

Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Amani, M;Tan, C;Zhang, G;Zhao, C;Bullock, J;Song, X;Kim, H;Shrestha, VR;Gao, Y;Crozier, KB;Scott, M;Javey, A

Title:

Solution-Synthesized High-Mobility Tellurium Nanoflakes for Short-Wave Infrared Photodetectors

Date:

2018-07-24

Citation:

Amani, M., Tan, C., Zhang, G., Zhao, C., Bullock, J., Song, X., Kim, H., Shrestha, V. R., Gao, Y., Crozier, K. B., Scott, M. & Javey, A. (2018). Solution-Synthesized High-Mobility Tellurium Nanoflakes for Short-Wave Infrared Photodetectors. *ACS Nano*, 12 (7), pp.7253-7263. <https://doi.org/10.1021/acsnano.8b03424>.

Persistent Link:

<https://hdl.handle.net/11343/294886>

# Solution-Synthesized High-Mobility Tellurium Nanoflakes for Short-Wave Infrared Photodetectors

*Matin Amani*, <sup>#,1,2</sup>, *Chaoliang Tan* <sup>#,1,2</sup>, *George Zhang*<sup>1,2</sup>, *Chunsong Zhao*<sup>1,2,3</sup>,  
*James Bullock*<sup>1,2</sup>, *Xiaohui Song*<sup>3,4</sup>, *Hyungjin Kim*<sup>1,2</sup>, *Vivek Raj Shrestha*<sup>5</sup>, *Yang  
Gao*<sup>6</sup>, *Kenneth B. Crozier*<sup>5,6</sup>, *Mary Scott*<sup>3,4</sup>, and *Ali Javey*<sup>1,2,\*</sup>

<sup>1</sup>Electrical Engineering and Computer Sciences, University of California at  
Berkeley, Berkeley, CA 94720, United States

<sup>2</sup>Materials Sciences Division, Lawrence Berkeley National Laboratory,  
Berkeley, CA 94720, United States

<sup>3</sup>Department of Materials Science and Engineering, University of California at  
Berkeley, Berkeley, CA 94720, United States

<sup>4</sup>The Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley,  
CA, 94720

<sup>5</sup>School of Physics, University of Melbourne, VIC 3010, Australia

<sup>6</sup>Department of Electrical and Electronic Engineering, University of  
Melbourne, Victoria 3010, Australia

\*Address correspondence to [ajavey@eecs.berkeley.edu](mailto:ajavey@eecs.berkeley.edu)

□These authors contribute equally to this work.

**Keywords:** tellurium, 2D materials, solution-synthesized, high-mobility,  
short-wave infrared, photodetectors

## Abstract

Two-dimensional (2D) materials, particularly black phosphorous (bP), have  
demonstrated themselves to be excellent candidates for high-performance  
infrared photodetectors and transistors. However, high-quality bP can be  
only obtained *via* mechanical exfoliation from high temperature- and high-  
pressure-grown bulk crystals and degrades rapidly when exposed to ambient  
conditions. Here, we report solution-synthesized and air-stable quasi-2D  
tellurium (Te) nanoflakes for short-wave infrared (SWIR) photodetectors. We

34 perform comprehensive optical characterization *via* polarization-resolved  
35 transmission and reflection measurements, and report the absorbance and  
36 complex refractive index of Te crystals. It is found that this material is an  
37 indirect semiconductor with a bandgap of 0.31 eV. From temperature-  
38 dependent electrical measurements, we confirm this bandgap value and find  
39 that 12 nm thick Te nanoflake show high hole mobilities of 450 and 1430 cm<sup>2</sup>  
40 V<sup>-1</sup> s<sup>-1</sup> at 300K and 77K, respectively. Finally, we demonstrate that despite its  
41 indirect bandgap, Te can be utilized for high-performance SWIR  
42 photodetectors by employing optical cavity substrates consisting of Au/Al<sub>2</sub>O<sub>3</sub>  
43 to dramatically increase the absorption in the semiconductor. By changing  
44 the thickness of the Al<sub>2</sub>O<sub>3</sub> cavity, the peak responsivity of Te  
45 photoconductors can be tuned from 1.4 μm (13 A/W) to 2.4 μm (8 A/W) with  
46 a cut-off wavelength of 3.4 μm, fully capturing the SWIR band. An optimized  
47 room temperature specific detectivity ( $D^*$ ) of  $2 \times 10^9$  cm Hz<sup>1/2</sup> W<sup>-1</sup> is obtained  
48 at a wavelength of 1.7 μm.

49

50       Narrow bandgap semiconductors, with bandgaps in the range of 0.7 to  
51 0.3 eV, have been heavily investigated for numerous applications. These  
52 include high-speed and high-performance transistors, which typically require  
53 materials with high mobility and low effective mass.<sup>1,2</sup> Additionally,  
54 photodetectors and light sources which can operate in the short-wave  
55 infrared (SWIR, 1.4 μm - 3 μm) band are heavily utilized for imaging and  
56 optical communication.<sup>3-5</sup> This area has typically been dominated by III-V  
57 semiconductors such as indium gallium arsenide (InGaAs) and indium

58 gallium arsenide phosphide (InGaAsP), which have excellent performance but  
59 require complex growth and fabrication procedures.<sup>6,7</sup> Numerous research  
60 groups have investigated techniques to achieve III-V semiconductors through  
61 non-epitaxial growth on silicon or by layer transfer.<sup>8-11</sup> However, these  
62 techniques still introduce significant complexity and may require high growth  
63 temperature. Moreover, key limitations still exist in InGaAs-based devices; an  
64 example being edge-recombination in scaled InGaAs photodiodes which  
65 limits pixel sizes in focal plane arrays to dimensions of 5-6  $\mu\text{m}$ , well above  
66 the diffraction limit.<sup>12</sup> As such, there is a pressing need to find suitable  
67 materials that can either improve the performance and/or reduce the costs  
68 of these devices.

69         One such potential material system is two-dimensional (2D) materials,  
70 which have been heavily studied over the past decade. One of the key  
71 advantages of 2D materials, which enables their high performance, is their  
72 naturally terminated surfaces; *i.e.* since the out-of-plane bonds in these  
73 materials are van der Waals rather than covalent.<sup>13,14</sup> As such, they do not  
74 suffer from the surface-induced performance degradation commonly  
75 observed in three-dimensional (3D) semiconductors, which require surface  
76 passivation (typically in the form of cladding layers). This has enabled  
77 extraordinary electronic and optical properties of these materials such as  
78 photoluminescence quantum yields approaching unity and their exceptional  
79 thickness scalability down to the monolayer limit.<sup>15,16</sup> Devices which have  
80 exploited the advantages and physics of 2D systems have demonstrated  
81 dramatic scaling as well as new devices paradigms.<sup>17-19</sup> However, edges in 2D

82 layers still act as recombination centers and are analogous to a surface in a  
83 3D crystal structure.<sup>20</sup> A recent work by Wang *et al.* demonstrated the  
84 solution synthesis of air-stable quasi-2D Te nanosheets and its high-  
85 performance for field-effect transistors.<sup>21</sup> Note that Te is a true one-  
86 dimensional (1D) system, which can potentially overcome some of these  
87 limitations since it consists of van der Waals bonded molecular chains.<sup>22</sup> As  
88 such these material systems naturally possess no dangling bonds when  
89 scaled, with the exception of the ends of the molecular chains.<sup>22</sup> **Importantly,**  
90 **this material also possesses a small, thickness tunable bandgap enabling its**  
91 **potential use in SWIR photodetectors. Recent theoretical works have**  
92 **predicated an indirect gap of 0.35 eV in bulk and a direct gap of 1.04 eV in**  
93 **the monolayer case.**<sup>23,24</sup>

94 Here, we systematically study the optical and electrical properties of  
95 solution-synthesized quasi-2D Te nanoflakes. From polarization-resolved IR  
96 transmission and reflection measurements, we experimentally extract the  
97 bandgap, absorbance, and complex refractive index of this material.  
98 Temperature-dependent electrical measurements were performed to verify  
99 the optically measured bandgap values as well as determine the carrier  
100 transport properties as a function of temperature in quasi-2D Te nanoflakes.  
101 Finally, we demonstrate SWIR photoconductive detectors based on thin (16-  
102 20 nm) quasi-2D Te nanoflakes. Although this material has low absorbance in  
103 the SWIR ( $6 \times 10^5 \text{ cm}^{-1}$  for wavelengths in the range of 2 to 3.5  $\mu\text{m}$ ) induced  
104 by the indirect bandgap, the Te nanoflake-based photodetectors exhibit high  
105 photoresponsivity and specific detectivity by leveraging optical cavities

106 engineered to maximize absorption at various technologically important  
107 wavelengths in the SWIR range.

## 108 **RESULTS and DISCUSSION**

### 109 **Material Synthesis and Characterization.**

110 Quasi-2D Te nanoflakes with varying thickness in the range of 10-200  
111 nm were synthesized by a hydrothermal method *via* reduction of sodium  
112 tellurite with hydrazine hydrate in the presence of poly(-vinyl pyrrolidone) in  
113 an aqueous alkaline solution at 180°C for certain varying times (details are  
114 provided in methods).<sup>21,25</sup> The crystal structure of Te is shown in Figure 1a-c.  
115 The Te crystallizes in a structure composed of Te atomic chains in a  
116 triangular helix that are stacked together *via* van der Waals forces in a  
117 hexagonal array (Figure 1a). In this structure, Te atoms only form covalent  
118 bonds to the two nearest neighbor Te atoms in the helical chain (Figure 1b).  
119 Therefore, Te is a true 1D system rather than a 2D van der Waals crystal.  
120 When it is viewed from x-axis, the zig-zag layers are seen to be stacked  
121 together *via* van der Waals forces to form a 3D structure (Figure 1c). Figure  
122 1d shows the transmission electron microscope (TEM) image of a typical Te  
123 nanoflake with a length of 15  $\mu\text{m}$  and width of 4  $\mu\text{m}$ . The corresponding high-  
124 resolution TEM (HR-TEM) image shows the continuous crystal lattice of the Te  
125 nanoflake and the measured the lattice constant is  $\sim 2 \text{ \AA}$  (Figure 1e), which is  
126 assignable to the (003) planes of the Te crystal. The corresponding selected  
127 area electron diffraction (SAED) pattern of the Te nanoflake shows bright  
128 diffraction spots with a rectangular shape, in which the nearest two spots to

129 the diffraction center correspond to the (110) and (001) planes of the Te  
130 crystal (Figure 1f). Both the HR-TEM and SAED pattern results indicate that  
131 the solution-synthesized Te nanoflake is single-crystalline. The optical image  
132 shows that Te nanoflakes have an irregular shape with length of tens of  
133 micrometers, width of few micrometers and thickness of 10-30 nm (Figure  
134 2a). Note that there are always some Te nanowires along Te nanoflakes in  
135 the growth solution, but Te nanowires can be partially removed from the  
136 solution by proper centrifugation (see the details in Methods). An atomic  
137 force microscope (AFM) image of a Te nanoflake with a thickness of 16.1 nm  
138 is shown in Figure 2b. Raman spectrum of tellurium nanoflakes gives three  
139 vibrational modes at 92, 121, 141  $\text{cm}^{-1}$  (Figure 2c) corresponding to the  $E_1$ -  
140  $TO$ ,  $A_1$ , and  $E_2$  peaks, which are consistent with previous literature  
141 reports.<sup>21,26</sup> The X-ray diffraction (XRD) peaks of Te nanoflakes match well  
142 with the simulated reference (Figure 2d). Both Raman and XRD analysis  
143 further confirm the successful preparation of Te nanoflakes.<sup>21,25</sup>

#### 144 **Electrical Properties.**

145 We now turn our attention to the electrical properties and performance  
146 of the quasi-2D Te nanoflakes. To this end, back-gated field-effect transistors  
147 were fabricated on Si/50 nm  $\text{SiO}_2$  by patterning Pd (40 nm thick) electrodes  
148 on Te nanoflakes with thickness ranging from 10-20 nm using electron-beam  
149 lithography.<sup>21</sup> The  $I_d$ - $V_d$  characteristics of a 12.3 nm thick quasi-2D Te field-  
150 effect transistor, as well as an optical image of the measured device ( $L = 6.8$   
151  $\mu\text{m}$ ,  $W = 1.5 \mu\text{m}$ , where  $L$  and  $W$  are length and width respectively) are  
152 shown in Figure 3a. The device shows dominantly  $p$ -type transport

153 characteristics and a peak current density of  $116 \mu\text{A}/\mu\text{m}$  at a  $V_d = -1 \text{ V}$  and  $V_g$   
154  $= -20 \text{ V}$ . It should be noted that in some devices (Figure S1) ambipolar  
155 transport characteristics are observed, indicating that via proper contact  
156 engineering n-type transport could be obtained. Additionally, this device  
157 shows a current on/off ratio of  $\sim 3 \times 10^3$ , which is expected for a material with  
158 a small bulk bandgap of  $\sim 0.31 \text{ eV}$ . The output characteristics of this device  
159 are shown in Figure 3b, and show current saturation at high drain bias, as  
160 well as linear behavior at low drain biases, indicating low contact resistance.  
161 We then utilize the square law model to calculate the effective mobility ( $\mu_{\text{Eff}}$ )  
162 in this device as a function of gate field (Figure 3c) using  $\mu_{\text{Eff}} = (dI_d/dV_d)/C_{\text{ox}}$ ,  
163 where  $C_{\text{ox}}$  is the gate capacitance ( $69.1 \text{ nF cm}^{-2}$  in the case of  $50 \text{ nm SiO}_2$ )  
164 and  $V_t$  is the threshold voltage. We extract a high peak  $\mu_{\text{Eff}}$  of  $619 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$   
165 for holes, which is very competitive with high-performance p-type  
166 semiconductors with similar bandgaps such as InGaSb and bP, especially  
167 considering that the material is prepared by a solution-based method.<sup>27-29</sup>  
168 The thickness-dependent transport properties of quasi-2D Te nanoflakes  
169 were also investigated over a range of 11 to 36 nm as shown in Figure 3d  
170 and 3e. As the overall thickness of the Te nanoflakes is reduced a dramatic  
171 improvement in the ratio of the on/off currents from  $\sim 30\times$  to  $\sim 4000\times$  can be  
172 observed, which can be attributed to reduced gating efficiency in the device.  
173 Furthermore, over this measured thickness range, we find that there is  
174 negligible variation in the peak effective mobility which has an average value  
175 of  $424 \pm 74 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$  over thirty-nine measured samples.

176 To better understand the transport in this material, we performed  
177 temperature-dependent electrical characterization of the devices.  $I_d$ - $V_g$   
178 characteristics of quasi-2D Te nanoflakes with different thicknesses  
179 measured over a temperature range of 77K to 350K are shown in Figure 4a  
180 and Figure S1. A clear increase in the current on/off ratio can be observed  
181 when the device is cooled, which is consistent with small bandgap materials,  
182 where thermal generation dramatically increases the carrier densities at  
183 elevated temperatures. From the temperature-dependent measurements, we  
184 extract the  $\mu_{\text{Eff}}$  at a gate overdrive of -10 V as a function of temperature for  
185 different layer thicknesses as shown in Figure 4b. For all thicknesses, the  
186 mobility increases as the temperature is reduced, with the 12 nm thick  
187 device showing a  $\mu_{\text{Eff}}$  of 1430 and 450  $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$  at 77K and 300K respectively.  
188 For all three thicknesses, we observe the temperature dependence of  
189 mobility can be fitted with a power law,  $\mu_{\text{Eff}} \propto T^{-\gamma}$ , where  $\gamma = -1.03$  in our case.  
190 This indicates that the mobility in this material is limited by phonon  
191 scattering and not ionized impurities.<sup>30</sup> Additionally, we estimate the  
192 bandgap using temperature-dependent measurements on a device prepared  
193 on a 260 nm gate oxide. In this case, the minimum drain currents,  $I_{d,\text{min}}$ , is  
194 determined by thermal activation of carriers over the contact Schottky  
195 barrier height.<sup>31</sup> The resulting data, shown in Figure 4c, can be fit using:

196 
$$I_{d,\text{min}} \propto \exp(-E_g/kT)$$

197 where  $T$  is the temperature,  $E_g$  is the transport bandgap, and  $k$  is the  
198 Boltzmann constant. We extract an  $E_g$  of 280 meV for a 11.8 nm thick

199 sample, and it is important to note that this method is expected to  
200 underestimate the bandgap due to contributions from trap states.

### 201 **Optical Properties.**

202 To identify the optical bandgap of the quasi-2D Te nanoflakes, we  
203 performed polarization-resolved transmission and reflection measurements  
204 on Te nanoflakes which were transferred onto KBr. Polarization-resolved  
205 transmission and reflection spectra measured on a 111 nm thick sample are  
206 shown in Figure 5a. In order to accurately extract the absorption in the  
207 sample, the optical path was kept constant for both the transmission and  
208 reflection measurements, as annotated in the Figure 5a. Transmission and  
209 reflection spectra were taken in reference to the blank KBr substrate and an  
210 Au mirror, respectively. The total absorption and the corresponding  
211 absorption coefficient in the material can then be calculated as  $100\% -$   
212  $\text{Reflection-Transmission}$  as shown in Figure 5b and 5c. For light polarized  
213 along the direction of the Te molecular wires (defined as  $90^\circ$ ), we measure a  
214 strong absorption that can be fitted to a direct bandgap (Figure 5c and  
215 Figure S2) at 0.71 eV. However, when the light is polarized perpendicular to  
216 the axis of the Te molecular wires (defined as  $0^\circ$ ) a significantly weaker  
217 absorption edge is observed at lower wavelengths. From similar analysis, the  
218 transition can be fitted to an indirect bandgap at 0.31 eV. Importantly, while  
219 the absorption coefficient for wavelengths below  $1.6 \mu\text{m}$  is high ( $4.5 \times 10^6 \text{ cm}^{-1}$ ),  
220 the absorption for longer wavelengths ( $1.6 \mu\text{m} < \lambda < 3.4 \mu\text{m}$ ) is an order  
221 of magnitude lower ( $6 \times 10^5 \text{ cm}^{-1}$ ). As such, in order to effectively utilize this

222 material in the full SWIR band, it is necessary to increase the absorption *via*  
223 proper optical engineering.<sup>32</sup>

224 To this end, we extracted the complex refractive index ( $n, k$ ) which can  
225 be used to estimate the total absorption in the quasi-2D Te layers in  
226 combination with optical cavities, back-reflectors, or anti-reflection coatings.  
227 The refractive index was extracted using a previously established technique  
228 for nanoscale materials for unpolarized light, where reflection is measured as  
229 a function of oxide or sample thickness.<sup>33</sup> In our case, quasi-2D Te nanoflakes  
230 of thicknesses varying from 16 nm to 180 nm were drop-casted on Au  
231 substrates, and the reflection spectra were measured using an Fourier  
232 transform infrared spectrometer (FTIR). The resulting reflection data are  
233 plotted as a function of thickness and wavelength. (Figure 6a and Figure S3).  
234 To extract the complex refractive index from the reflection measurements,  
235 we utilize the transfer matrix method to fit a refractive index to the  
236 measured reflection *versus* thickness at each wavelength.<sup>34</sup> The extracted  $n$   
237 and  $k$  values are plotted in Figure 6b; the extracted extinction coefficient  
238 clearly shows absorption resulting from both the indirect and direct  
239 transitions at the expected wavelengths and corroborates the results from  
240 absorption measurements shown in Figure 5c.

### 241 **Optical Cavity Enhanced Gated-Photoconductors.**

242 Based on the optical properties and electrical properties of quasi-2D  
243 Te, the device structure shown in Figure 7a was chosen to optimize  
244 photoconductive detectors targeting the SWIR spectrum. Here, we selected  
245 thicknesses in the range of 16-20 nm for the quasi-2D Te layers, which

246 provides desired electrical characteristics, the most important of which  
247 being a low dark current.<sup>35</sup> To increase the absorption, an optical cavity  
248 consisting of an optically thick Au film (100 nm) and an Al<sub>2</sub>O<sub>3</sub> dielectric  
249 spacer layer was utilized. The predicted absorption for an 18 nm thick Te  
250 layer as a function of wavelength and Al<sub>2</sub>O<sub>3</sub> thickness was calculated using  
251 the transfer matrix method and is shown in Figure 7b. From these  
252 simulations, it can be clearly seen that by adjusting the thickness of the Al<sub>2</sub>O<sub>3</sub>  
253 layer, the peak absorption wavelength can be tuned over a large range and  
254 the total absorption in the material can be increased by over two orders of  
255 magnitude relative to a sample on Si/SiO<sub>2</sub> (Figure S4). Additionally, the  
256 optical cavity simultaneously acts as the gate stack in this structure.

257 Figure 7c shows optical images of devices fabricated on three different  
258 Al<sub>2</sub>O<sub>3</sub> spacer thickness (550 nm (i), 150 nm (ii), and 350 nm (iii)), which are  
259 selected to provide optimized absorption at 1.4 μm, 1.8 μm, and 2.2 μm,  
260 respectively (reflection spectra of devices on these substrates are shown in  
261 Figure S5). The spectral responsivity of these devices to SWIR illumination  
262 was characterized using an FTIR, by placing the devices in place of the  
263 internal detector and focusing the light source of the FTIR on the device with  
264 a CaF<sub>2</sub> lens. To calibrate the measurements, the internal Deuterated  
265 Triglycine Sulfate (DTGS) in the FTIR, which has a wavelength independent  
266 responsivity, was used to determine the relative intensity of the light source  
267 while a NIST traceable Ge photodiode was used to determine the absolute  
268 intensity of the illumination (further measurement details are provided in the  
269 methods and ref. 35). The final responsivity ( $R$ ) is then calculated as  $R(\lambda) =$

270  $I_{\text{ph}}(\lambda)/P_{\text{in}}(\lambda)$ , where  $I_{\text{ph}}$  is the photocurrent and  $P_{\text{in}}$  is the incident optical power  
271 on the device. The spectral responsivity for representative devices fabricated  
272 on the three different optical cavity substrates are shown in Figure 7d.  
273 Devices fabricated on these three substrates were measured at a drain bias  
274 of  $V_d = 5$  V, and the gate voltage was adjusted to maximize the responsivity.  
275 The measured responsivity curves closely match the calculated absorption  
276 curves which further confirms the estimated refractive index values.

### 277 **Gate-dependent Photoresponse, Detectivity, and Frequency** 278 **Response.**

279 To further characterize the performance of these photodetectors,  
280 additional measurements were performed on an 18.8 nm thick device  
281 fabricated on a Au/150 nm  $\text{Al}_2\text{O}_3$  substrate. The  $I_d$ - $V_g$  characteristics of a  
282 device measured at 78K and 297K without the presence of a cold shield is  
283 shown in Figure 8a. The gate and drain bias dependence of the device at an  
284 incident wavelength of 1.7  $\mu\text{m}$  are shown in Figure 8b and 8c, respectively.  
285 We can see that the photoresponse can be strongly modulated by the gate  
286 bias and is maximized when the device is biased such that drain current is  
287 minimized, similar to what has previously been observed in bP  
288 photoconductors<sup>35,36</sup>. This can be seen in the clear peak responsivity of 27 A/  
289 W at 78K, while the responsivity at 297K saturates with increasing gate  
290 biases to a peak measured value of 16 A/W. Additionally, the device shows  
291 an approximately linearly increasing responsivity at low  $V_d$ , and begins to  
292 show saturation at high  $V_d$ . The full spectral responsivity of the device is

293 shown in Figure 8d. For  $V_d = 5$  V, this detector shows a peak responsivity at  $\lambda$   
294  $= 1.7 \mu\text{m}$  of 27 A/W and 16 A/W at 78K and 297K, respectively.

295 To calculate the specific detectivity of this device, the noise current  
296 density is measured under bias conditions which give maximum responsivity  
297 at an integration time ( $\Delta f$ ) of one second and is shown in Figure 8e. The  
298 noise currents clearly show the expected  $1/f$  (where  $f$  is frequency) flicker  
299 noise which is typically attributed to charge trapping/de-trapping. Utilizing  
300 the noise and responsivity measurements, we calculate the specific  
301 detectivity ( $D^*$ ) using:

$$302 \quad D^i = \frac{\sqrt{A\Delta f}}{NEP} = \frac{R\sqrt{A\Delta f}}{i_n}$$

303 where  $A$  is the detector area, NEP is noise equivalent power, and  $i_n$  is the  
304 noise current. In the ideal case for photoconductors, the  $i_n$  is limited by shot  
305 noise and can be calculated from dark current using:  $\langle i_S^2 \rangle = 2qI_{G-R}\Delta f$ .<sup>37,38</sup> This  
306 typically overestimates noise current; thus, we utilized the experimental  
307 noise currents taken at a modulation frequency of 1 kHz, which was selected  
308 to minimize the contribution of  $1/f$  noise. The specific detectivity as a  
309 function of wavelength is shown in Figure 8f for both 78K and 297K. At room  
310 temperature these devices show a peak  $D^*$  of  $2.9 \times 10^9 \text{ cmHz}^{1/2}\text{W}^{-1}$ . This value  
311 dramatically increases at low temperatures due to the large decrease in the  
312 noise current as well as the improved responsivity to a peak value of  
313  $2.6 \times 10^{11} \text{ cmHz}^{1/2}\text{W}^{-1}$ .

314 To characterize the speed of this device, a directly modulated laser  
315 diode ( $\lambda = 1.55 \mu\text{m}$ ) was utilized to excite the photoconductor. The response

316 of the device to a low-frequency and high-frequency square wave are shown  
317 in Figure 9a and 9b, respectively. From both of the step responses shown in  
318 Figure 9a and 9b, a slow and fast component of the rise/fall time can be  
319 observed. To more clearly characterize this behavior, the photoresponse was  
320 measured with a sinusoidally modulated incident light over a wide frequency  
321 range (100 mHz to 100 kHz) as shown in Figure 9c. Over this measured  
322 spectral range, a clear 3dB cutoff wavelength cannot be observed, indicating  
323 that it is higher than the measured range. However, the device shows a  
324 weak increase in response for light modulated at low frequencies; *i.e.* the  
325 photoresponse at a 100 kHz shows only a  $\sim 5\times$  drop relative to the low  
326 frequency ( $\sim 0.1$  Hz) photoresponse. It is likely that this behavior is a result  
327 of photoconductive gain present in the device which consistent with the high  
328 responsivity and the short carrier transit time ( $\tau_{tr}$ ), which is calculated to be  
329 0.4 ns according to  $\tau_{tr} = L^2/(\mu V_d)$ , where  $L$  is channel length (8.9  $\mu\text{m}$ ) and  $\mu$  in  
330 this case is  $392 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ . The exact mechanisms of the gain likely is a result  
331 of the population and depopulation of trap states, which show saturation at  
332 high illumination powers.<sup>39-41</sup> This is particularly likely given the fact that the  
333 Te nanoflakes in this work were prepared using solution-based synthesis.

### 334 **Polarization-Resolved Photoresponse.**

335 Finally, we investigated the polarization-dependent photoresponse of  
336 Te nanoflake-based photodetectors. We chose a device fabricated on a 350  
337 nm thick  $\text{Al}_2\text{O}_3$  substrate as an example to measure the responsivity, which  
338 provides strong absorption enhancement at wavelengths covering indirect  
339 gap band edge. Figure 10a shows the responsivity of an 18.8 nm thick Te

340 photoconductor measured at various incident polarization angles, with 0°  
341 and 90° corresponding to light polarized perpendicular and parallel to the  
342 molecular wires, respectively. A clear drop in the responsivity for  
343 wavelengths greater 1.5 μm can be observed when the incident light is  
344 polarized at 90°, consistent with the indirect band edge. A polar plot showing  
345 the responsivity as a function of polarization at wavelengths of 3 μm and 1.5  
346 μm is shown in Figure 10b, and clearly shows the highly anisotropic  
347 responsivity of the indirect gap, while the direct gap shows minimal  
348 dependence on the polarization of the light.

#### 349 **CONCLUSION**

350 In summary, we have performed a systematic study on the electrical  
351 and optical properties of solution-synthesized quasi-2D Te, an indirect, small  
352 bandgap (0.31 eV) semiconductor. The Te nanoflake-transistor shows high  
353 effective hole mobilities of 450 and 1430 cm<sup>2</sup> V<sup>-1</sup> s<sup>-1</sup> at 300K and 77K  
354 respectively. The absorbance and complex refractive index of Te were also  
355 extracted based on the polarization-resolved transmission and reflection  
356 measurements. Furthermore, the Te gated photodetectors exhibit high  
357 responsivities over the entire SWIR range with a cut-off wavelength of 3.4  
358 μm. Importantly, using the extracted optical parameters, we dramatically  
359 enhanced the responsivity and specific detectivity of Te photodetectors  
360 using optical cavity substrates. We show that the peak wavelength can be  
361 tuned from 1.4 to 2.4 μm by changing the thickness of the Al<sub>2</sub>O<sub>3</sub> cavity on  
362 Au. This simple substrate engineering technique can be a general way to  
363 significantly enhance the performance of other 2D material-based

364 photodetectors. In addition, due to the anisotropic crystal structure of the Te  
365 nanoflakes, the devices possess a polarization-sensitive SWIR  
366 photoresponse. Our electrical and optoelectronic study indicate that Te is a  
367 promising material for high-performance and low-cost electronic and  
368 optoelectronic devices. Finally, this material has a high potential for wafer-  
369 scale production either through the assembly of solution-processed  
370 nanoflakes to form semi-continuous thin films or through techniques such as  
371 chemical vapor deposition or epitaxial growth.

## 372 **METHODS**

### 373 **Chemicals**

374 Sodium tellurite ( $\text{Na}_2\text{TeO}_3$ ), hydrazine monohydrate ( $\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$ ) and  
375 ammonium hydroxide solution ( $\text{NH}_3 \cdot \text{H}_2\text{O}$ , 28%) were purchased from Sigma-  
376 Aldrich (USA). Poly(-vinyl pyrrolidone) (PVP, average M.W. 58,000) was  
377 purchased from Alfa Aesar (USA). All the chemicals were used as received  
378 without further purification. Milli-Q water (Milli-Q System, Millipore) was used  
379 in all experiments.

### 380 **Synthesis of tellurium nanoflakes**

381 Tellurium nanoflakes were synthesized by a hydrothermal method according  
382 to a previously reported procedure with slight modifications.<sup>21,25</sup> In a typical  
383 procedure, 1.5 g of PVP was first dissolved in 16 mL DI water and 46 mg of  
384  $\text{Na}_2\text{TeO}_3$  was then added and dissolved into the PVP solution to form a clear  
385 solution. Then, 1.66 mL of ammonium hydroxide solution and 0.838 mL of  
386 hydrazine monohydrate was added into the above solution in sequence. The  
387 solution was then transferred into a 25 mL Teflon-lined stainless steel

388 autoclave. The autoclave was sealed well and then placed in an oven. The  
389 autoclave was heated up to 180°C from room temperature with ramp rate of  
390 3 °C/min and then maintained at 180°C for 4 hours. After, the autoclave was  
391 removed from the oven and cooled to room temperature by running water  
392 immediately. The resulting product was purified and washed with DI water  
393 three times by centrifugation at 3000 r.p.m for 2 min. After washing and  
394 purification, the final tellurium solution is a silver-gray color. Note that there  
395 are always some Te nanowires coexisting along with Te nanoflakes and it is  
396 challenging to fully separate the nanowires from the nanoflakes. The final  
397 product was redispersed in pure ethanol before being transferred to the  
398 target substrate for characterization and device fabrication by drop-casting.  
399 **Maintaining the autoclave in oven at 180°C for 4h will produce the tellurium**  
400 **nanoflakes with a typical thickness in the range of 10-30 nm, with typical**  
401 **lateral dimensions of 10-50 μm.** It is important to point out that the thickness  
402 of tellurium nanoflakes can be roughly controlled by controlling the reaction  
403 time (4-30 hours) at 180°C. The thickness of tellurium nanoflakes can be  
404 increased by prolonging the reaction.

#### 405 **Device Fabrication**

406 Te nanoflakes were transferred onto p<sup>++</sup> Si/SiO<sub>2</sub> chips with a 50 nm oxide or  
407 back reflector Al<sub>2</sub>O<sub>3</sub>/Au chips with varying thicknesses of Al<sub>2</sub>O<sub>3</sub> by drop-  
408 casting the tellurium ethanol solution. Back reflector substrates were  
409 prepared by evaporating Ti/Au/Ti (10 nm/200 nm/1 nm) on Si substrates,  
410 followed by atomic layer deposition of Al<sub>2</sub>O<sub>3</sub> (Cambridge Nanotech). The final  
411 Al<sub>2</sub>O<sub>3</sub> thickness was determined by ellipsometry. Suitable Te nanoflakes were

412 then located on an optical microscope and devices were fabricated using  
413 standard e-beam lithography techniques. After development, 40 nm thick Pd  
414 was evaporated as electrode contacts *via* e-beam evaporation and lift-off  
415 was performed using acetone.

#### 416 **Material Characterization**

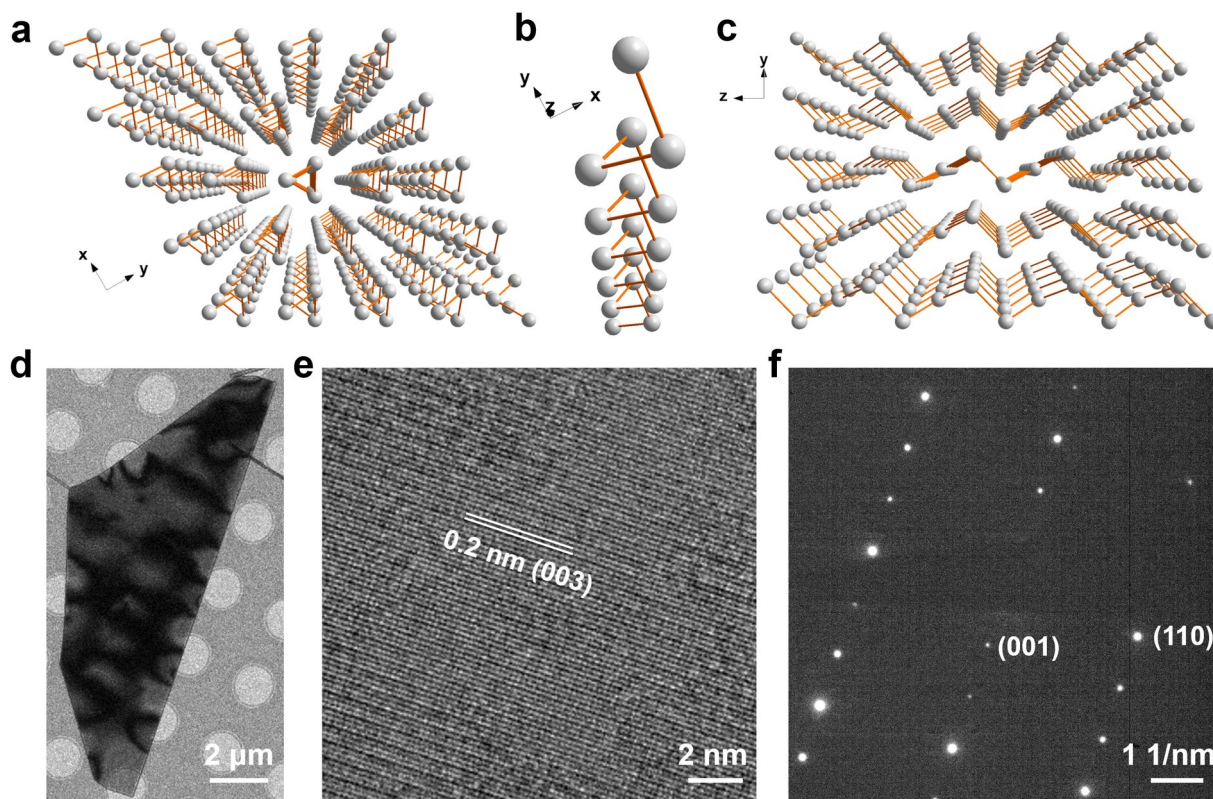
417 Transmission electron microscopy (TEM) images were performed at the  
418 National Center for Electron Microscopy at Laurence Berkeley National  
419 Laboratory using a FEI Titan 60–300 microscope operated at 200kV. Tapping  
420 mode atomic force microscope (AFM) measurements were conducted on a  
421 Dimension ICON AFM (Bruker, Germany) under ambient conditions. A AXS D8  
422 Discover GADDS X-ray diffractometer (Bruker, Germany) equipped with a  
423 Vantec-500 area detector and a Co K $\alpha$  ( $\lambda=1.7903$  Å) X-ray source was used  
424 to measure the powder X-ray diffraction (XRD) pattern. The Raman spectrum  
425 was measured on Horiba Jobin Yvon LabRAM ARAMIS automated scanning  
426 confocal Raman microscope system with the excitation line of 532 nm  
427 (Horiba, Ltd. Japan). The Raman band of a silicon wafer at 520 cm $^{-1}$  was used  
428 as the reference to calibrate the spectrometer.

#### 429 **Optical/Electrical Characterization**

430 Samples for absorption/reflection measurements were transferred onto KBr  
431 substrates using a previously established dry transfer technique and were  
432 measured in an FTIR microscope (ThermoFisher).<sup>35</sup> Electrical measurements  
433 were performed in a cryogenic protestation (LakeShore) with a B1500a  
434 Semiconductor Parameter Analyzer (Agilent). Spectral photoresponse  
435 measurements were performed in a FTIR spectrometer (ThermoFisher) with a

436 customized Janis cryostat equipped with a CaF<sub>2</sub> window. Devices were wire  
437 bonded in a 24 pin chip carrier and evacuated to a base pressure of < 10<sup>-5</sup>  
438 Torr. The cryostat was then placed at the auxiliary exit port of the FTIR, and  
439 the exciting illumination from the tungsten lamp source was focused on the  
440 sample using either a CaF<sub>2</sub> lens or a 15× Schwarzschild objective. The optical  
441 velocity of the FITR was set to either 0.1515 or 0.4747 cm s<sup>-1</sup>; the resulting  
442 modulation frequency range (7.5 kHz to 300 Hz) is within the operating  
443 regime of the frequency response. The photocurrent from the Te devices was  
444 then sent to a current amplifier (Stanford Research Systems), which also  
445 provided the bias voltage. The resulting signal was subsequently returned to  
446 the external detector interface of the FTIR. The relative intensity of the  
447 illumination source was measured using the internal Deuterated Triglycine  
448 Sulfate (DTGS) detector of the FTIR with identical measurement conditions.  
449 The photoresponse was calibrated using a NIST traceable Ge photodiode  
450 (ThorLabs) with a 100 μm aperture placed in the same position as the device  
451 under measurement. The frequency response of the devices was measured  
452 using a directly modulated 1550 nm laser diode. Further details and a  
453 schematic of the measurement setup are provided in ref. 35.

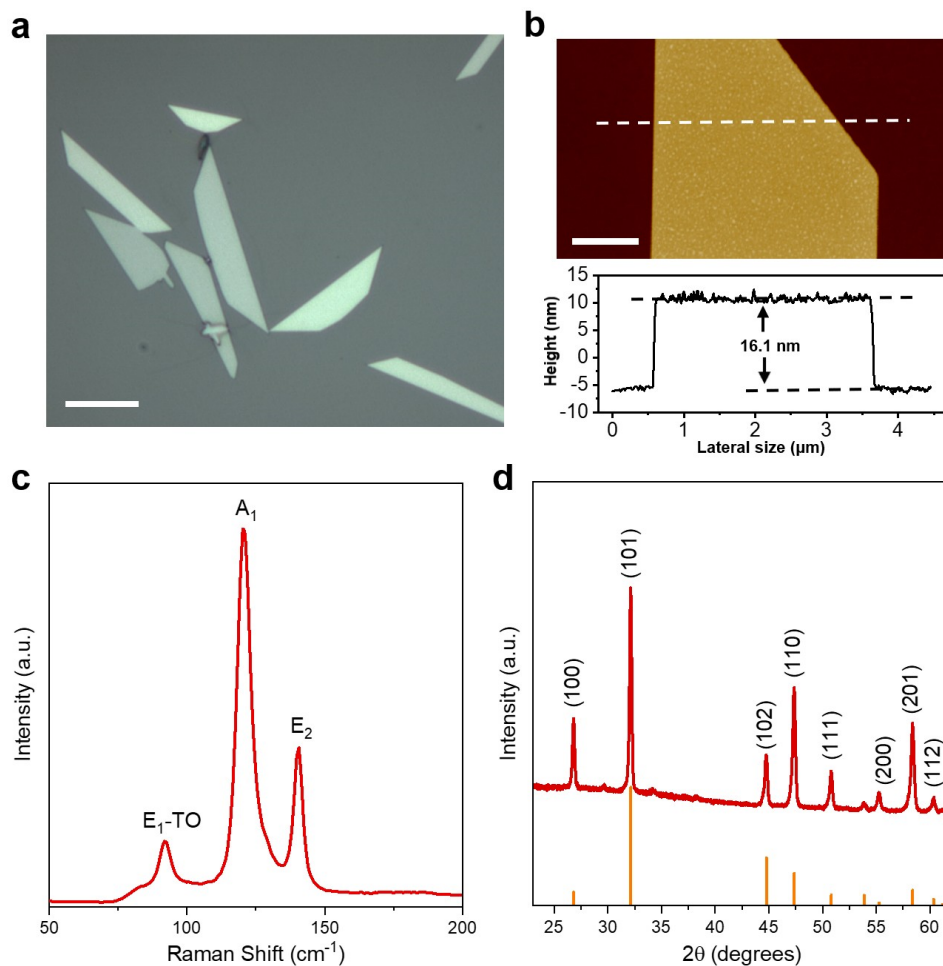
454



455

456 **Figure 1.** Crystal structure of tellurium: (a) viewed from x-axis, (b) single-  
 457 molecular chain and (c) viewed from z-axis. (d) TEM image, (e)  
 458 corresponding HR-TEM image and (f) SAED pattern of a typical tellurium  
 459 nanoflake.

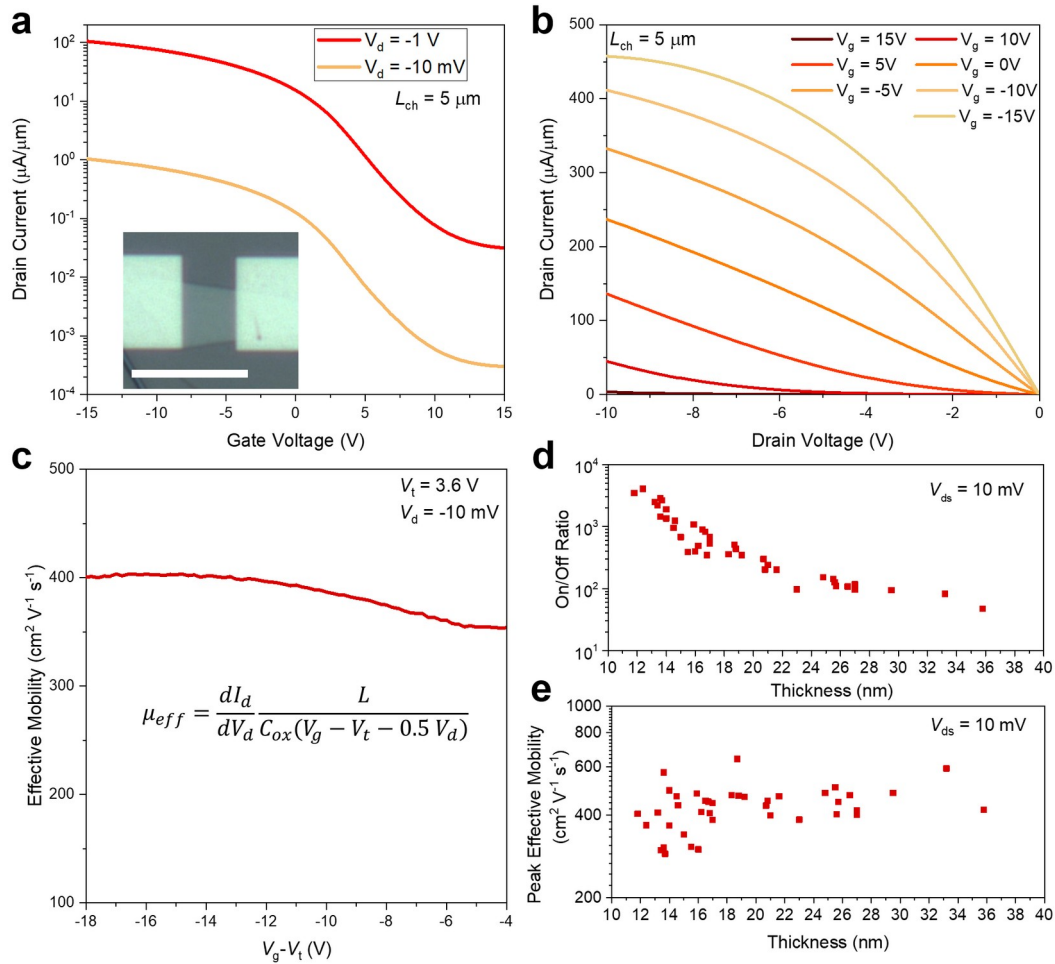
460



461

462 **Figure 2.** (a) Optical microscope image of tellurium nanoflakes deposited on  
 463 a SiO<sub>2</sub>/Si substrate, scale bar is 10 μm. (b) AFM image of typical tellurium  
 464 nanoflake (top) and the corresponding height profile (bottom), scale bar is 1  
 465 μm. (c) Raman spectrum of tellurium nanoflakes. (d) XRD pattern of dried  
 466 tellurium nanoflake powder.

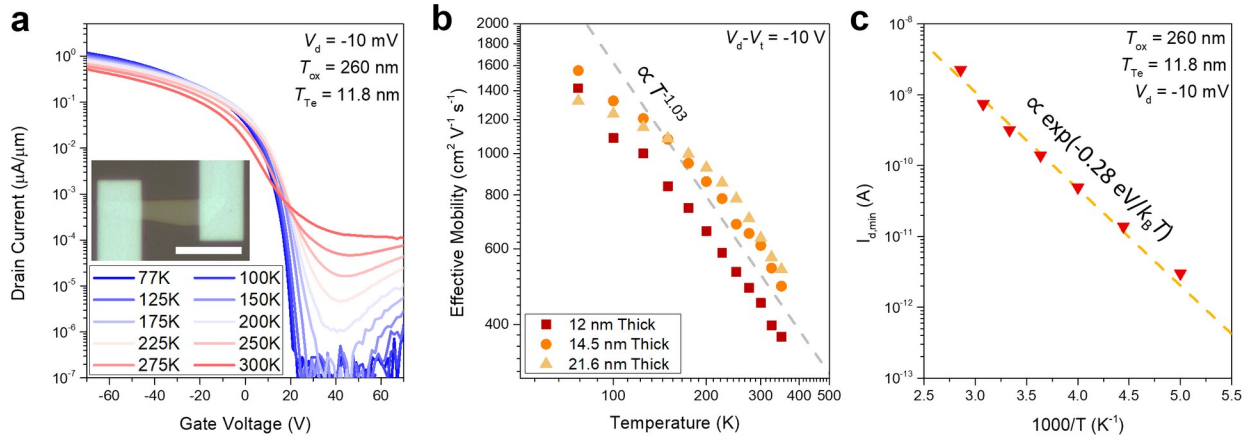
467



468

469 **Figure 3.** (a) Back-gated  $I_d$ - $V_g$  characteristics of a 12.3 nm thick Te  
 470 nanoflake with Pd contacts on 50 nm  $\text{SiO}_2$  measured at room temperature;  
 471 inset shows optical image of the device, scale bar is 10  $\mu\text{m}$ . (b)  $I_d$ - $V_d$   
 472 measured for the same device as shown in panel (a). (c) Effective mobility as  
 473 a function of gate overdrive voltage for the device shown in panel (a) under  
 474 a  $V_d$  of -10 mV, giving a peak mobility value of 619  $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ . (d) Thickness  
 475 dependence of the on/off ratio measured for Te nanoflakes of varying  
 476 thickness in the range of 12-36 nm. (e) Thickness dependence of the peak  
 477 effective mobility measured for Te nanoflakes of varying thickness in the  
 478 range of 12-36 nm.

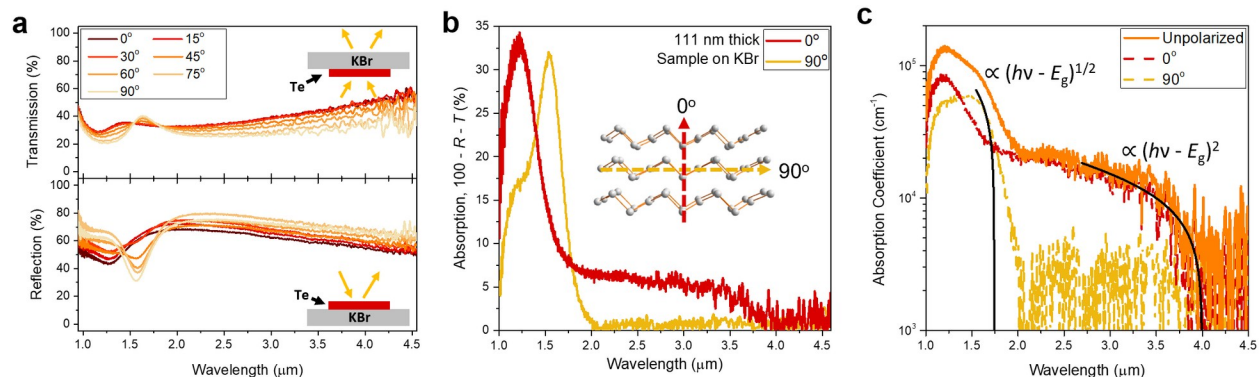




480

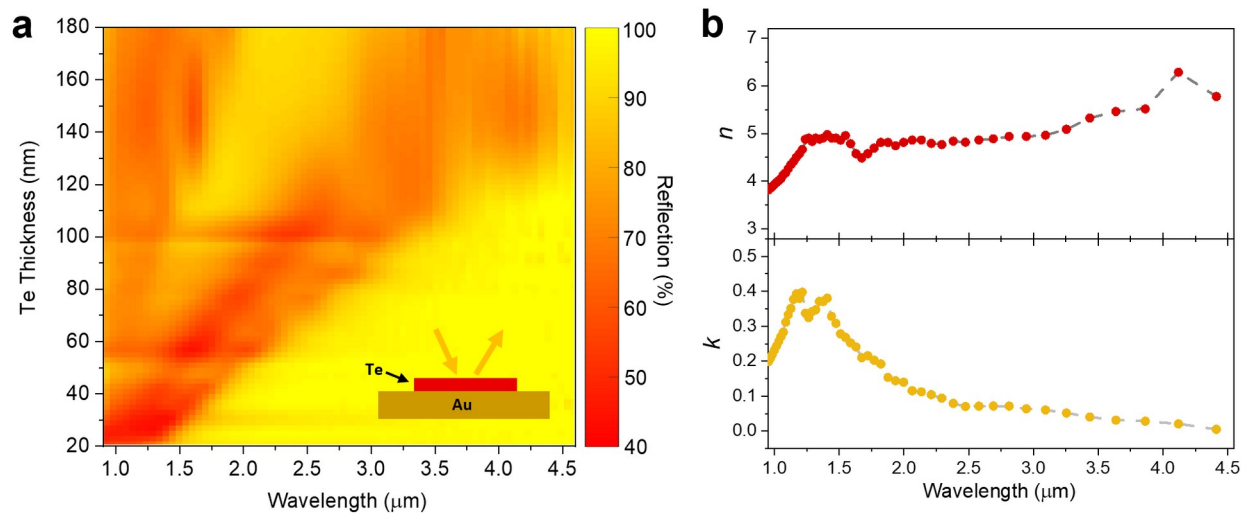
481 **Figure 4.** (a) Temperature dependent  $I_d$ - $V_g$  characteristics of a 12 nm thick  
 482 Te nanoflake, measured at a low  $V_d$  of -10 mV. Scale bar is 5  $\mu\text{m}$ . (b)  
 483 Effective mobility for quasi-2D Te nanoflakes with varying thickness as a  
 484 function of temperature extracted from panel (a) and Figure S1 at a constant  
 485 gate overdrive voltage of -10 V, dashed line shows a power law fit. (c)  
 486 Arrhenius plot showing the minimum drain source current ( $I_{d,\text{min}}$ ) as a function  
 487 of temperature extracted from the data shown in panel (a).

488



489

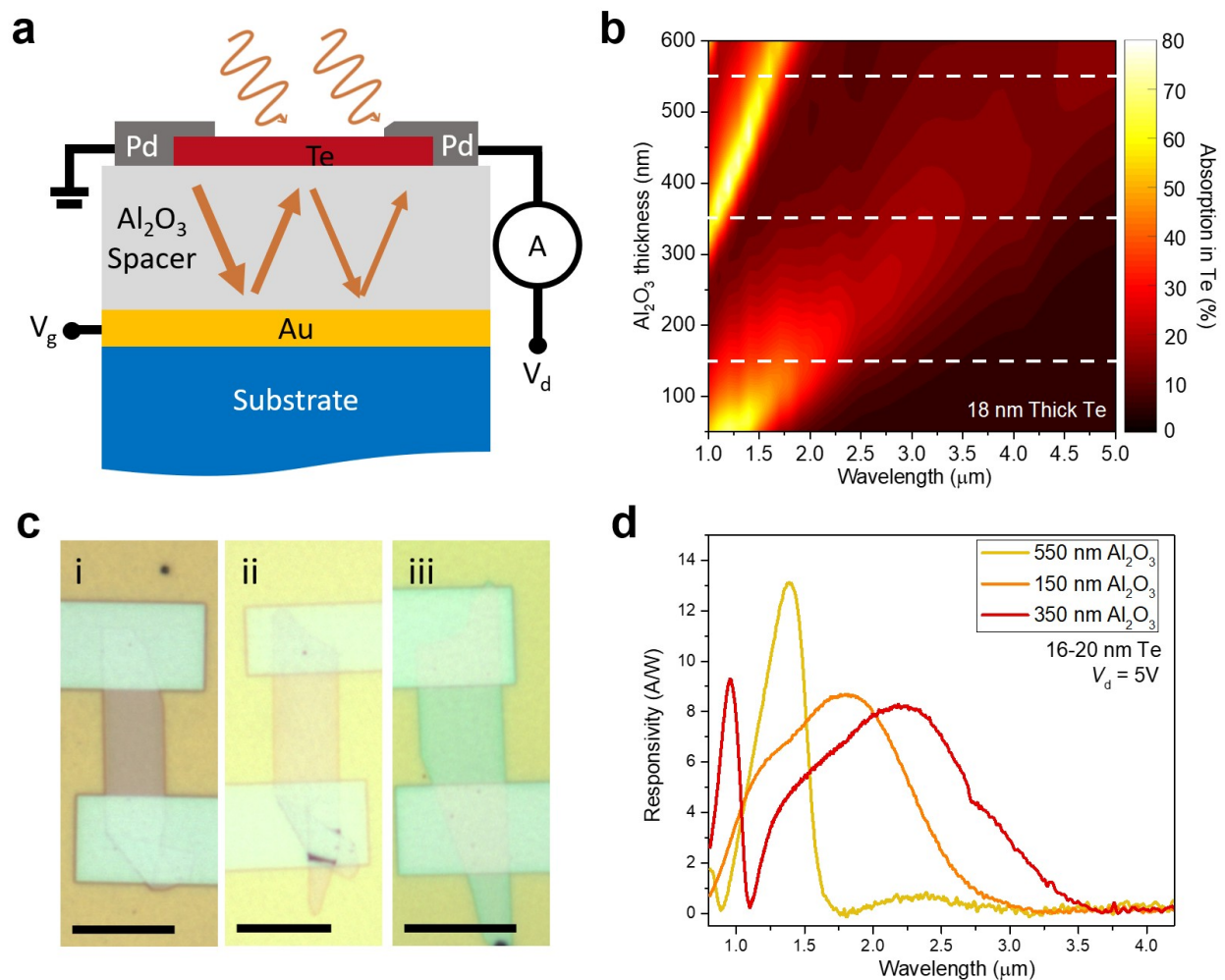
490 **Figure 5.** (a) Polarization resolved transmission and reflection spectra  
 491 measured for a 111 nm thick Te nanoflake transferred on a KBr substrate,  
 492 insets show the optical configuration used during measurements. (b)  
 493 Absorption spectra for the nanoflake measured in panel (a), calculated from  
 494  $100\% - T - R$ . Inset shows the Te crystal directions of  $0^\circ$  and  $90^\circ$ . (c) Absorption  
 495 coefficient of tellurium for unpolarized light, as well as light aligned parallel  
 496 to z-axis ( $0^\circ$ ) and y-axis ( $90^\circ$ ) of Te crystal; Tauc plots and optical bandgap  
 497 extraction for light polarized perpendicular and parallel to the wire axis are  
 498 shown in Figure S2.



499

500 **Figure 6.** (a) Reflection of quasi-2D Te nanoflakes on Au substrates, with Te  
 501 thickness ranging from 20 nm to 180 nm. Plot is obtained from interpolation  
 502 of spectra taken on 18 Te crystal nanoflakes of varying thicknesses, shown in  
 503 Figure S3. (b) Complex refractive index of quasi-2D Te nanoflakes calculated  
 504 by fitting measured reflection data as a function of thickness.

505

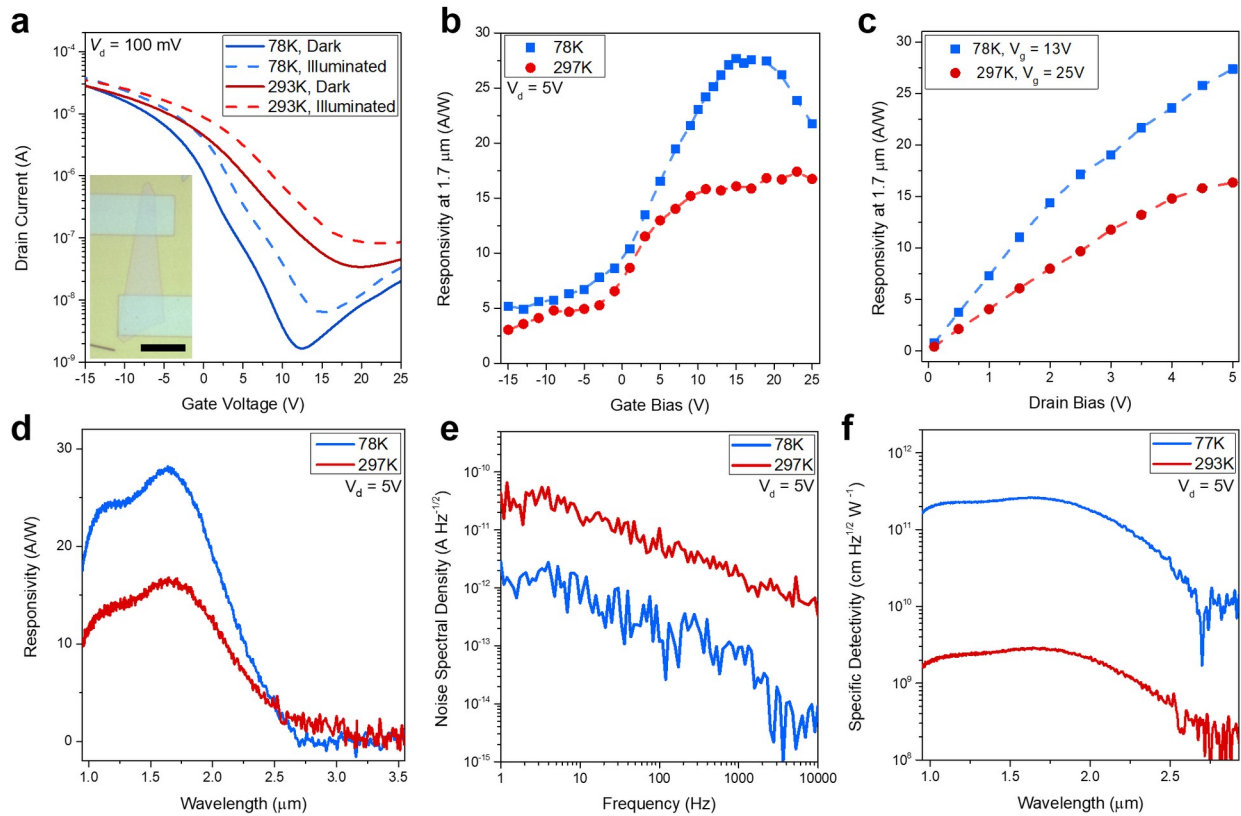


506

507 **Figure 7.** (a) Schematic showing the optical cavity structure used to  
 508 fabricate SWIR photoconductors from quasi-2D Te nanoflakes in this study.  
 509 An evaporated Au film acts as the gate electrode and back-reflector, while a  
 510 Al<sub>2</sub>O<sub>3</sub> dielectric layer acts as a  $\sim\lambda/4$  spacer as well as the gate oxide. (b)  
 511 Calculated absorption in the Te layer, as a function of wavelength and Al<sub>2</sub>O<sub>3</sub>  
 512 thickness for a fixed semiconductor thickness of 18 nm. (c) Optical images of  
 513 SWIR photoconductors fabricated on optical cavities with Al<sub>2</sub>O<sub>3</sub> thickness of  
 514 550 nm (i), 150 nm (ii), and 350 nm (iii); scale bar is 10 μm. (d) Measured

515 responsivities of quasi-2D Te nanoflakes fabricated on optical cavities with  
516 different Al<sub>2</sub>O<sub>3</sub> thicknesses.

517

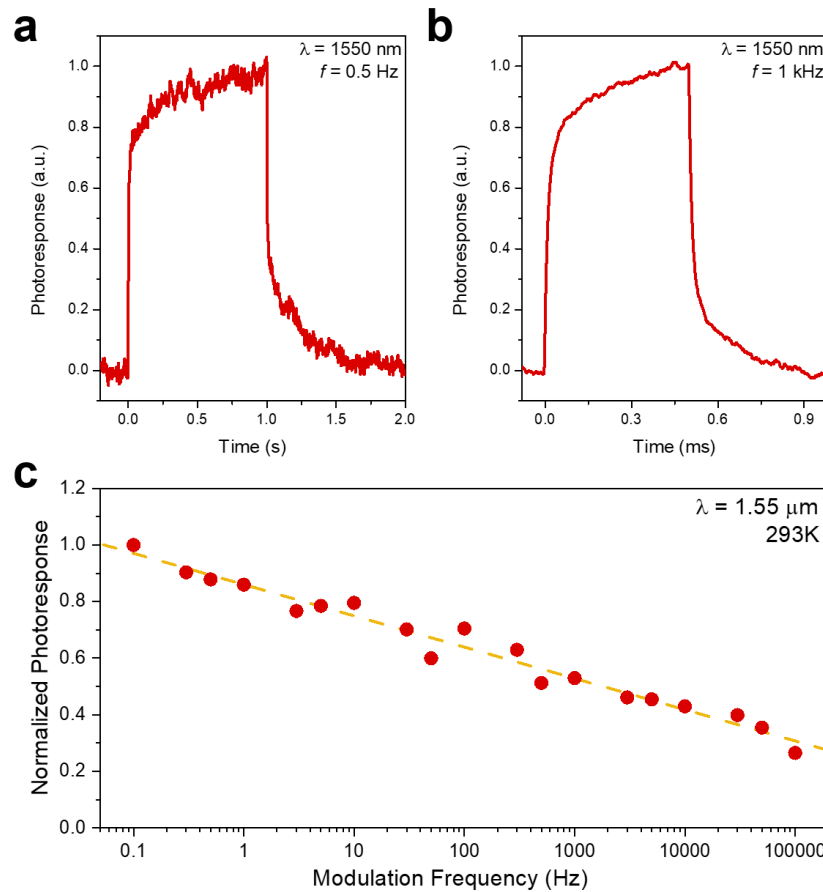


518

519 **Figure 8.** (a)  $I_d$ - $V_g$  characteristics of an 18.8 nm Te photoconductor  
 520 measured at 297K and 78K under illumination and in the dark. Inset shows  
 521 optical image of the measured device; scale bar is 10  $\mu$ m. (b) Responsivity at  
 522 1.7  $\mu$ m measured at 297K and 78K as a function of gate bias, at a constant  
 523 drain bias of  $V_d = 5$  V. (c) Responsivity at 1.7  $\mu$ m measured at 297K and 78K  
 524 as a function of drain bias at an optimized gate bias ( $V_g = 13$  V at 78K and  $V_g$   
 525 = 25 V at 297K). (d) Spectral responsivity per watt of a Te photoconductor  
 526 measured at 78K and 297K under optimized gate bias and  $V_d = 5$  V. (e) Noise  
 527 spectrum measured at room temperature for a Te photoconductor operated  
 528 with optimized gate bias and a  $V_d = 5$  V and optimized gate bias. (f) Specific  
 529 detectivity of Te photoconductors with optimized thickness; measurements  
 530 were performed under gating conditions which maximized detectivity for the

531 specific device at room temperature. Note that an Au/Al<sub>2</sub>O<sub>3</sub> substrate with an  
532 Al<sub>2</sub>O<sub>3</sub> thickness of 150 nm was used for the measurements.

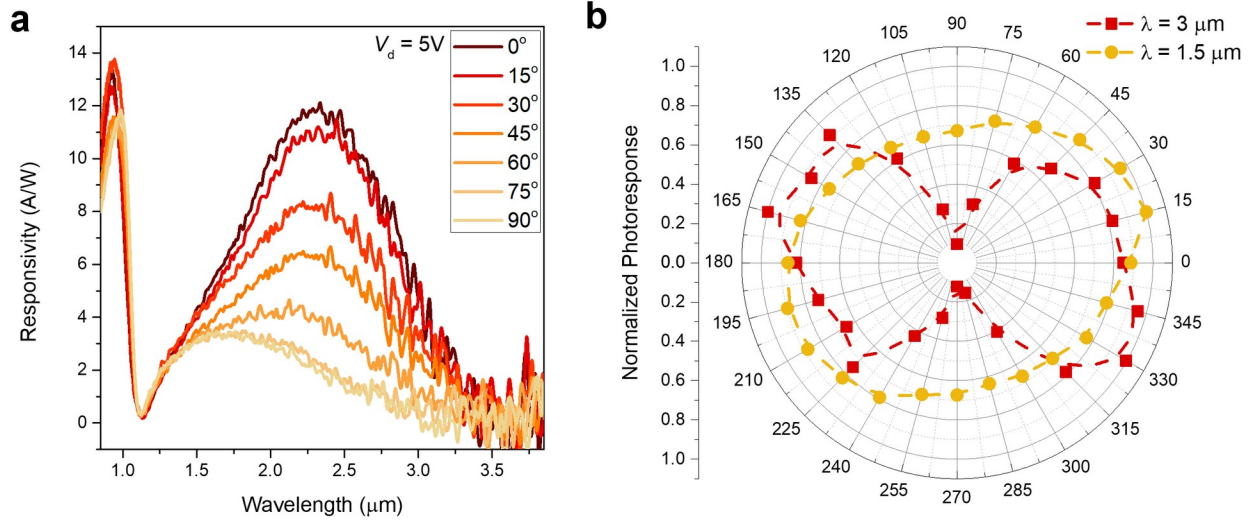
533



534  
535 **Figure 9.** (a) Room-temperature step response of an 18.8nm thick Te  
536 photoconductor, excited by a 1550-nm laser modulated  $\lambda$  by a 0.5 Hz square  
537 wave. (b) Room-temperature step response of a Te photoconductor, excited  
538 by a 1550 nm laser modulated by a 1 kHz square wave. (c) Normalized  
539 photoresponse of a Te photoconductor *versus* modulation frequency; the  
540 device is excited using a sinusoidally modulated 1550 nm laser. Note that an  
541 Au/Al<sub>2</sub>O<sub>3</sub> substrate with an Al<sub>2</sub>O<sub>3</sub> thickness of 150 nm was used for the  
542 measurements.

543

544



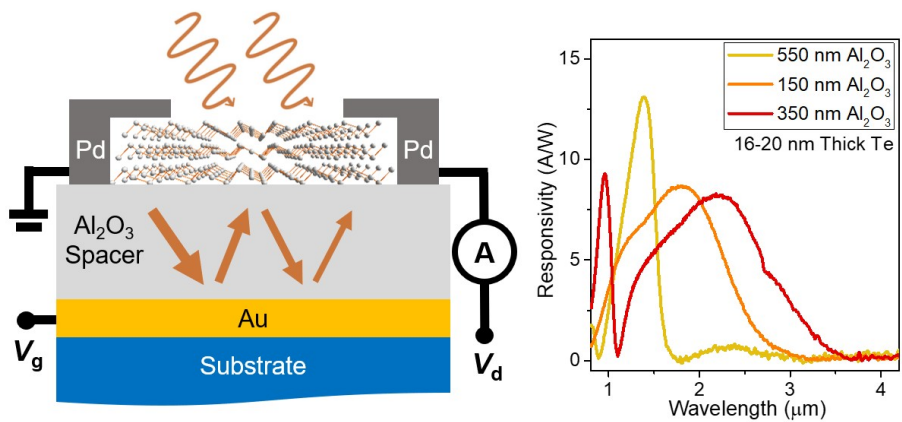
545

546 **Figure 10.** (a) Polarization resolved photoresponse of an 18.8 nm thick  
 547 quasi-2D Te nanoflake fabricated on an optical cavity with a 350 nm thick  
 548  $\text{Al}_2\text{O}_3$ . (b) Polar plot showing the relative response of the device shown in  
 549 panel (a) at wavelengths of 3 μm and 1.5 μm as a function of polarization.

550

551

### TOC Graphic



552

553

554 ASSOCIATED CONTENT

555 **Supporting Information**

556 The Supporting Information is available free of charge on the ACS  
557 Publications website.

558 Temperature dependent electrical characterization of additional  
559 devices. Tauc plot used to extract direct and indirect bandgap of Te.  
560 Reflection spectra used to create plot in Fig. 6a. Photoresponse  
561 measurements for devices prepared on Si/SiO<sub>2</sub> substrates. Reflection  
562 spectra taken on Te photoconductors.

563 AUTHOR INFORMATION

564 **Corresponding Author**

565 \*E-mail: ajavey@berkeley.edu

566

567 **ORCID**

568 Matin Amani: 0000-0002-7912-6559

569 Chaoliang Tan: 0000-0003-1695-5285

570 George Zhang: 0000-0002-1741-5267

571 James Bullock: 0000-0001-7903-9642

572 Xiaohui Song: 0000-0001-7713-1373

573 Vivek Raj Shrestha: 0000-0002-7731-7677

574 Yang Gao: 0000-0002-9004-8483

575 Kenneth Crozier: 0000-0003-0947-001X

576 Mary Scott: 0000-0002-9543-6725

577 Ali Javey: 0000-0001-7214-7931

578

579 **ACKNOWLEDGEMENT**

580 Device fabrication and measurements were supported by the Defense  
581 Advanced Research Projects Agency under contract no. HR0011-16-1-0004.  
582 Synthesis work was supported by the U.S. Department of Energy, Office of  
583 Science, Office of Basic Energy Sciences, Materials Sciences and Engineering  
584 Division under contract no. DE-AC02-05CH11231 within the Electronic  
585 Materials Program (KC1201). Work at the Molecular Foundry was supported

586 by the Office of Science, Office of Basic Energy Sciences, of the U.S.  
587 Department of Energy under Contract No. DE-AC02-05CH11231.  
588

589 **References**

- 590 1. Alamo, J. A. Nanometre-Scale Electronics with III-V Compound  
591 Semiconductors. *Nature* **2011**, 479, 317-323.
- 592 2. Chuang, S.; Gao, Q.; Kapadia, R.; Ford, A. C.; Guo, J.; Javey, A. Ballistic InAs  
593 Nanowire Transistors. *Nano Lett.* **2012**, 13, 555-558.
- 594 3. Barve, A. V.; Lee, S. J.; Noh, S. K.; Krishna, S. Review of Current Progress in  
595 Quantum Dot Infrared Photodetectors. *Laser Photon. Rev.* **2009**, 4, 738-  
596 750.
- 597 4. Hoang, A. M.; Dehzangi, A.; Adhikary, S.; Razeghi, M. High Performance  
598 Bias-Selectable Three-Color Short-Wave/Mid-Wave/Long-Wave in Infrared  
599 Photodetectors based on Type-II InAs/GaSb/AlSb Superlattices. *Sci. Rep.*  
600 **2016**, 6, 24144.
- 601 5. Martyniuk, P.; Antoszewski, J.; Martyniuk, M.; Faraone, L.; Rogalski, A. New  
602 Concepts in Infrared Photodetector Designs. *Appl. Phys. Rev.* **2014**, 1,  
603 041102.
- 604 6. Martinelli, R. U.; Zamerowski, T. J.; Longeway, P. A. 2.6  $\mu\text{m}$  InGaAs  
605 Photodiodes. *Appl. Phys. Lett.* **1988**, 53, 989-991.
- 606 7. Nishida, K.; Taguchi, K.; Matsumoto, Y. InGaAsP Heterostructure Avalanche  
607 Photodiodes With High Avalanche Gain. *Appl. Phys. Lett.* **1979**, 35, 251-  
608 253.
- 609 8. Chen, K.; Kapadia, R.; Harker, A.; Desai, S.; Kang, J. S.; Chuang, S.; Tosun,  
610 M.; Sutter-Fella, C. M.; Tsang, M.; Zeng, Y.; Kiriya, D.; Hazra, J.;  
611 Madhvapathy, S. R.; Hettick, M.; Chen, Y.-Z.; Mastandrea, J.; Amani, M.;  
612 Cabrini, S.; Chueh, Y.-L.; Ager, J. W.; Chrzan, D. C.; Javey, A. Direct Growth

- 613 of Single Crystalline III-V Semiconductors on Amorphous Substrates. *Nat.*  
614 *Comm.* **2016**, 7, 10502.
- 615 9. Ko, H.; Takei, K.; Kapadia, R.; Chuang, S.; Fang, H.; Leu, P. W.; Ganapathi,  
616 K.; Plis, E.; Chen, S.-Y.; Madsen, M.; Ford, A. C.; Chueh, Y.-L.; Krishna, S.;  
617 Salahuddin, S.; Javey, A. Ultrathin Compound Semiconductor on Insulator  
618 Layers for High-Performance Nanoscale Transistors. *Nature* **2010**, 468,  
619 286-289.
- 620 10. Fitzgerald, E. A.; Xie, Y.-H.; Monroe, D.; Silverman, P. J.; Kuo, J. M.;  
621 Kortan, A. R.; Thiel, F. A.; Weir, B. E. Relaxed  $\text{Ge}_x\text{Si}_{1-x}$  Structures for III-V  
622 Integration with Si and High Mobility Two-Dimensional Electron Gasses in  
623 Si. *J. Vac. Sci. Technol. B* **1992**, 10, 1807-1819.
- 624 11. Kim, Y.; Cruz, S. S.; Lee, K.; Alawode, B. O.; Choi, C.; Song, Y.; Johnson, J.  
625 M.; Heidelberger, C.; Kong, W.; Choi, S.; Qiao, K.; Almansouri, I.; Fitzgerald,  
626 E. A.; Kong, J.; Kolpak, A. M.; Hwang, J.; Kim, J. Remote Epitaxy Through  
627 Graphene Enables Two-Dimensional Material-Based Layer Transfer. *Nature*  
628 **2017**, 554, 340-343.
- 629 12. Li, T.; Cheng, J.-F.; Shao, X.-M.; Deng, H.-H.; Chen, Y.; Tang, H.-J.; Li, X.;  
630 Gong, H.-M. Performance of Low Dark Current InGaAs Shortwave Infrared  
631 Detector. *Proc. SPIE.* **2012**, 8419.
- 632 13. Tan, C.; Cao, X.; Wu, X.-J.; He, Q.; Yang, J.; Zhang, X.; Chen, J.; Zhao, W.;  
633 Han, S.; Nam, G.-H.; Sindoro, M.; Zhang, H. Recent Advances in Ultrathin  
634 Two-Dimensional Materials. *Chem. Rev.* **2017**, 117, 6225-6331.
- 635 14. Lin, Z.; McCreary, A.; Briggs, N.; Subramanian, S.; Zhang, K.; Sun, Y.; Li,  
636 X.; Borys, N. J.; Yuan, H.; Fullerton-Shirey, S. K.; Chernikov, A.; Zhao, H.;

637 McDonnell, S.; Lindenberg, A. M.; Xiao, K.; LeRoy, B. J.; Drndić, M.; Hwang,  
638 J. C.M.; Park, J.; Chhowalla, M.; *et al.* 2D Materials Advances: From Large  
639 Scale Synthesis and Controlled Heterostructures to Improved  
640 Characterization Techniques, Defects and Applications. *2D Mater.* **2016**, 3,  
641 042001.

642 15. Amani, M.; Lien, D.-H.; Kiriya, D.; Xiao, J.; Azcatl, A.; Noh, J.;  
643 Madhvapathy, S. R.; Addou, R.; Kc, S.; Dubey, M.; Cho, K.; Wallace, R. M.;  
644 Lee, S.-C.; He, J.-H.; Ager, J. W.; Zhang, X.; Yablonovitch, E.; Javey, A. Near-  
645 Unity Photoluminescence Quantum Yield in MoS<sub>2</sub>. *Science* **2015**, 350,  
646 1065-1068.

647 16. Amani, M.; Taheri, P.; Addou, R.; Ahn, G. H.; Kiriya, D.; Lien, D.-H.; Ager,  
648 J. W.; Wallace, R. M.; Javey, A. Recombination Kinetics and Effects of  
649 Superacid Treatment in Sulfur- and Selenium Based Transition Metal  
650 Dichalcogenides. *Nano Lett.* **2016**, 16, 2786-2791.

651 17. Desai, S. B.; Madhvapathy, S. R.; Sachid, A. B.; Llinas, J. P.; Wang, Q.;  
652 Ahn, G. H.; Pitner, G.; Kim, M. J.; Bokor, J.; Hu, C.; Wong, H.-S. P.; Javey, A.  
653 MoS<sub>2</sub> Transistors with 1-Nanometer Gate Lengths. *Science* **2016**, 354, 99-  
654 102.

655 18. Lien, D.-H.; Amani, M.; Desai, S. B.; Ahn, G. H.; Han, K.; He, J.-H.; Ager,  
656 J. W.; Wu, M. C.; Javey, A. Large-Area and Bright Pulsed  
657 Electroluminescence in Monolayer Semiconductors. *Nat. Comm.* **2018**, 9,  
658 1299.

659 19. Zhang, Y. J.; Oka, T.; Suzuki, R.; Ye, J. T.; Iwasa, Y. Electrically Switchable  
660 Chiral Light-Emitting Transistor. *Science* **2014**, 344, 725-728.

- 661 20. Zhao, P.; Amani, M.; Lien, D.-H.; Ahn, G. H.; Kiriya, D.; Mastandrea, J. P.;  
662 Ager, J. W.; Yablonovitch, E.; Chrzan, D. C.; Javey, A. Measuring the Edge  
663 Recombination Velocity of Monolayer Semiconductors. *Nano Lett.* **2017**,  
664 17, 5356-5360.
- 665 21. Wang, Y.; Qiu, G.; Wang, R.; Huang, S.; Wang, Q.; Liu, Y.; Du, Y.;  
666 Goddard, W. A.; Kim, M. J.; Xu, X.; Ye, P. D.; Wu, W. Field-Effect Transistors  
667 made from Solution-Grown Two-Dimensional Tellurene. *Nat. Electron.*  
668 **2018**, 1, 228-236.
- 669 22. von Hippel, A. Structure and Conductivity in the VIb Group of the  
670 Periodic System. *J. Chem. Phys.* **1948**, 16, 372-380.
- 671 23. Yi, S.; Zhu, Z.; Cai, X.; Jia, Y.; Cho, J.-H. The Nature of Bonding in Bulk  
672 Tellurium Composed of One-Dimensional Helical Chains. *Inorg. Chem.*  
673 **2018**, DOI: 10.1021/acs.inorgchem.7b03244.
- 674 24. Wu, B.; Liu, X.; Yin, J.; Lee, H. Bulk  $\beta$ -Te to Few Layered  $\beta$ -Tellurenes:  
675 Indirect to Direct Band-Gap Transitions Showing Semiconductor Property.  
676 *Mater. Res. Express* **2017**, 4,095902.
- 677 25. Qian, H.; Yu, S.; Gong, J.; Luo, L.; Fei, L. High-Quality Luminescent  
678 Tellurium Nanowires of Several Nanometers in Diameter and High Aspect  
679 Ratio Synthesized by a Poly(Vinyl Pyrrolidone)-Assisted Hydrothermal  
680 Process. *Langmuir* **2006**, 22, 3830-3835
- 681 26. Du, Y.; Qiu, G.; Wang, Y.; Si, M.; Xu, X.; Wu, W.; Ye, P. D. 1D van der  
682 Waals Material Tellurium: Raman Spectroscopy under Strain and Magneto-  
683 transport  
684 Source. *Nano Lett.* **2017**, 17, 3965-3973.

- 685 27. Liu, H.; Neal, A. T.; Zhu, Z.; Luo, Z.; Xu, X.; Tomanek, D.; Ye, P. D.  
686 Phosphorene: An Unexplored 2D Semiconductor with a High Hole Mobility.  
687 *ACS Nano* **2014**, 8, 4033-4041.
- 688 28. Li, L.; Yu, Y.; Ye, G. J.; Ge, Q.; Ou, X.; Wu, H.; Feng, D.; Chen, X. H.;  
689 Zhang, Y. Black Phosphorus Field-Effect Transistors. *Nat. Nano.* **2014**, 9,  
690 372-377.
- 691 29. Takei, K.; Madsen, M.; Fang, H.; Kapadia, R.; Chuang, S.; Kim, H. S.; Liu,  
692 C.-H.; Plis, E.; Nah, J.; Krishna, S.; Chueh, Y.-L. Guo, J.; Javey, A. Nanoscale  
693 InGaSb Heterostructure Membranes on Si Substrates for High Hole  
694 Mobility Transistors. *Nano Lett.* **2012**, 12, 2060-2066.
- 695 30. Radisavljevic, B.; Kis A. Mobility Engineering and a Metal-Insulator  
696 Transition in Monolayer MoS<sub>2</sub>. *Nat. Matter.* **2013**, 12, 815-820.
- 697 31. Javey, A.; Guo, J.; Farmer, D. B.; Wang, Q.; Wang, D.; Gordon, R. C.;  
698 Lundstrom, M.; Dai, H. Carbon Nanotube Field-Effect Transistors with  
699 Integrated Ohmic Contacts and High-κ Gate Dielectrics. *Nano Lett.* **2004**,  
700 4, 447-450.
- 701 32. Lien, D.-H.; Kang, J. S.; Amani, M.; Chen, K.; Tosun, M.; Wang, H.-P.; Roy,  
702 T.; Eggleston, M. S.; Wu, M. C.; Dubey, M.; Lee, S.-C.; He, J.-H.; Javey, A.  
703 Engineering Light Outcoupling in 2D Materials. *Nano Lett.* **2015**, 15, 1356-  
704 1361.
- 705 33. Zhang, H.; Ma, Y.; Wan, Y.; Rong, X.; Xie, Z.; Wang, W.; Dai, L. Measuring  
706 the Refractive Index of Highly Crystalline, Monolayer MoS<sub>2</sub> with High  
707 Confidence. *Sci. Rep.* **2015**, 5, 8440.
- 708 34. Born, M.; Wolf. E. Principles of optics: Electromagnetic Theory of

709 Propagation, Interference and Diffraction Light. Cambridge University  
710 Press, Cambridge (2002).

711 35. Amani, M.; Regan, E.; Bullock, J.; Ahn, G. H.; Javey, A. Mid-Wave  
712 Infrared Photoconductors based on Black Phosphorous-Arsenic Alloys. *ACS*  
713 *Nano* **2017**, 11, 11724-11731.

714 36. Guo, Q.; Pospischil, A.; Bhuiyan, M. Jiang, H.; Tian, H.; Farmer, D.; Deng,  
715 B.; Li, C.; Han, S.-J.; Wang, H.; Xia, Q.; Ma, T.-P. Mueller, T.; Xia, F. Black  
716 Phosphorus Mid-Infrared Photodetectors with High Gain. *Nano Lett.* **2016**,  
717 16, 4648-4655.

718 37. Piotrowski, J.; Gawron, W. Ultimate Performance of Infrared  
719 Photodetectors and Figure of Merit of Detector Material. *Infar. Phys.*  
720 *Technol.* **1997**, 38, 63-68.

721 38. Vincent, J. D. Fundamentals of Infrared Detector Operation and Testing.  
722 Wiley, New York (1990).

723 39. Petritz, R. L. Theory of Photoconductivity in Semiconductor Film. *Phys.*  
724 *Rev.* **1956**, 104, 1508-1516.

725 40. Beck, W. A. Photoconductive Gain and Generation-Recombination Noise  
726 in Multiple-Quantum-Well Infrared Detectors. *Appl. Phys. Lett.* **1993**, 63,  
727 3589-3591.

728 41. Ye, Z.; Campbell, J. C.; Chen, Z.; Kim, E.-T., Madhukar, A. Noise and  
729 Photoconductive Gain in InAs Quantum-Dot Infrared Photodetectors. *Appl.*  
730 *Phys. Lett.* **2003**, 83, 1234-1236.

731  
732