

基于二维碲薄膜/金字塔硅异质结阵列的宽波段光电探测与成像器件

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摘要 光电探测器在现代光电器件中发挥着举足轻重的作用, 尤其是近红外波段的光电探测器在遥感通信、激光雷达等领域具有重要的应用。然而, 由于硅(Si)宽禁带的限制以及大多数近红外光电材料与传统集成电路的不兼容, 开发适合小型化和集成化的高性能、宽光谱近红外探测器仍然面临许多挑战。基于此, 本文提出构筑一种基于二维碲薄膜/金字塔硅异质结(Te/pyramid Si, Te/py-Si)的可见-近红外宽谱光电探测器。通过磁控溅射在金字塔硅上沉积图案化的Te薄膜, 获得Te/py-Si异质结阵列, 进而先后沉积氧化铝绝缘层和金电极, 制备出大面积Te/py-Si光电探测器阵列。金字塔硅表面微结构的限光效应可有效提高异质结对光的利用率, 且异质结界面处大的内建电场可有效促进光生载流子的分离。因此, 所得Te/py-Si异质结器件表现出显著的整流行为(4.1×10^2 的整流比)和优异的光响应性能, 包括从520 nm到1064 nm的宽光谱响应、6.95 mA/W的高响应度、 1.36×10^9 Jones的比探测率, 以及超快的响应速度(上升时间129 μ s, 下降时间237 μ s)。此外, Te/py-Si异质结器件阵列优异的光响应性质使其实现了不同波长下的高分辨光电成像。本工作构筑的Te/py-Si异质结探测器展现出良好的红外成像应用前景, 为构筑高性能、宽光谱响应的光电探测器提供了新的思路。

关键词 Te薄膜, 碲-硅异质结, 光电探测器, 近红外, 光电成像

光电探测器是一种将光信号转换为电信号的电子元器件, 被广泛应用于通信、检测和环境等各个领域^[1,2]。随着信息技术的飞速发展, 人们对光电探测器的性能和功能提出了更高要求, 例如更小尺寸、更高灵敏度、更宽光谱响应范围, 以及更多功能集成^[3]。在现有各类光电探测器中, 硅(Si)基器件因其成熟的制备

工艺、优异的光电转换性能以及显著的成本优势, 已成为应用最为广泛的光电器件。然而, 由于带隙的限制, 硅基光电探测器主要应用于可见波段, 其对近红外波段的探测受到限制^[4,5]。当前, 主流的近红外探测器(如PbS, InGaAs)普遍存在材料毒性大或制备流程复杂、成本高昂等问题^[6,7]。近年来, 范德华(van der

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Waals, vdW)材料凭借其独特的结构和物理化学特性,成为光电子器件领域备受关注的研究焦点材料^[8]。一系列具有窄带隙的vdW材料,如黑磷(BP)、二硒化钼(PdSe₂)以及碲(Te)等被陆续发掘出来,其在红外光电探测领域展现出巨大的应用潜力^[9-14]。例如,Yu等人开发的基于窄带隙的双层PtSe₂的光电探测器实现了从可见光至中红外波段(10.0 μm)的超宽光谱响应^[15]。此外,这类vdW材料表面不存在悬挂键,易于转移,在构筑异质结时无需严格的晶格匹配,因而能够便捷地与其他材料异质集成^[16-19]。研究者已成功将窄带隙vdW材料与硅材料集成(如PtSe₂-Si)^[20,21],结合其各自性质优势,构筑出优异性能的宽光谱光电探测器^[22,23]。为了进一步提升vdW材料-硅基光电器件的性能,亟需发展新的vdW材料体系和器件构架。金字塔硅(pyramid Si, py-Si)是一种表面布满了微米级尺寸金字塔形微结构的硅片。相比于平整硅表面,金字塔硅表面的微结构会将入射光限域在微结构的间隙中,使得入射光线在其表面发生多次反射和折射,即产生“陷光效应”^[24,25]。因此,将金字塔硅应用于构筑光电探测器,有望提高器件对入射光的吸收效率。

碲(Te)作为硫族(VIA)族元素之一,具有独特的准一维Te螺旋链vdW堆叠结构,是一种p型窄带隙半导体^[26-28]。研究者发现Te材料具有诸多优异的光学和电学性质,如:超高载流子迁移率(1430 cm² V⁻¹ s⁻¹)、厚度依赖的带隙(0.35~1.26 eV),在构筑新型电子和光电子器件方面展现出巨大的应用前景^[29,30]。Te薄膜具有窄的光学带隙,其在近红外光谱范围具有强的光-物质相互作用,这使其成为构筑高性能近红外光电探测器的理想候选材料^[31-33]。鉴于上述py-Si的“陷光效应”和Te薄膜优异的宽光谱吸收性质,构筑Te/py-Si异质结有望获得高性能的近红外光电探测器。同时,Te和py-Si分别为P型和N型半导体,因而Te/py-Si的集成可有效形成PN结,有望提升载流子的分离。

本文提出将二维Te薄膜与py-Si异质集成,构筑一种Te/py-Si异质结的宽光谱光电探测器。本文采用磁控溅射制备厘米级尺寸的Te薄膜,通过调整溅射参数在室温下制备了不同厚度的Te薄膜,并研究了其对可见-近红外光的反射情况。随后,使用硬掩膜方法在n型金字塔硅表面制备出图案化的Te薄膜,进而通过器件加工构筑出8×8的Te/py-Si光电探测器阵列。反射光谱和理论模拟显示,Te薄膜可降低近红外光的反射率,金字塔硅可提高可见光的利用率。光电测试显示Te/py-Si器

件具有显著的光电二极管效应,在可见光/近红外照射下展现出良好的宽光谱光电响应,其在980 nm照明下的开关比、响应率和比探测率分别达 4.1×10^2 、6.95 mA/W和 1.36×10^9 Jones。最后,对Te/py-Si光电探测器阵列及其像素单元进行可见光和近红外光电成像测试,所得图像具有清晰、锐利的轮廓,表明Te/py-Si光电探测器在未来的可见-近红外光电器件中有很好的应用前景。本工作为构筑高性能、可见到近红外的宽光谱光电探测器提供了一种新的思路。

1 实验与方法

本实验选用py-Si作为衬底兼n型半导体材料。为保证py-Si表面的清洁,将其用超纯水、丙酮、乙醇和超纯水先后超声清洗10分钟,以除去表面杂质与油污,进而使用高纯氮气吹干备用。使用碲靶材(99.99%)、氧化铝(Al₂O₃)靶材(99.99%)和高纯金(Au)丝(99.999%)分别作为Te、Al₂O₃和Au源。采用磁控溅射结合硬掩膜法,在py-Si表面先后沉积图案化的Al₂O₃薄膜和Te薄膜,进而通过热蒸镀法制备图案化Au电极,最终获得Te/py-Si光电探测器阵列。通过调节磁控溅射参数(功率和溅射时间),可以调控所得Te薄膜的厚度。

使用扫描电子显微镜(Nova NanoSEM 450, FEI)对金字塔硅进行表面形貌表征;使用原子力显微镜(Bruker Dimension ICON)对Te薄膜厚度进行测试;使用紫外近红外分光光度计(Lambda 950)进行反射率测试;使用显微共聚焦拉曼光谱仪(inVia Reflex)在532 nm激发波长下测试Te薄膜、py-Si以及Te/py-Si异质结的拉曼光谱。Te/py-Si异质结器件的电学与光电性能使用Agilent B2912A源仪表单元和Agilent Technologies B1500A在室温大气条件下进行测试,使用光源的波长为520、532、638、785、850、980和1064 nm。

2 结果与讨论

本文在py-Si上沉积了图案化的Al₂O₃和Te薄膜,制备出Te/py-Si异质结光电探测器阵列。图1(a)为Te/py-Si光电探测器阵列及像素单元器件的分层结构示意图,整个器件阵列由8×8个像素单元构成,单个像素单元由Te/py-Si异质结构成。对于像素单元,由下而上依次是底电极(Au)、py-Si、图案化的Al₂O₃绝缘层、图案化的Te薄膜、图案化的顶电极(Au)。图1(b)所示为Te/py-Si光电探测器阵列的实物图,其光学照片显示各层薄膜边缘清晰、整齐。本工作中所使用的金字塔硅扫描

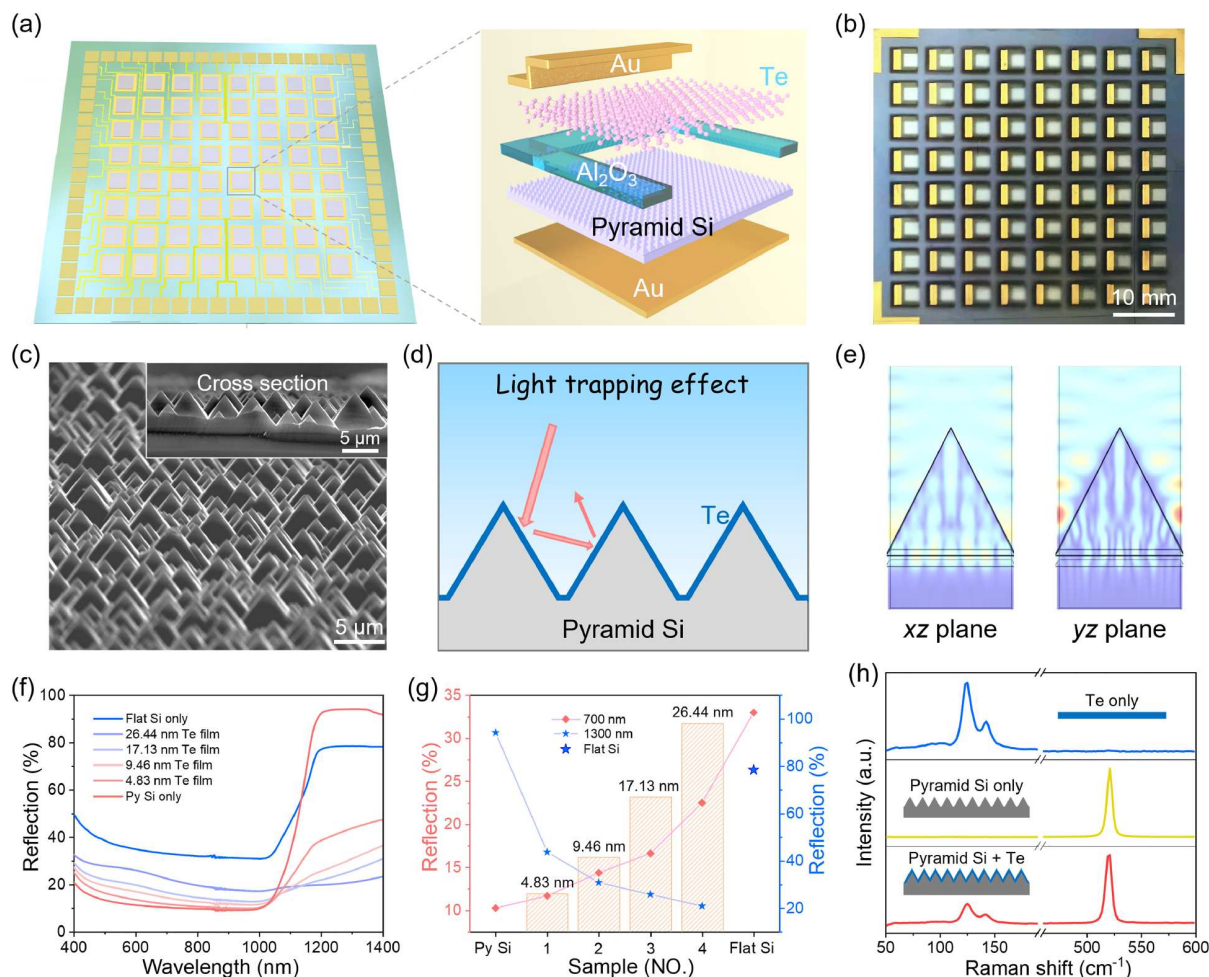


图 1 (网络版彩色) Te/py-Si 异质结器件阵列的基本表征. (a) Te/py-Si 器件阵列的结构示意图和单个像素器件的分层结构图; (b) Te/py-Si 器件阵列的数码照片; (c) Te/py-Si 异质结的截面 SEM 图; (d) Te/py-Si 异质结“陷光效应”原理示意图; (e) 入射光波长为 980 nm 时 Te/py-Si 异质结表面的电场能量分布模拟; (f) py-Si、抛光面硅以及表面沉积了不同厚度 Te 薄膜金字塔硅的反射率曲线和 (g) 对应波长为 700 和 1300 nm 时的反射值; (h) py-Si、Te 薄膜以及 Te/py-Si 异质结的拉曼光谱

Figure 1 (Color online) The typical characterization of Te/py-Si device arrays. (a) The schematic diagram of the Te/py-Si device array, and the layered structure diagram of a single pixel device; (b) photograph of the Te/py-Si device array; (c) a typical cross-sectional SEM image of Te/py-Si heterojunction; (d) schematic diagram of the “light trapping effect” of Te/py-Si heterostructure; (e) simulation of electric field energy distribution of the Te/py-Si heterojunction surface with a wavelength of 980 nm; (f) the reflectance curves of py-Si, polished silicon and Te films with different thicknesses on py-Si, as well as (g) the reflection values at wavelengths of 700 and 1300 nm; (h) Raman spectra of py-Si, Te films and Te/py-Si heterojunction

电子显微镜(scanning electron microscope, SEM)图像如图1(c)和图S1所示, 可以清楚地看到金字塔状微结构均匀分布, 平均高度约5 μm , 底边边长约5 μm . 如图1(d)所示, 这种py-Si表面的金字塔微结构可以最大限度地减少光的反射损失, 迫使光线在材料内部经历多次反射和散射, 延长其传播路径, 增加光被材料吸收的几率, 从而产生“陷光效应”. 此外, 本文利用时域有限差分(finite-difference time-domain, FDTD)方法研究了异质结处的光场分布, 进一步证实了金字塔硅显著的陷光

效应^[24]. 图1(e)展示了光照射下Te/py-Si异质结的电位密度分布, 在金字塔形Si周围和底部有电场增强. 因此, 具有光捕获结构的金字塔形硅可以大大提高光电探测器的吸光度和探测能力.

为探究异质结对入射光利用率最大时Te薄膜的厚度, 本文制备了不同厚度的Te薄膜(图S2(a)所示), 原子力显微镜测试(图S2(b)所示)显示所得Te薄膜表面平整, 厚度分别为4.83、9.46、17.13和26.44 nm. 图S2(a)为不同厚度Te薄膜在石英衬底上的光学照片, 随着Te薄膜

厚度逐渐增加,薄膜由透明的浅灰色逐渐变成具有金属光泽的银色,背景中的“SNNU”字样对比度逐渐降低,表明Te薄膜厚度增大,对可见光的透射率减弱,反射率逐渐增强.图1(f)为py-Si衬底、平整硅衬底以及不同厚度Te薄膜的Te/py-Si异质结的反射光谱,可以看出py-Si对可见光的反射率明显低于平整硅片,表明py-Si表面的微结构可以有效提高可见光的吸收.随着py-Si表面Te薄膜厚度的增加,其在可见光波段的反射率逐渐增加,而在近红外波段的反射率降低.这是由于Te的窄带隙使得厚层Te薄膜对可见光反射增大,而对红外光吸收增强.图1(g)为提取上述各反射光谱中波长700和1300 nm处的反射率,当Te薄膜厚度为9.46 nm时,其反射率分别为14.29%和30.02%.相比其他厚度Te薄膜异质结,这一厚度Te薄膜异质结对可见光与红外光的利用率都较高,因而后续异质结器件中Te薄膜均采用9.46 nm的厚度.

图1(h)为py-Si、Te薄膜以及Te/py-Si异质结的拉曼

光谱,从Te薄膜的拉曼光谱中可以观察到在94、123和140 cm^{-1} 处三个明显的拉曼峰,分别对应于Te单质的 E_1 、 A_1 和 E_2 三个振动模式^[34];py-Si的拉曼光谱在520 cm^{-1} 处有显著的硅特征峰;从Te/py-Si异质结的拉曼光谱中可以观察到Te和Si的特征峰同时存在,表明异质结的成功制备.此外,Te/py-Si异质结的X射线衍射(X-ray diffraction, XRD)测试(图S3(a))表明磁控溅射所得Te薄膜为非晶态,金字塔硅为单晶.图S3(b)为异质结中Te薄膜的X射线光电子能谱学(X-ray photoelectron spectroscopy, XPS)谱,其中主要存在4个特征峰,结合能位于573.1和583.6 eV的峰为Te元素的 $3d_{5/2}$ 和 $3d_{3/2}$ 峰,结合能位于576.4和586.9 eV的峰归属于Te-O,表明Te薄膜表面略微有氧化^[35].图S3(c)为金字塔硅的XPS图谱,99.5 eV处为Si 2p单质特征峰,103.1 eV处为Si-O的2p特征峰.

图2(a)为Te/py-Si异质结器件电学输运测试示意图.如图2(b)所示,暗态下的电流-电压(I - V)曲线在正向开

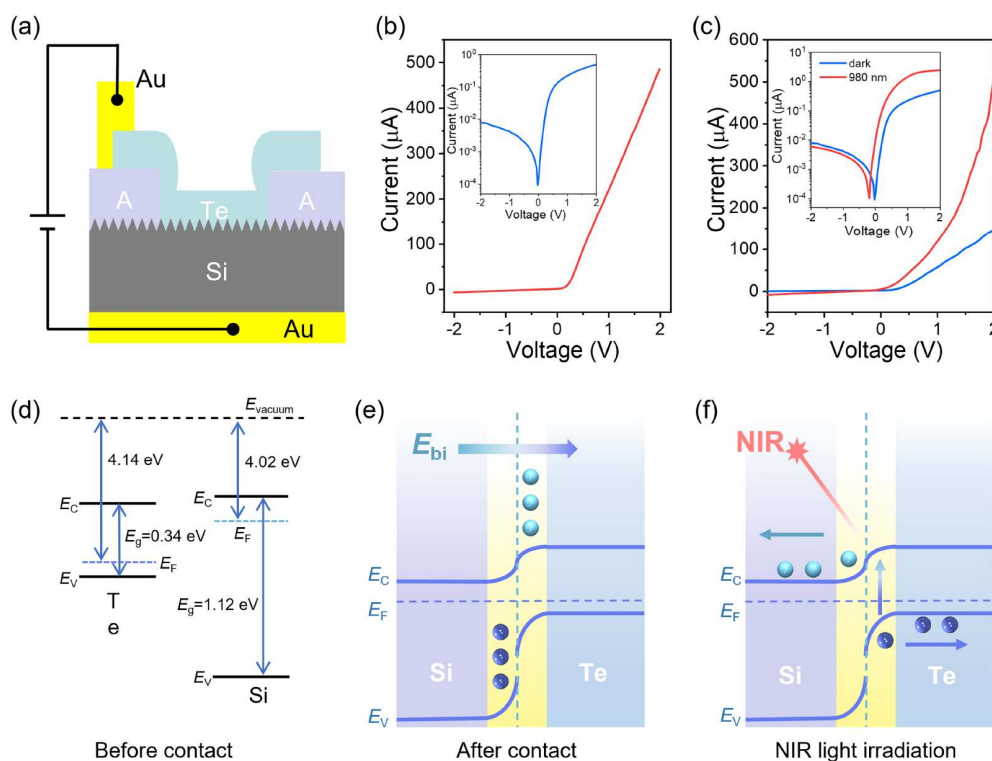


图2 (网络版彩色)Te/py-Si异质结器件的电学输运和光电响应及其能带结构. (a) Te/py-Si器件结构及电流-电压测试电路示意图; (b), (c) Te/py-Si器件在(b) 黑暗状态以及(c) 波长为980 nm光照射下的电流-电压曲线, 插图为对数坐标下的电流-电压曲线; (d), (e) Te与py-Si(d) 未接触时与(e) 接触时的能带排列情况; (f) 980 nm光照射下的电子-空穴迁移示意图

Figure 2 (Color online) Electrical transport, photoresponse and band structure of Te/py-Si heterostructure devices. (a) Schematic diagram of Te/py-Si device structure and current-voltage test circuit; (b), (c) current-voltage curves of the Te/py-Si device under (b) dark state and (c) 980 nm light irradiation, the inset are those curves in logarithmic coordinates; (d), (e) the energy band arrangement of Te and py-Si (d) before contact and (e) after contact; (f) schematic diagram of electron-hole migration of the heterojunction under 980 nm laser irradiation

启, 反向截止, 表现出显著的整流特性^[36]. 图2(c)为暗态和近红外光照下(980 nm, 有效辐照面积为0.26 cm²)的 $I-V$ 曲线, 当 $V \geq 0$ 时器件表现出显著的正向光电响应. 其器件的光电响应机制可通过界面处Te和Si的能带排列进行分析. 图2(d)为Te和Si的能带结构, 其带隙分别为0.34和1.12 eV^[37], 形成I型能带排列. 当Te和Si接触时, 在其界面处形成从Si到Te方向的内建电场, 形成II型异质结(图2(e)), Te/py-Si异质结中耗尽区的形成抑制了载流子的移动, 进而显著抑制了暗电流. 当光照射Te/py-Si异质结时, 价带电子跃迁至导带, 形成光生电子-空穴对(图2(f)). 由于Te带隙较窄及异质结耗尽区的

存在, 电子也可以被较低能量的近红外光激发到导带, 从而拓宽光谱响应范围. 此外, 由于异质结中内建电场的存在, 耗尽区的光生电子和空穴分别向py-Si和Te移动, 从而降低了载流子复合概率, 延长了载流子的寿命. 随着Te中空穴和py-Si中电子的积累, 形成了由py-Si向Te方向的空间电场. 因此, Te/py-Si异质结中光生电子和空穴在耗尽区分别向py-Si和Te的迁移不受势垒阻碍, 故而可获得较大的光电响应.

基于上述结果, 我们进一步研究了Te/py-Si异质结器件的光电响应特性. 图3(a)为Te/py-Si异质结器件在可见光(520、638和785 nm)和近红外光(850、980和

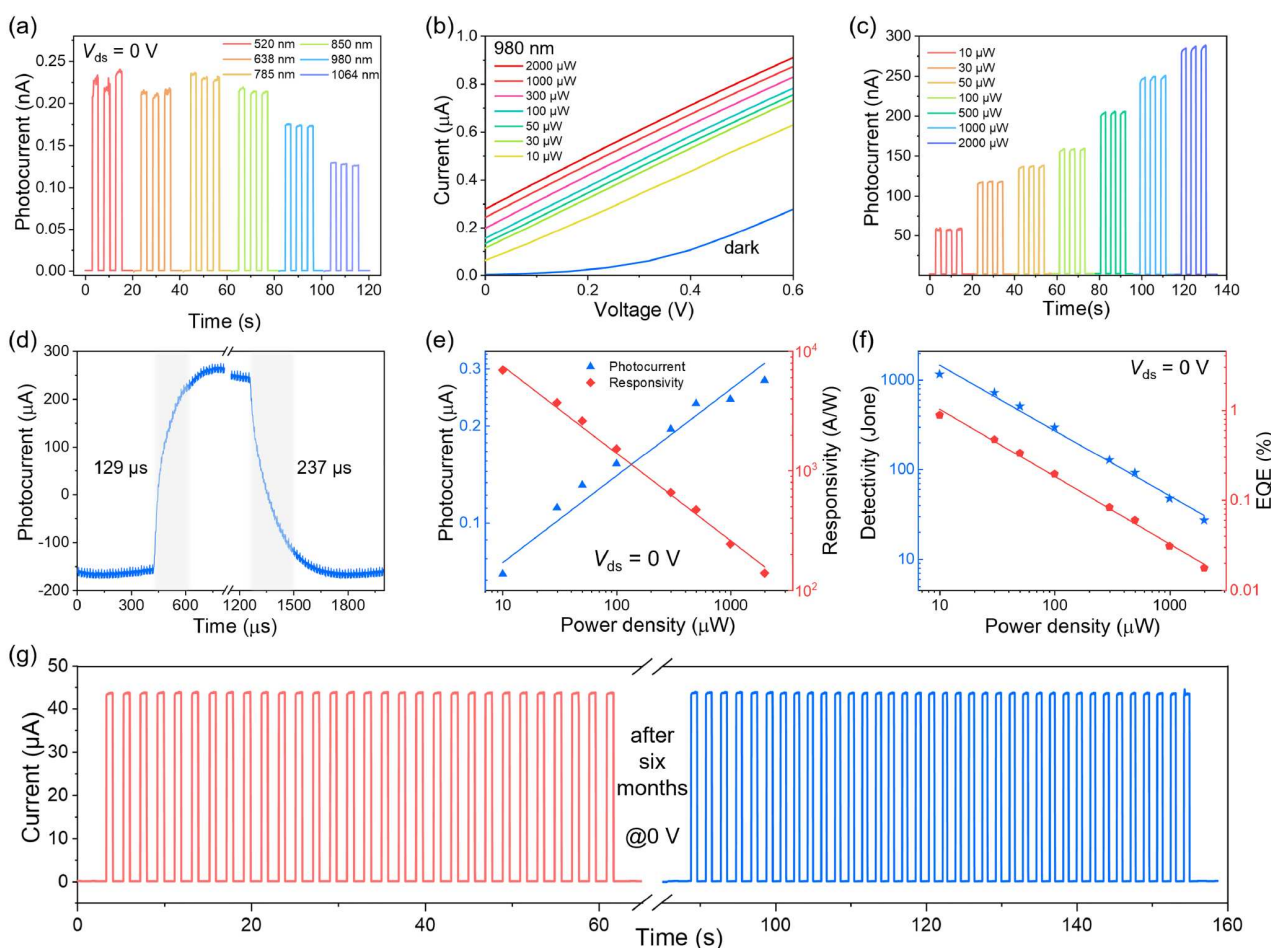


图 3 (网络版彩色)Te/py-Si器件阵列中像素单元器件的光电性能. (a) 不同激光波长下Te/py-Si光电探测器的光响应情况; (b), (c) 不同激光功率下Te/py-Si光电探测器的(b) 电流-电压曲线和(c) 光响应(电流-时间)曲线, 其激光波长为980 nm; (d) Te/py-Si器件的瞬态光响应曲线; (e), (f) Te/py-Si光电探测器的(e) 光电流、响应度以及(f) 探测率、外量子效率随激光功率变化曲线; (g) 器件在980 nm光照下的光响应曲线及其放置六个月后的光响应曲线

Figure 3 (Color online) Photoelectric properties of pixel unit devices in Te/py-Si devices array. (a) The photoresponse of the Te/py-Si photodetector under different laser wavelengths; (b), (c) the (b) current-voltage curve and (c) photoresponse (current-time) curve of the photodetector under different light powers, with a light wavelength of 980 nm; (d) transient photoresponse curves of Te/py-Si devices; (e), (f) the curves of (e) photocurrent, responsivity and (f) detectivity and external quantum efficiency the varying with light power; (g) the photoresponse curve of the device under 980 nm light and that after six months

1064 nm)光照下的光电响应, 其表现出从可见到近红外波段的宽光谱、稳定光电响应. 为了展现Te/py-Si器件的近红外光电响应特性, 后续光电性质测试均在980 nm光照下进行. 图3(b)为不同激光功率照射下器件的 $I-V$ 曲线, 可以看出其光电流随入射光功率的增大而增大. 此外, 光照下的 $I-V$ 曲线不过零点, 其短路电流随光功率的增大而增大, 表现出显著的光伏效应. 图3(c)

为不同光功率下的 $I-T$ 曲线, 其在零偏置电压下展现出快速稳定的光响应, 表明该器件实现了自供电光探测. 为进一步分析该器件的光电探测性能, 我们从图3(c)中提取了光电流($I_{ph}=I_{light}-I_{dark}$)和入射光功率(power density, P), 其依赖关系如图3(e)所示, 光电流大小随功率对数值呈线性变化. Te/py-Si光电探测器的近红外探测性能, 如响应度(R_d)和比探测率(D^*)使用如下方程计

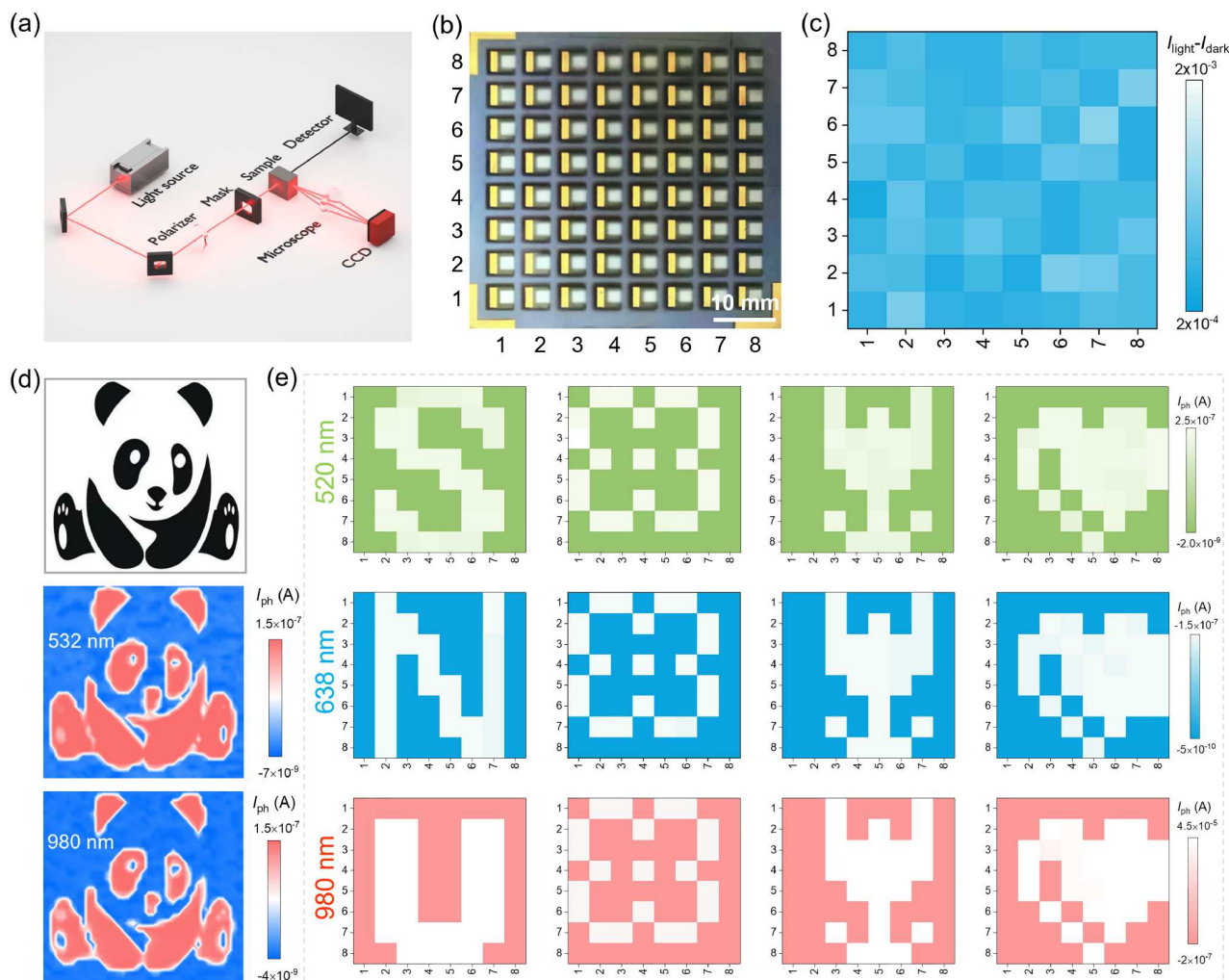


图4 (网络版彩色)Te/py-Si器件的光电成像. (a) 光电成像装置示意图; (b) Te/py-Si器件阵列的照片及各像素单元坐标; (c) 各像素单元在980 nm光照及2 V偏压时的光电流热图, 光源功率统一为100 μ W; (d) Te/py-Si光电探测器单元的单点探测成像. 上方为虚拟模板的图像, 下方为在532和980 nm光照下的单点探测成像图, 偏压为0 V, 探测器阵列的扫描区域为47 $\times$ 44 pixels, 测试时单像素点照射时间为500 ms, 相连两个像素点扫描间隔时间为500 ms; (e) Te/py-Si器件阵列对不同字母及图案在520 nm(上排)、638 nm(中排)及980 nm(下排)光照下的成像图, 偏压为0 V

Figure 4 (Color online) Photoelectric imaging of Te/py-Si devices. (a) Schematic diagram of the photoelectric imaging device; (b) photo of the Te/py-Si devices array and the coordinates of each pixel unit. (c) Photocurrent heat maps of each pixel unit under 980 nm light irradiation and voltage of 2 V. The light power is uniformly set at 100 μ W. (d) Single-point detection imaging of the pixel unit device. The upper one is the image of the virtual mask, and the lower ones are the single-point detection images under 532 and 980 nm light irradiation. The scanning area of the detector array is 47 $\times$ 44 pixels. During the test, the irradiation time of a single pixel is 500 ms, the scanning interval between two connected pixels is also 500 ms, and the bias voltage is 0 V. (e) Imaging of different letters and figures of the Te/py-Si devices array under 520 nm (upper row), 638 nm (middle row) and 980 nm (lower row) light irradiation. The bias voltage is 0 V

算^[38,39]:

$$R_{\lambda} = \frac{I_{\text{light}} - I_{\text{dark}}}{P}, \quad (1)$$

$$D^* = R_{\lambda} \sqrt{\frac{S}{2qI_{\text{dark}}}}, \quad (2)$$

其中, I_{light} 和 I_{dark} 分别为光电流和暗电流, S 为入射光源有效照射面积、 q 为电荷量^[38]. R_{λ} 和 D^* 与光功率的依赖关系图(图3(d,e))显示其都随着光强的增加而逐渐降低, 在入射光功率为10 μW 时 R_{λ} 和 D^* 达到最大值, 分别为6.95 mA W^{-1} 和 1.36×10^9 Jones. 图3(d)为Te/py-Si异质结器件在600 Hz调制频率时的瞬态光电响应, 其上升和衰减时间分别为129和237 μs (图3(f)), 展现出超快的光响应性质. 不同频率(0.1~10 Hz)下的瞬态光电响应测试显示其在10 Hz下仍有高分辨的光电响应(图S4). 为研究Te/py-Si光电探测器的稳定性, 在频率为0.5 Hz脉冲激光下持续测试其光响应(图3(g)), 其展现出稳定的光响应. 器件经六个月静置后进行复测, 结果显示, 光电流未发生显著衰减, 表明该器件拥有出色的长期稳定性.

基于Te/py-Si器件以上优异的光电响应性能, 我们进一步探究了Te/py-Si异质结器件阵列的光电成像. 图4(a)为光电成像的光路示意图, 将不同波长的激光器作为光源置于图像掩膜前方, 激光通过掩膜落在不同器件单元上, 通过半导体分析仪及计算机实时记录分析得到器件阵列的成像图. 图4(b)为Te/py-Si器件阵列的照片及各像素单元坐标. 为探究Te/py-Si异质结阵列各器件单元成像的均匀性, 对所有器件单元进行光电测试. 图4(c)为各器件单元在光波长为980 nm, 偏压为2 V时对应的光电流热图, 所有的器件单元表现出近乎一致的光电流值, 表明所制备光电探测器阵列具有近

乎100%的良率. 此外, 相同条件下, 偏压为0 V时对应的光电流热图也展现出近乎100%的良率(图S5). 如图4(d)所示, 通过实时记录器件单元在532和980 nm光照下的光电流, 获得了高分辨的熊猫图案, 表明该器件单元具有稳定的宽波段光电成像能力. 进而, 我们探究了Te/py-Si器件阵列在可见光和近红外光照射条件下的成像, 如图4(e)所示, 在520、638和980 nm三个波长下获得了具有清晰边界的“S”“N”“U”形字母, 以及“四叶草”“郁金香”和“爱心”形图像, 表明该探测器阵列具有稳定、优异的光电成像能力, 展现出在高集成度光电子器件领域的巨大应用潜力.

3 总结与展望

本工作构筑了一种Te/py-Si异质结光电探测器阵列, 探究了其可见-近红外光电探测和成像. 当Te薄膜厚度约为10 nm时, 对可见-近红外光均有较高的利用率, 其反射率分别为14.29%与30.02%. FDTD模拟表明, py-Si的陷光效应对提升异质结的光吸收效率起到了关键作用. 电学和光电测试显示Te/py-Si器件具有明显的整流特性和光电二极管性质, 显著的光伏效应赋予该器件自供电光电探测能力. 此外, 该器件实现了可见光到近红外(520~1064 nm)宽波段响应, 其在980 nm的光照下表现出优异的光电性能, 获得了高达6.95 mA/W 的响应度、 1.36×10^9 Jones的探测率和129 μs 的光电响应速度. 基于以上优异的光电响应性能, Te/py-Si异质结器件单元和阵列展现出良好的光电成像能力. 本工作将传统硅半导体与新型范德华材料有效集成, 实现了器件对光的高效利用和载流子的有效分离, 为下一代光电子集成芯片的构筑提供了新的策略.

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补充材料

图S1 金字塔硅的形貌结构

图S2 石英衬底表面不同厚度Te薄膜的数码照片和相应的原子力显微镜照片

图S3 Te薄膜和Te/py-Si异质结的相结构和组分表征

图S4 Te/py-Si异质结器件在不同频率光脉冲下的瞬态光电响应

图S5 Te/py-Si异质结器件阵列各像素单元在980 nm光照射及0 V偏压时的光电流热图

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Summary for “基于二维碲薄膜/金字塔硅异质结阵列的宽波段光电探测与成像器件”

2D tellurium film/pyramid-silicon heterostructure arrays for broadband photoelectric detection and imaging device

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Since the invention of photodetectors, high-performance devices of various types, functions, and applications have been extensively used across diverse sectors of the economy and daily life. However, due to the limitations of the wide bandgap of silicon (Si) and the incompatibility of most near-infrared optoelectronic materials with traditional integrated circuits, the development of high-performance, broad-spectrum near-infrared detectors suitable for miniaturization and integration still faces many challenges. Van der Waals (vdW) materials have emerged as a prominent research focus in recent years owing to their unique physicochemical properties. A series of narrow-bandgap vdW materials—such as black phosphorus (BP) and palladium diselenide (PdSe₂) have been successively explored for infrared photodetection. As a chalcogen element, tellurium (Te) is a p-type narrow-bandgap semiconductor, which features a distinctive one-dimensional helical chain structure. It exhibits superior electrical properties, including ultrahigh carrier mobility and thickness-dependent bandgap, which make it a promising material for next-generation electronic and optoelectronic devices. Moreover, Te has a narrow optical bandgap of ~0.35 eV and strong light-matter interaction in the NIR spectrum. Considering the limitations of silicon in infrared photodetection, Te/Si heterostructures can be anticipated to deliver a desirable broadband response.

In this work, we propose a 2D Te film/pyramid-Si (Te/py-Si) heterostructure device array for NIR photodetection and imaging. Centimeter-scale Te films with different thicknesses were prepared at room temperature via magnetron sputtering. Using the mask-assisted magnetron sputtering, patterned Te films were fabricated on the surface of n-type py-Si, forming an 8×8 Te/py-Si heterostructure array. It was found that 2D Te film and py-Si can reduce the device's reflectivity at NIR and visible light, respectively, which subsequently enhances the overall light utilization of the device. As results, the Te/py-Si heterostructure device exhibits excellent photoelectrical performance under visible and NIR light illumination. Under 980 nm illumination, the device achieves a responsivity of 6.95 mA/W, photocurrent on/off ratio of 4.1×10^2 , and specific detectivity of 1.36×10^9 Jones. Furthermore, both the individual pixels photodetector and the photodetector array realize the visible and NIR photoelectric imaging with distinct and sharp contours, indicating the promising application of the Te/py-Si photodetectors in future optoelectronic imaging. This work not only presents a high-performance photodetector but also provides a new and versatile route for fabricating mixed-dimensional van der Waals heterostructures. By combining the advantages of 2D materials with microstructured Si substrates in a scalable process, it paves the way for implementing these advanced photodetectors in next-generation optoelectronic systems, including compact NIR cameras and integrated optical sensors.

Te thin-film, Te/Si heterojunction, photodetector, near-infrared, photoelectric imaging

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