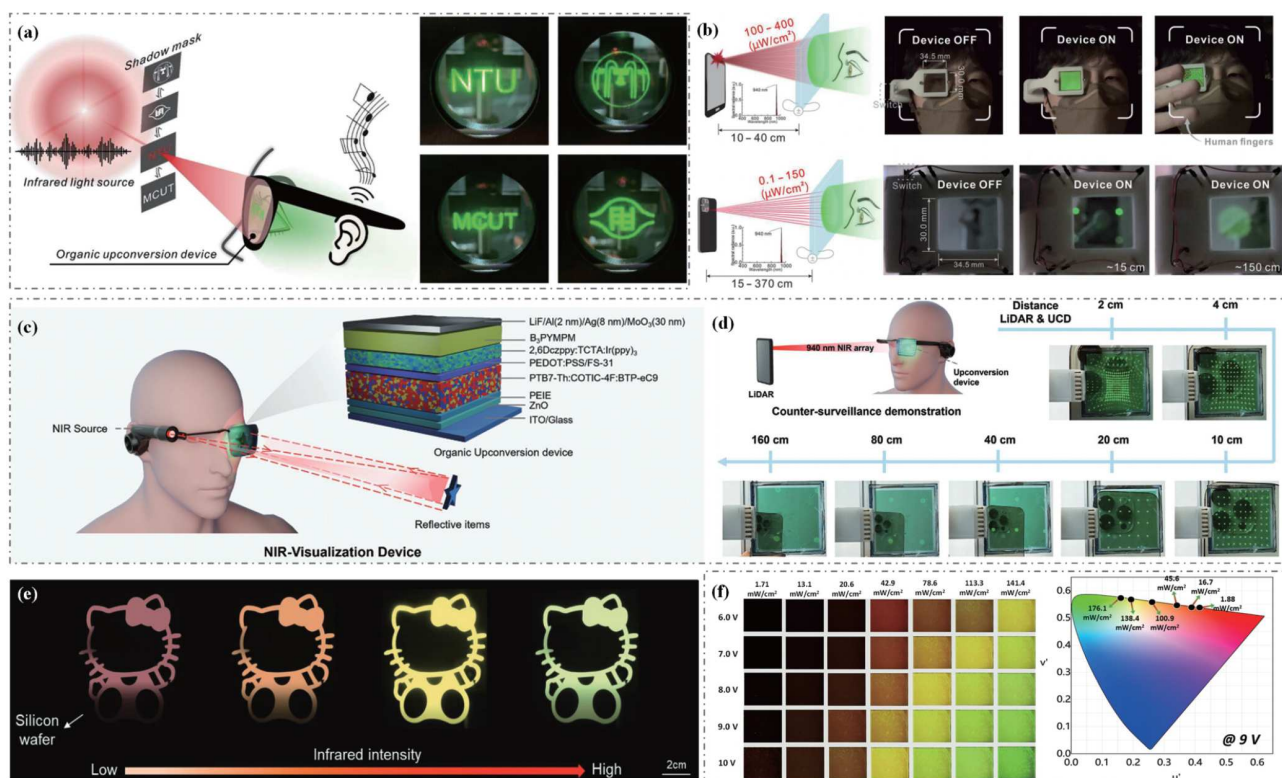


图 6 (网络版彩色)可穿戴电子与交互式彩色显示. (a) 由阴影掩膜(直流部分)和触发光源的音频信号(交流部分)定义的红外图像的无线双模式操作, 以及在透视上转换护目镜显示的红外图像照片^[78]; (b) 通过可穿戴、半透明、大面积和单像素上转换实现面部识别技术的红外可视化(940 nm红外刺激)和通过上转换面板对激光雷达功能进行940 nm红外可视化的演示过程^[47]; (c) 可穿戴主动式NIR可视化设备示意图和UCD结构; (d) 反监视演示示意图, 由数码相机拍摄的激光雷达与UCD之间不同距离的图像(Copyright © 2025, Wiley Online Library)^[22]; (e) 利用多刺激响应性硅传感器与颜色可调OLED集成器件在不同红外强度下的照片(Copyright © 2023, Wiley Online Library)^[91]; (f) 由NIR功率强度调制的颜色可调UCD的可视化图像以及CIE 1976色度坐标随NIR功率强度的变化(Copyright © 2023, AIP Publishing)^[92]

Figure 6 (Color online) Wearable electronics and interactive color displays. (a) Wireless dual-mode operation of an infrared image defined by a shadow mask (DC part) and an audio signal triggering the light source (AC part), and a photograph of an infrared image displayed by see-through up-converting goggles^[78]. (b) Infrared visualization (940-nm infrared stimulus) of the facial recognition technology by the wearable, semitransparent, large-area, and single-pixel upconversion panel and 940-nm infrared visualization of the LiDAR function by the upconversion panel^[47]. (c) Scheme of wearable active NIR visualization device and the structure of UCD. (d) Schematic illustrating the countersurveillance demonstration, images taken by digital camera at different distances between LiDAR and UCD (Copyright © 2025, Wiley Online Library)^[22]. (e) Photographs of an integrated device using a multi-stimulus responsive silicon sensor with color-tunable OLEDs at different infrared intensities (Copyright © 2023, Wiley Online Library)^[91]. (f) Visual NIR images of the color-tunable UCDs modulated by NIR power intensity, along with the evolution of CIE 1976 chromaticity coordinates with NIR power intensity (Copyright © 2023, AIP Publishing)^[92]

的新策略,如图6(f)所示.通过将红、绿QDs按优化比例共混形成单一发光层,在简化器件结构的同时实现了色域可调.然而,目前色彩调制范围仍受限于载流子平衡及暗电流抑制水平,后续需进一步优化材料体系与界面工程.

3.3 多功能可视化成像

与NIR相比,SWIR具有更强的穿透与散射抑制能力,可在烟雾或硅片遮挡条件下实现高对比度成像(图7(a))^[88].因此,开发基于SWIR的UCD将进一步突破成像技术的物理限制,实现夜间、雾霾、烟雾等多场景下的高对比度成像.其次,利用UCD无像素的特点,可以设计特定的掩膜来控制NIR光的形状,最终输出可视化图像. Lei等人利用UCD对不同图案和字母进行成像演示结果^[49],如图7(b)所示.

值得注意的是,图像质量主要受光学路径扰动及器件内横向载流子扩散的共同限制.此外, Ning等人^[93]进一步将UCD用于加密信息直接读取.如图7(c)

所示,过氧化物隐藏的“SHT”字符在可见光下不可见,而940 nm照射下可清晰呈现,展示了其在防伪与信息加密中的应用潜力.最近, Li等人^[24]则构建了基于双UCD的可见光通信链路,通过ASCII编码成功传输“HELLO”信息,收发端信号高度一致(图7(d)).该团队还将UCD用于微珠污染物的现场检测,凸显了其在环境监测与食品安全领域的广阔前景.

综上所述,基于光电上转换的红外可视化成像技术凭借低成本、低功耗、大面积、柔性及可穿戴等优势,已在脉搏监测、生物成像、面部识别、激光雷达探测及交互式彩色显示等领域展现出巨大潜力,有望成为新一代红外成像技术的核心候选方案.

4 总结与展望

4.1 现存挑战

尽管基于光电上转换的红外可视化探测技术已取得显著进展,但在迈向商业化与规模化应用的过程中,

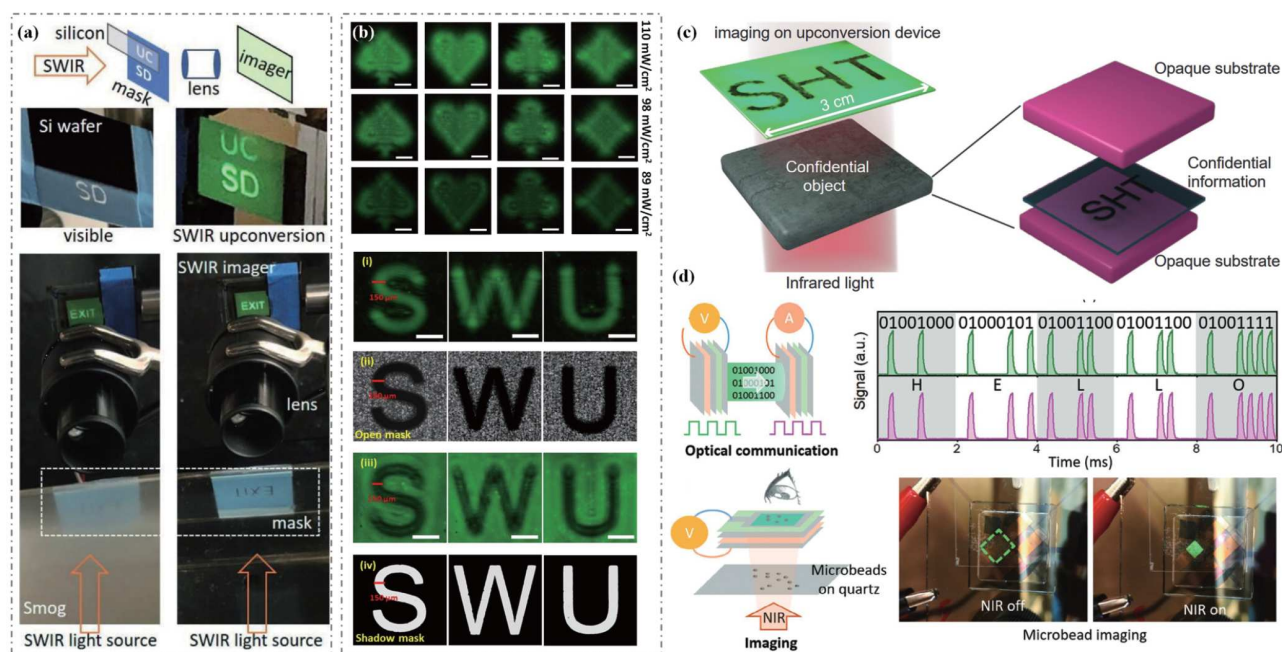


图 7 (网络版彩色)多功能可视化成像. (a) 利用SWIR光较强的透射能力,对硅片和烟雾后面的物体进行成像(Copyright © 2021, Wiley-VCH GmbH)^[88]; (b) 在不同的NIR功率强度和偏置电压下,通过UCD对不同形状图案进行无像素成像(Copyright © 2023, Wiley-VCH GmbH)^[49]; (c) 隐藏在两层胶片之间的机密信息在可见光下不透明,在红外光照射下,机密信息显示在UCD上,图像为红外光照射下的成像照片(Copyright © 2025, Elsevier)^[93]; (d) 由两个UCD组成的可见光通信系统,和使用UCD对微珠进行成像的演示(Copyright © 2024, Wiley-VCH GmbH)^[24]

Figure 7 (Color online) Multifunctional visualization imaging. (a) Imaging of silicon wafers and objects behind the smoke by using the strong transmittance of SWIR light (Copyright © 2021, Wiley-VCH GmbH)^[88]. (b) Pixel-free imaging of different shapes of patterns by UCDs under different NIR power intensities and bias voltages (Copyright © 2023, Wiley-VCH GmbH)^[49]. (c) Confidential information hidden between two layers of film is opaque under visible light, and under infrared light, the secret information is displayed on the UCD. A photograph of the imaging under infrared illumination is shown (Copyright © 2025, Elsevier)^[93]. (d) A visible light communication system consisting of two UCDs, and the demonstration of imaging a microbead by using the UCDs (Copyright © 2024, Wiley-VCH GmbH)^[24]

仍面临以下关键瓶颈。

(1) 材料性能的局限性。首先, 有机半导体材料吸收边普遍位于NIR, SWIR及中红外响应不足, 难以满足侦察、热成像等高灵敏度场景需求。其次, QDs虽具宽谱可调优势, 但含Pb、Hg等重金属带来的毒性与环境风险, 已成为其产业化落地的“红线”。此外, 无机体系成本高、外延温度高, 与柔性电子发展趋势相悖, 限制了其在可穿戴及大面积场景中的拓展。

(2) 效率与弱光响应不足。当前, 红外可视化探测器的关键指标, 包括比探测率($10^9 \sim 10^{12}$ Jones)^[51,91]、外部量子效率(40%~70%)^[47,78,80]以及响应度(0.1~0.6 A/W)^[24,51,91]在NIR波段可以达到较高水平。然而, 器件的整体上转换效率(光子-光子)仍普遍低于10%^[24,49,68,75,79,93], 这主要受限于载流子注入失衡、界面复合及光子再吸收损耗; 串联结构虽可提升效率至30%以上^[77,78,94], 却伴随工艺复杂度上升与良率下降。其次, 弱光响应能力($0.01 \sim 1000 \mu\text{W}/\text{cm}^2$)^[22,23,46,47]与线性动态范围(50~90 dB)^[22,23,48]仍难以覆盖实际场景的宽辐照波动; 此外, 长期工作中, 有机材料的氧化降解及QDs的光漂白问题进一步削弱器件稳定性。

(3) 工艺与集成化难题。首先, 溶液法多层堆叠时, 溶剂正交性、界面缺陷及层间互溶难以兼顾, 尤其在大面积串联器件中尤为突出。其次, 高分辨率成像需抑制横向载流子扩散, 但材料本征迁移率与现有图形化精度限制了像素密度的持续提升。此外, 大面积、透明、多模态集成对器件结构、驱动电路及封装技术提出更高要求, 尚无成熟方案。

4.2 未来展望

为突破上述瓶颈, 后续研究可从以下四个维度协

同推进。

(1) 新材料创制。开发窄带隙非富勒烯受体、donor-acceptor-donor(D-A-D)型共轭聚合物, 延伸有机材料吸收至SWIR; 重点攻关无铅钙钛矿、铜基或铜基QDs, 兼顾高性能与环境友好性; 利用二维材料高迁移率与钙钛矿强吸收协同, 构筑高效、柔性、透明光敏平台。

(2) 结构创新。通过能级梯度设计, 实现电子与空穴在串联单元中的对称提取, 降低驱动电压; 构建“探测波长→发光颜色”直接关联的像素化器件, 实现多波段信息的彩色可视化; 将微型驱动电路、传感阵列与UCD像素阵列单片集成, 提升系统集成度与可靠性。

(3) 工艺优化。在器件设计阶段, 协同优化光场分布与能带匹配, 调控各层光学厚度, 使入射红外光场局域于PSL以最大化吸收, 同时确保EML发射的可见光高效出射, 从而系统提升器件的量子效率。另外, 发展喷墨打印、转印、卷对卷涂布等低温工艺, 兼容poly(ethylene terephthalate)(PET)、poly(ethylene naphthalate)(PEN)等柔性衬底, 推动低成本大面积制造; 引入自组装单分子层、化学交联层或原子层沉积钝化层, 抑制界面缺陷与溶剂渗透; 开发柔性、透明、阻水氧封装方案, 延长器件在复杂环境中的服役寿命。

(4) 应用拓展。探索高穿透成像用于术中血管显影、早期肿瘤筛查; 将UCD集成至AR/VR(augmented reality/virtual reality)头盔、智能护目镜, 实现手势识别、信息加密显示与多模态交互; 基于波长选择性UCD的“光学指纹”标签, 用于证件、药品及高价值商品的溯源与防伪。

综上所述, 通过跨学科协作与技术创新, 基于UCD的红外可视化成像技术有望在医疗诊断、环境监测及人机交互等领域实现革命性突破, 推动其商业化进程。

参考文献

- 1 Han X, Xu Z, Wu W, et al. Recent progress in optoelectronic synapses for artificial visual-perception system. *Small Struct*, 2020, 1: 2000029
- 2 Rao T, Chen M, Mu G, et al. Infrared-to-visible upconversion devices. *Coatings*, 2022, 12: 456
- 3 Chen J, Tao J, Ban D, et al. Hybrid organic/inorganic optical up-converter for pixel-less near-infrared imaging. *Adv Mater*, 2012, 24: 3138–3142
- 4 Qin T, Mu G, Zhao P, et al. Mercury telluride colloidal quantum-dot focal plane array with planar p-n junctions enabled by *in situ* electric field-activated doping. *Sci Adv*, 2023, 9: eadg7827
- 5 Zhang S, Bi C, Qin T, et al. Wafer-scale fabrication of CMOS-compatible trapping-mode infrared imagers with colloidal quantum dots. *ACS Photonics*, 2023, 10: 673–682
- 6 Zhang S, Bi C, Tan Y, et al. Direct optical lithography enabled multispectral colloidal quantum-dot imagers from ultraviolet to short-wave infrared. *ACS Nano*, 2022, 16: 18822–18829
- 7 Hu Y, Wang K, Chen L, et al. Visualization of invisible near-infrared light. *TIMS*, 2024, 2: 100067
- 8 Kim D Y, Lai T H, Lee J W, et al. Multi-spectral imaging with infrared sensitive organic light emitting diode. *Sci Rep*, 2014, 4: 5946

- 9 Li N, Lau Y S, Xiao Z, et al. NIR to visible light upconversion devices comprising an NIR charge generation layer and a perovskite emitter. *Adv Opt Mater*, 2018, 6: 1801084
- 10 Yu B H, Cheng Y, Li M, et al. Sub-band gap turn-on near-infrared-to-visible up-conversion device enabled by an organic-inorganic hybrid perovskite photovoltaic absorber. *ACS Appl Mater Interfaces*, 2018, 10: 15920–15925
- 11 Kim J H, Lee J, Lim C, et al. Highly efficient top-emitting infrared-to-visible up-conversion device enabled by microcavity effect. *Adv Funct Mater*, 2023, 33: 2214530
- 12 Wu M, Congreve D N, Wilson M W B, et al. Solid-state infrared-to-visible upconversion sensitized by colloidal nanocrystals. *Nat Photon*, 2016, 10: 31–34
- 13 Nienhaus L, Correa-Baena J P, Wieghold S, et al. Triplet-sensitization by lead halide perovskite thin films for near-infrared-to-visible upconversion. *ACS Energy Lett*, 2019, 4: 888–895
- 14 Xu Z, Huang Z, Li C, et al. Tuning the quantum dot (QD)/mediator interface for optimal efficiency of QD-sensitized near-infrared-to-visible photon upconversion systems. *ACS Appl Mater Interfaces*, 2020, 12: 36558–36567
- 15 Xu J, Xu L, Wang C, et al. Near-infrared-triggered photodynamic therapy with multitasking upconversion nanoparticles in combination with checkpoint blockade for immunotherapy of colorectal cancer. *ACS Nano*, 2017, 11: 4463–4474
- 16 Liu Y, Lu Y, Yang X, et al. Amplified stimulated emission in upconversion nanoparticles for super-resolution nanoscopy. *Nature*, 2017, 543: 229–233
- 17 Wen S, Zhou J, Zheng K, et al. Advances in highly doped upconversion nanoparticles. *Nat Commun*, 2018, 9: 2415
- 18 Zhang L, Sun Y, Jiang Y, et al. Transparent fluoride glass-ceramics with phase-selective crystallization for middle IR photonics. *J Mater Chem C*, 2022, 10: 12947–12956
- 19 Zhang L, Liu R, Wang Z, et al. Er^{3+} concentration-dependent microstructural and upconversion luminescence process of transparent perfluoride composite glass. *J Eur Ceramic Soc*, 2022, 42: 4335–4342
- 20 Zhang L, Yan T, Jiang Y, et al. Stokes/anti-Stokes luminescence in Er^{3+} -doped fluoride glass enabled dual-mode ultraviolet/infrared photodetection and visible-display integration for secure optical communication. *Sci Bull*, 2025, 70: 3553–3561
- 21 He Z, Du X, Zheng C, et al. High-quality artery monitoring and pathology imaging achieved by high-performance synchronous electrical and optical output of near-infrared organic photodetector. *Adv Sci*, 2023, 10: 2203870
- 22 Dong S, Li J, Ma T, et al. Ternary compensation enables high-sensitive efficient upconversion device for NIR visualization. *Adv Mater*, 2025, 37: 2412678
- 23 Du X, Han J, He Z, et al. Efficient organic upconversion devices for low energy consumption and high-quality noninvasive imaging. *Adv Mater*, 2021, 33: 2102812
- 24 Li N, Hu X, Lu Y, et al. Wavelength-selective near-infrared organic upconversion detectors for miniaturized light detection and visualization. *Adv Funct Mater*, 2024, 34: 2411626
- 25 Minotto A, Haigh P A, Łukasiewicz Ł G, et al. Visible light communication with efficient far-red/near-infrared polymer light-emitting diodes. *Light Sci Appl*, 2020, 9: 70
- 26 Chen M, Lu H, Abdelazim N M, et al. Mercury telluride quantum dot based phototransistor enabling high-sensitivity room-temperature photodetection at 2000 nm. *ACS Nano*, 2017, 11: 5614–5622
- 27 Schreiner K. Night vision: infrared takes to the road. *IEEE Comput Grap Appl*, 1999, 19: 6–10
- 28 Fu C, Mu G, Weng K, et al. Advances in organic upconversion devices. *Photonics*, 2024, 11: 808
- 29 Hu X, Xiao G, Li Y, et al. Infrared-light visualization by organic upconversion devices. *ACS Appl Electron Mater*, 2023, 5: 5378–5385
- 30 Luo C, Zheng Z, Ding Y, et al. High-resolution, highly transparent, and efficient quantum dot light-emitting diodes. *Adv Mater*, 2023, 35: 2303329
- 31 Meng T, Zheng Y, Zhao D, et al. Ultrahigh-resolution quantum-dot light-emitting diodes. *Nat Photon*, 2022, 16: 297–303
- 32 Shen H, Gao Q, Zhang Y, et al. Visible quantum dot light-emitting diodes with simultaneous high brightness and efficiency. *Nat Photon*, 2019, 13: 192–197
- 33 Luo Y, Tan Y, Bi C, et al. Megapixel large-format colloidal quantum-dot infrared imagers with resonant-cavity enhanced photoresponse. *APL Photonics*, 2023, 8: 056109
- 34 Zhao P, Qin T, Mu G, et al. Band-engineered dual-band visible and short-wave infrared photodetector with metal chalcogenide colloidal quantum dots. *J Mater Chem C*, 2023, 11: 2842–2850
- 35 Zhang W, Fang F, Zhong H, et al. Converting perovskite nanocrystals to PbS quantum dots toward short-wave infrared photodetectors. *Adv Opt Mater*, 2025, 13: 2402740
- 36 Liu Y, Wu H, Shi G, et al. Merging passivation in synthesis enabling the lowest open-circuit voltage loss for PbS quantum dot solar cells. *Adv Mater*, 2023, 35: 2207293
- 37 Tang H, Cheng S, Chen W, et al. High-performance shortwave infrared detection and imaging based on colloidal quantum dots (in Chinese). *Chin*

- [Sci Bull](#), 2025, doi: 10.1360/CSB-2025-5138 [唐浩东, 程硕, 陈威, 等. 高性能胶体量子点短波红外探测及成像技术. 科学通报, 2025, doi: 10.1360/CSB-2025-5138]
- 38 Wu Q, Gong X, Zhao D, et al. Efficient tandem quantum-dot LEDs enabled by an inorganic semiconductor-metal-dielectric interconnecting layer stack. [Adv Mater](#), 2022, 34: 2108150
 - 39 Cao F, Liu Y, Zhang X, et al. Lead-free single crystal metal halide perovskite detectors. [Mater Sci Eng-R-Rep](#), 2025, 164: 100991
 - 40 Chi W, Banerjee S K. Performance improvement of perovskite solar cells by interactions between nano-sized quantum dots and perovskite. [Adv Funct Mater](#), 2022, 32: 2200029
 - 41 Jeong J, Park J H, Jang C H, et al. Multifunctional charge transporting materials for perovskite light-emitting diodes. [Adv Mater](#), 2020, 32: 2002176
 - 42 Cao F, Hong E, Li Z, et al. Real-time UVC imaging and high safety communication based on dual-detectable lead-free perovskite heterostructure. [Adv Funct Mater](#), 2025, 35: 2422161
 - 43 Cao F, Hu Z, Yan T, et al. A dual-functional perovskite-based photodetector and memristor for visual memory. [Adv Mater](#), 2023, 35: 2304550
 - 44 Wu X, Song J, Zhao W, et al. The current status and challenges of two-dimensional infrared detectors based on interlayer excitons (in Chinese). [Chin Sci Bull](#), 2025, doi: 10.1360/CSB-2025-5043 [吴夏睿, 宋俊明, 赵伟玮, 等. 基于层间激子的二维红外探测器的现状和挑战. 科学通报, 2025, doi: 10.1360/CSB-2025-5043]
 - 45 Ji H, Song Z, Wu A, et al. Recent advances in the fundamentals and *in situ* characterizations for mechanics in 2D materials. [Nanoscale](#), 2025, 17: 7574–7599
 - 46 Shih C, Li Y, Li M, et al. Transparent organic upconversion device targeting high-grade infrared visual image. [Nano Energy](#), 2021, 86: 106043
 - 47 Shih C, Huang Y, Wang T, et al. Transparent organic upconversion devices displaying high-resolution, single-pixel, low-power infrared images perceived by human vision. [Sci Adv](#), 2023, 9: eadd7526
 - 48 Dong S, Zhang Y, Wang Z, et al. Solution-processed efficient organic upconversion device for direct NIR imaging. [Adv Opt Mater](#), 2024, 12: 2400912
 - 49 Hu Y, Chen L, Li H, et al. Decoupling the trade-off between the photosignal and photon noise in upconversion devices through a solution-processed nickel oxide interconnecting layer. [Adv Opt Mater](#), 2024, 12: 2302021
 - 50 Zhou W, Shang Y, García de Arquer F P, et al. Solution-processed upconversion photodetectors based on quantum dots. [Nat Electron](#), 2020, 3: 251–258
 - 51 He Z, Zhang H, Du X, et al. A high-performance dual-functional organic upconversion device with detectivity approaching 10^{13} Jones and photon-to-photon efficiency over 20%. [Mater Horiz](#), 2023, 10: 5950–5961
 - 52 Lv W, Zhong J, Peng Y, et al. Organic near-infrared upconversion devices: design principles and operation mechanisms. [Org Electron](#), 2016, 31: 258–265
 - 53 Lv W, Zheng H, Li X, et al. Enhancing upconversion efficiency of organic near infrared upconversion devices based on inverted phosphorescent OLEDs as emitters by introducing connecting layer. [IEEE Trans Electron Devices](#), 2024, 71: 2165–2170
 - 54 Kruse P W, Pribble F C, Schulze R G. Solid-state infrared-wavelength converter employing high-quantum-efficiency Ge-GaAs heterojunction. [J Appl Phys](#), 1967, 38: 1718–1720
 - 55 Liu H, Li J, Wasilewski Z, et al. Integrated quantum well intersubband photodetector and light-emitting diode for thermal imaging. [Proc SPIE](#), 1995, 2552: 336–342
 - 56 Ban D, Luo H, Liu H C, et al. Optimized GaAs/AlGaAs light-emitting diodes and high efficiency wafer-fused optical up-conversion devices. [J Appl Phys](#), 2004, 96: 5243–5248
 - 57 Yang Y, Shen W Z, Liu H C, et al. Near-infrared photon upconversion devices based on GaNAsSb active layer lattice matched to GaAs. [Appl Phys Lett](#), 2009, 94: 093504
 - 58 Jingping Ni J N, Takanori Tano T T, Yoshiro Ichino Y I, et al. Organic light-emitting diode with TiOPc layer—A new multifunctional optoelectronic device. [Jpn J Appl Phys](#), 2001, 40: L948
 - 59 Kim D Y, Song D W, Chopra N, et al. Organic infrared upconversion device. [Adv Mater](#), 2010, 22: 2260–2263
 - 60 Li D, Hu Y, Zhang N, et al. Near-infrared to visible organic upconversion devices based on organic light-emitting field effect transistors. [ACS Appl Mater Interfaces](#), 2017, 9: 36103–36110
 - 61 Tachibana H, Aizawa N, Hidaka Y, et al. Tunable full-color electroluminescence from all-organic optical upconversion devices by near-infrared sensing. [ACS Photonics](#), 2017, 4: 223–227
 - 62 Song Q, Lin T, Su Z, et al. Organic upconversion display with an over 100% photon-to-photon upconversion efficiency and a simple pixelless device structure. [J Phys Chem Lett](#), 2018, 9: 6818–6824
 - 63 Yeddu V, Seo G, Cruciani F, et al. Low-band-gap polymer-based infrared-to-visible upconversion organic light-emitting diodes with infrared sensitivity up to 1.1 μm . [ACS Photonics](#), 2019, 6: 2368–2374

- 64 Chen J, Ban D, Helander M G, et al. Near-infrared inorganic/organic optical upconverter with an external power efficiency of >100%. *Adv Mater*, 2010, 22: 4900–4904
- 65 Kim D Y, Choudhury K R, Lee J W, et al. PbSe nanocrystal-based infrared-to-visible up-conversion device. *Nano Lett*, 2011, 11: 2109–2113
- 66 Ban D, Han S, Lu Z H, et al. Near-infrared to visible light optical upconversion by direct tandem integration of organic light-emitting diode and inorganic photodetector. *Appl Phys Lett*, 2007, 90: 093108
- 67 Yu H, Kim D, Lee J, et al. High-gain infrared-to-visible upconversion light-emitting phototransistors. *Nat Photon*, 2016, 10: 129–134
- 68 Wang K, Hu Y, Chen L, et al. High-performing organic/quantum dot hybrid upconversion device based on a single-component near-infrared-sensitive layer. *Appl Phys Lett*, 2024, 125: 113302
- 69 Chen L, Chen S, Uma K, et al. High-leakage-resistance and low-turn-on-voltage upconversion devices based on perovskite quantum dots. *Adv Funct Mater*, 2024, 34: 2309589
- 70 Tang H, Shi K, Zhang N, et al. Up-conversion device based on quantum dots with high-conversion efficiency over 6%. *IEEE Access*, 2020, 8: 71041–71049
- 71 Jiang Z, Lin H, Chen Y, et al. An electrical and infrared controllable color emission quantum dot light-emitting diode. *AIP Adv*, 2022, 12: 085013
- 72 Liu J, Yang X, Xu Q, et al. Unraveling the efficiency losses and improving methods in quantum dot-based infrared up-conversion photodetectors. *OES*, 2024, 3: 230029
- 73 Zhang N, Tang H, Shi K, et al. High-performance all-solution-processed quantum dot near-infrared-to-visible upconversion devices for harvesting photogenerated electrons. *Appl Phys Lett*, 2019, 115: 221103
- 74 Mu G, Rao T, Zhang S, et al. Ultrasensitive colloidal quantum-dot upconverters for extended short-wave Infrared. *ACS Appl Mater Interfaces*, 2022, 14: 45553–45561
- 75 Xu Q, Yang X, Liu J J, et al. Elaborating the interplay between the detecting unit and emitting unit in infrared quantum dot up-conversion photodetectors. *Nanoscale*, 2023, 15: 8197–8203
- 76 He S J, Wang D K, Yang Z X, et al. Integrated tandem device with photoactive layer for near-infrared to visible upconversion imaging. *Appl Phys Lett*, 2018, 112: 243301
- 77 Yang D, Zhou X, Ma D, et al. Near infrared to visible light organic up-conversion devices with photon-to-photon conversion efficiency approaching 30%. *Mater Horiz*, 2018, 5: 874–882
- 78 Shih C, Lin C, Chen K, et al. Semi-transparent, pixel-free upconversion goggles with dual audio-visual communication. *Adv Sci*, 2023, 10: 2302631
- 79 Kwon T H, Kim H B, Kwak D G, et al. Quantum dot-based three-stack tandem near-infrared-to-visible optoelectric upconversion devices. *ACS Nano*, 2024, 18: 21957–21965
- 80 Han X, Han C, He M, et al. Ultralow turn-on voltage organic upconversion devices for high-resolution imaging based on near-infrared homotandem photodetector. *Laser Photonics Rev*, 2025, 19: 2401375
- 81 He Z, Du X, Yu X, et al. Reverse-distribution phase featured gradient heterojunction: a universal strategy to realize high-performance near-infrared organic photodetectors for real-time arterial monitoring. *Nano Energy*, 2023, 114: 108673
- 82 Huang J, Lee J, Vollbrecht J, et al. A high-performance solution-processed organic photodetector for near-infrared sensing. *Adv Mater*, 2020, 32: 1906027
- 83 Jacoutot P, Scaccabarozzi A D, Nodari D, et al. Enhanced sub-1 eV detection in organic photodetectors through tuning polymer energetics and microstructure. *Sci Adv*, 2023, 9: eadh2694
- 84 Zhao X, Wang J, Liu M, et al. Narrowband organic photodetectors: from fundamentals to prospects. *Adv Opt Mater*, 2024, 12: 2401087
- 85 Yan T, Li Z, Cao F, et al. An all-organic self-powered photodetector with ultraflexible dual-polarity output for biosignal detection. *Adv Mater*, 2022, 34: 2201303
- 86 Li N, Hu X, Tang Y, et al. Perovskite/organic tandem device to realize light detection and emission dual function. *Chem Eng J*, 2024, 490: 151573
- 87 Yuan C H, Lee C C, Liu C F, et al. Cathodic-controlled and near-infrared organic upconverter for local blood vessels mapping. *Sci Rep*, 2016, 6: 32324
- 88 Li N, Eedugurala N, Leem D, et al. Organic upconversion imager with dual electronic and optical readouts for shortwave infrared light detection. *Adv Funct Mater*, 2021, 31: 2100565
- 89 Zhang Y, He Z, Du X, et al. High-performance organic upconversion device with 12% photon to photon conversion efficiency at 980 nm and bio-imaging application in near-infrared region. *Opt Express*, 2022, 30: 16644
- 90 Wang X, Hu Y, Chen L, et al. Performance improvement of an upconversion device through optimized carrier injection balance. *Opt Lett*, 2025, 50: 1361
- 91 Mu G, Rao T, Qi Y, et al. Color-tunable organic light-emitting displays for interactive multi-signal visualization. *Adv Funct Mater*, 2023, 33: 2301280

- 92 Hu Y, Jiang H, Chen L, et al. Colorful visualization detection of near-infrared light enabled by an upconversion device with a color-tunable quantum dot light-emitting unit. [Appl Phys Lett](#), 2023, 123: 213301
- 93 Wang H, Zhou W, Liu Y, et al. Infrared visualization based on quantum dot upconversion photodetector using perovskite emitter. [Device](#), 2025, 3: 100661
- 94 Han X, Han J, He M, et al. Achieving over 30% photon-to-photon efficiency with tandem OLED structures in organic upconversion devices. [J Mater Chem C](#), 2025, 13: 11814–11822

Summary for “基于光电上转换的红外可视化探测研究进展”

Advances in infrared visualization via photoelectric upconversion

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Photoelectric upconversion for infrared visualization detection is an emerging and transformative area in optoelectronics, enabling the perception of light beyond the visible spectrum. This technology integrates a near-infrared (NIR) or short-wave infrared (SWIR) photodetector (PD) with a visible light-emitting diode (LED) within a single device, facilitating the direct conversion of infrared photons to electrons and subsequently to visible photons. This innovative approach marks a significant departure from traditional pixelated sensor technologies, offering numerous advantages such as non-invasive, real-time imaging; enhanced sampling ease; compact and possibly flexible designs; and the capability to extend the human visual range. As a result, photoelectric upconversion techniques have shown tremendous potential across multiple fields, including biomedical diagnostics, public safety, national defense, and advanced industrial inspection.

This review comprehensively explores the latest research developments in this rapidly evolving field. We begin by dissecting the fundamental components of infrared upconversion devices (UCDs), providing detailed insights into their material systems, device architectures, and operational mechanisms. The materials landscape is systematically categorized and critically analyzed, encompassing organic semiconductors, quantum dots (QDs), perovskites, and two-dimensional materials. Each material class is examined for its unique advantages and constraints. For example, organic materials are valued for their cost-effective processing and mechanical flexibility, while quantum dots offer tunable band gaps that significantly enhance detection capabilities into the SWIR range. Our discussion highlights the remarkable research progress originating from advancements in materials science and device physics, showcasing how organic materials have achieved substantial improvements in optoelectronic performance through their synthetic adaptability. Moreover, we underscore the achievements of QD-based UCDs, which have facilitated access to longer wavelengths, although challenges regarding material toxicity and stability persist. An essential architectural innovation is the introduction of multi-unit tandem structures, which involve stacking multiple PD or LED subunits to optimize the utilization of photogenerated charge carriers. This architectural development increases both upconversion efficiency and operating voltage beyond conventional limitations.

Aside from examining the core optoelectronic performance, we consider the broadening application prospects of UCD technology. Its practical value has been validated across various real-world scenarios, such as biomedical monitoring techniques that include photoplethysmography (PPG) for heart rate and blood oxygen saturation measurements, as well as non-invasive vascular imaging, where non-invasive capabilities prove critical. The integration of UCDs into wearable devices has led to developments in smart eyewear and anti-surveillance technologies for augmented reality and security applications. Furthermore, their incorporation into interactive color displays and multifunctional optical communication systems demonstrates key benefits, including low power consumption, high resolution, and the potential for large-area, pixelless imaging.

Finally, we summarize current challenges in achieving widespread commercialization of this promising technology, such as the limited spectral range and environmental stability of specific materials, the pursuit of higher efficiency under weak light conditions, and the complexities of scalable manufacturing and integration processes. We propose forward-looking solutions that emphasize the importance of innovative material design, precise device engineering, and optimized fabrication techniques, aiming to provide a robust theoretical framework and practical guidance for the future optimization and real-world application of high-performance infrared imaging devices.

infrared imaging, upconversion, photodetector, light-emitting diode, visualization

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