Electronic Supplementary Material (ESI) for Nanoscale.

Electronic Supplementary Information:

Ultra-sensitive graphene-bismuth telluride nano-wire hybrids for infra-red detection

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1. Fabrication of nano-wires:

(a) Growth procedure

The bismuth telluride (Bi_2Te_3) nano-wires were grown in two steps:

(1) Synthesis of tellurium (Te) nano-wires:

To synthesize Te nanowires, 0.2 g of poly-vinyl pyrrolidone (PVP) was dissolved in 5 ml of ethylene glycol. 0.3 mmol of TeO_2 and 10.7 mmol of KOH was added to the above solution and stirred continuously till it became a clear solution. The above solution was then transferred onto a microwave vial (maximum capacity-10ml) and then kept for microwave heating at 180^0 C for 15 min at 150 W power, at 250 psi pressure, with continuous stirring in a CEM DISCOVER-SP microwave.

(2) Synthesis of bismuth telluride nano-wires:

0.3 mmol of $Bi(NO_3)_3 \cdot 5H_2O$ was dissolved in 10 ml of ethylene glycol in a round bottom flask, onto which 5 ml of Tellurium nano-wire solution was added. The next step was to add 3 ml of hydrazine hydrate into the above solution, which leads to a reducing atmosphere. Finally, the solution was placed inside a microwave for heating at 120^0 C for 3 hours at 150 W power in a CEM DISCOVER-SP microwave.

(2) HR-TEM of the nanowires:

Sample preparation: The sample was cleaned thoroughly with ethanol and drop-casted on a formvar coated Cu grid for TEM analysis. Bright field TEM and the HRTEM images were captured in a FEI T20 super twin microscope, operated at 200 kV. The HAADF STEM imaging and the EDS mapping was done using FEI Titan microscope, operated at 300 kV, spot size 6, condenser aperture 50 µm, camera length 200 mm. Bi L-lines and Te L-lines were used for EDS quantitative analysis.

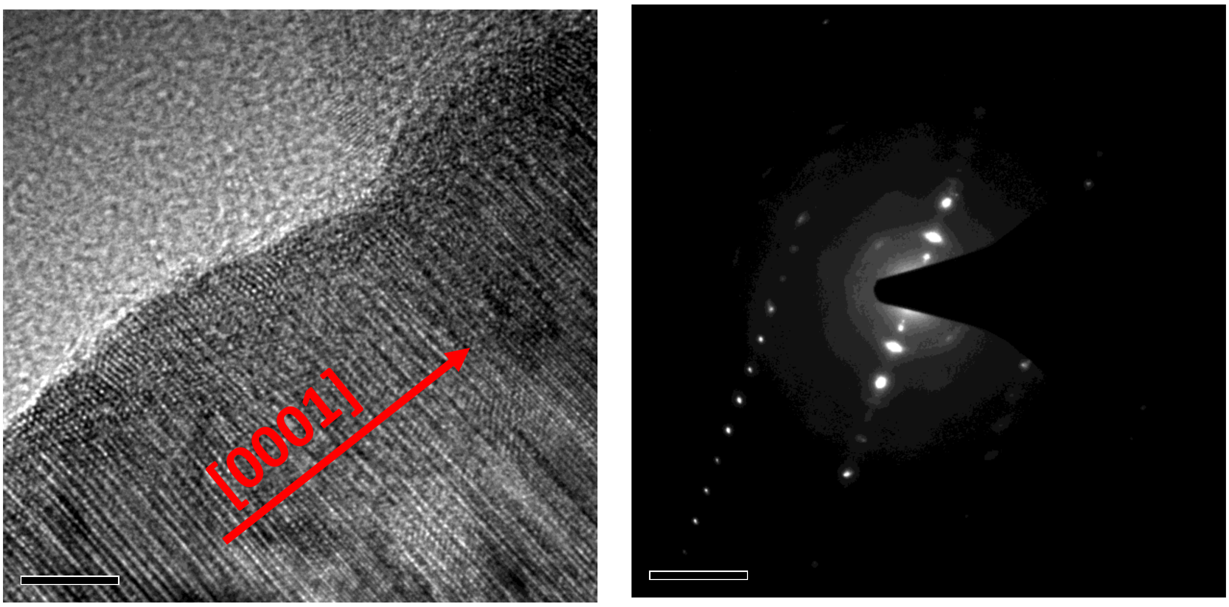

Figure S1: HR-TEM of the nano-wires showing the nanowire are separately single crystalline, with the growth direction being [0001] with respect to Te core

(3) Time scale of photo-response:

The time-scales for photo-response can be determined by modelling the resistance with an exponential function. We have fitted the resistance with a function of the form,

$$R(t) = R_0 + \Delta R\left(1 - exp\left(-\frac{t-t_0}{\tau}\right)\right) \qquad Eqn: 1$$

Here R_0 is the off-state resistance, ΔR is the change in the resistance between off and on state, and t_0 is the time when optical illumination is switched on. The time-scale can be estimated from the semi-log graph of $\gamma = 1 - \frac{R(t)-R_0}{\Delta R}$, plotted as a function of (t-t_0). The straight-line fit can be used to estimate the value as shown in the figure below. The time constant of these devices is 2-4 secs and is limited by the time constant of the lock-in amplifier (1 sec).

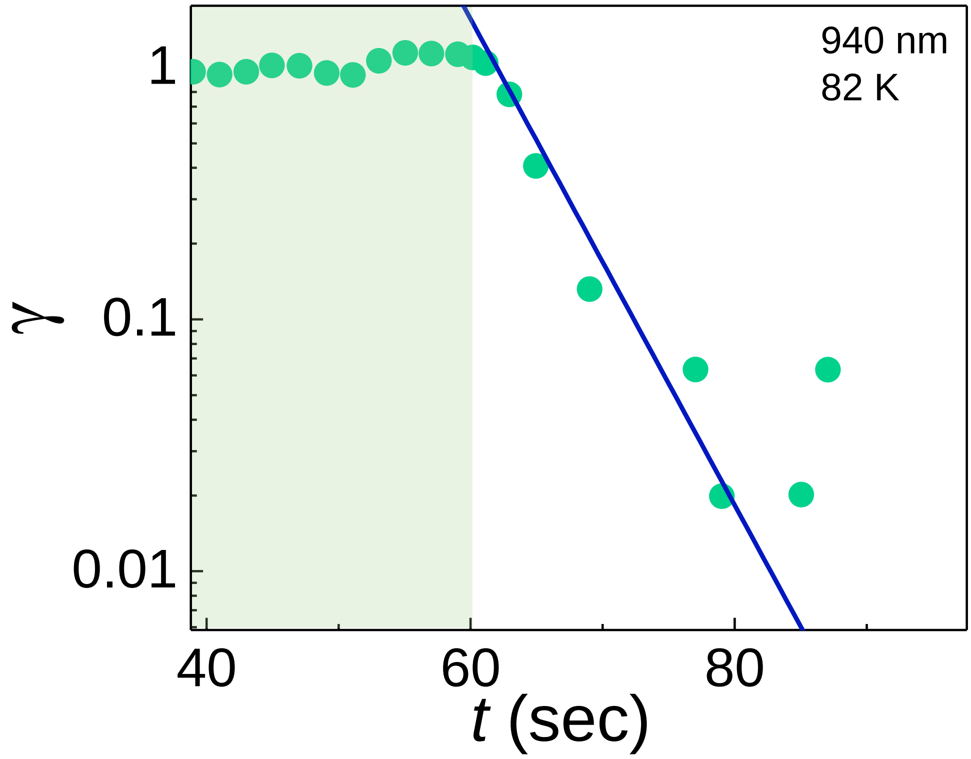

Figure S2: Extraction of time-scale of photo-response. The solid line is the fit to the date according to Eqn. 1.

4. Experimental evaluation of 1/*f* noise:

The magnitude of the flicker noise is given by the power spectra density (PSD) of the fluctuating quantity, in this case voltage, that is recorded as a function of time. The 1/*f* noise measurement was done using low-frequency AC-technique with carrier frequency of 227 Hz in a two-probe configuration. The 16-bit National Instrument DAQ card was used to transfer the data from the lock-in amplifier to the computer. The sampling frequency was 1000 Hz and the data were acquired for 300 secs. The time dependent voltage-fluctuation data was then processed digitally using a three-stage decimation process, followed by the power spectral-density (PSD) estimation. At T = 82 K, the magnitude of the current noise at frequency *f* = 1 Hz is ~ 2e-22 A^2Hz^{-1}.

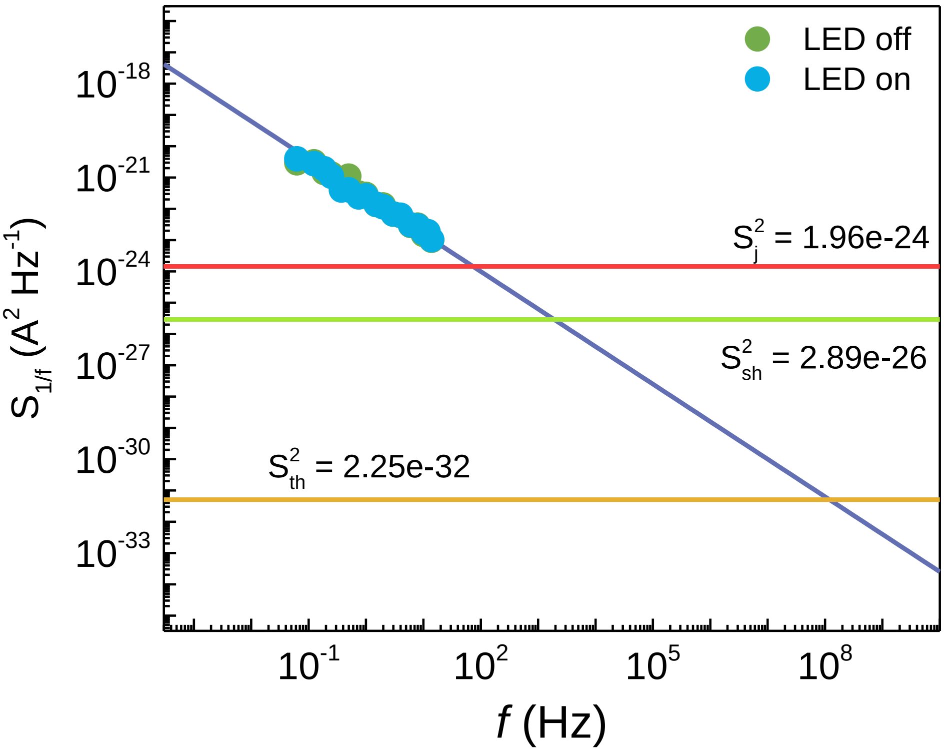

Figure S3: Experimental evaluation on 1/*f* noise when light is on and off. S_j, S_{sh}, and S_{th} denote the magnitude of Johnson's noise, Shot noise, and noise due to thermal fluctuations respectively.

5. Room temperature photo-response:

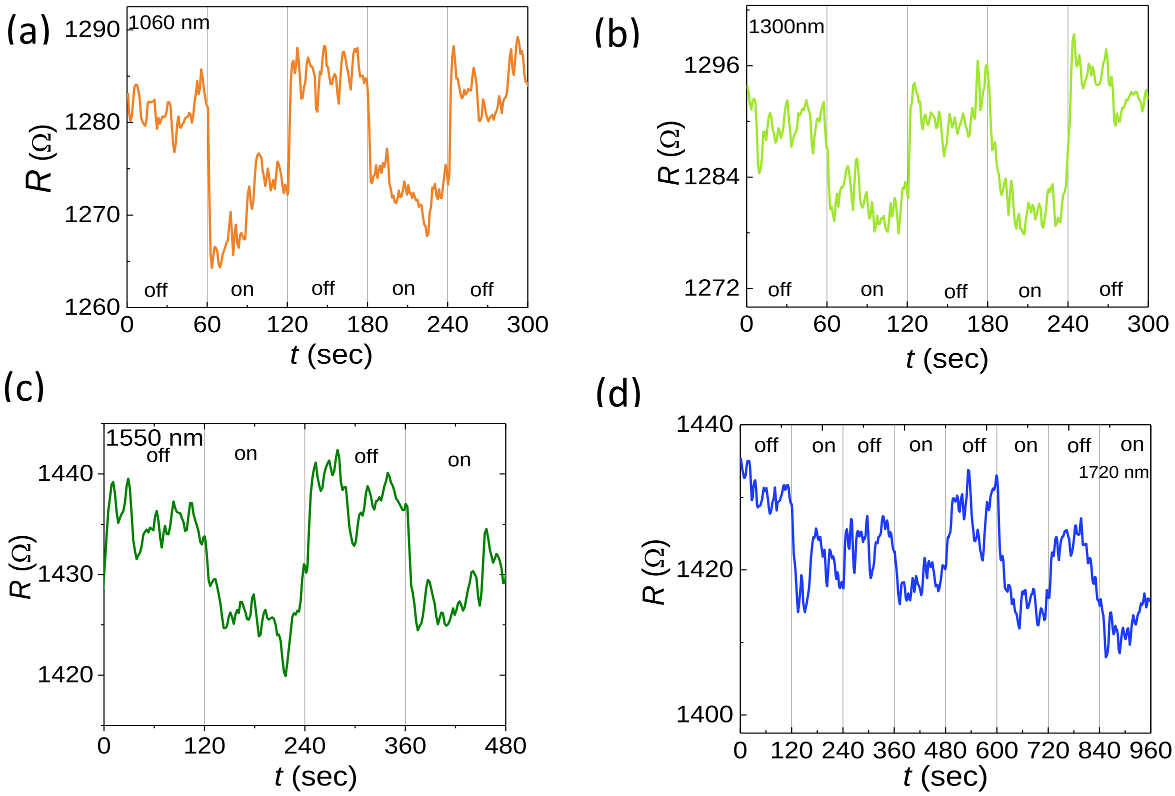

Figure S4: Opto-electronic response for different wavelengths in the NIR regime at 300 K: (a) 1060 nm (b) 1330 nm (c) 1550 nm (d) 1720 nm

6. Transmission electron microscope (TEM) image of Bi_2Te_3 nano-wires:

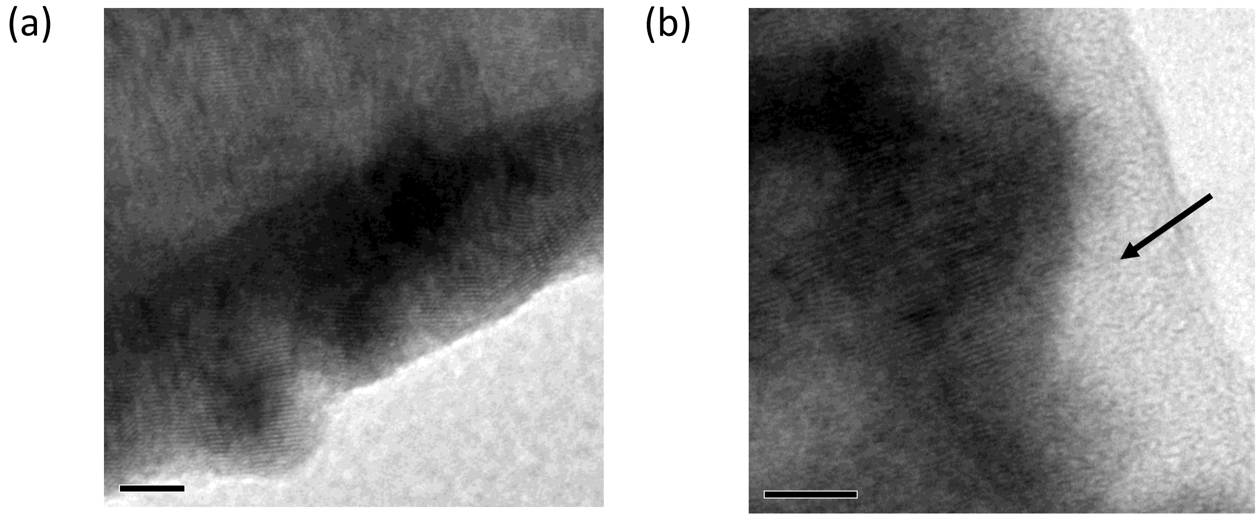

Figure S5: Transmission electron micrograph of the wires: (a) Before the measurement/ drop casting on the device (b) After measurement. The arrow indicates the formation of an amorphous layer during opto-electronic measurements.

7. Raman spectroscopy of Bi_2Te_3 nano-wires:

The Raman spectroscopy of the bismuth telluride nano-wires display three peaks around 39 cm^{-1}, 61 cm^{-1}, and 101 cm^{-1}, which are attributed to the E^1_g, A^1_g, and E^2_g modes respectively (Ref [80]). In addition to these, we have also observed peaks at 91 cm^{-1}, 123 cm^{-1}, and 140 cm^{-1}. The peaks are attributed to the formation of Bi_2O_3 and TeO_2, which serve as an additional proof of the oxidation of the nano-wires.

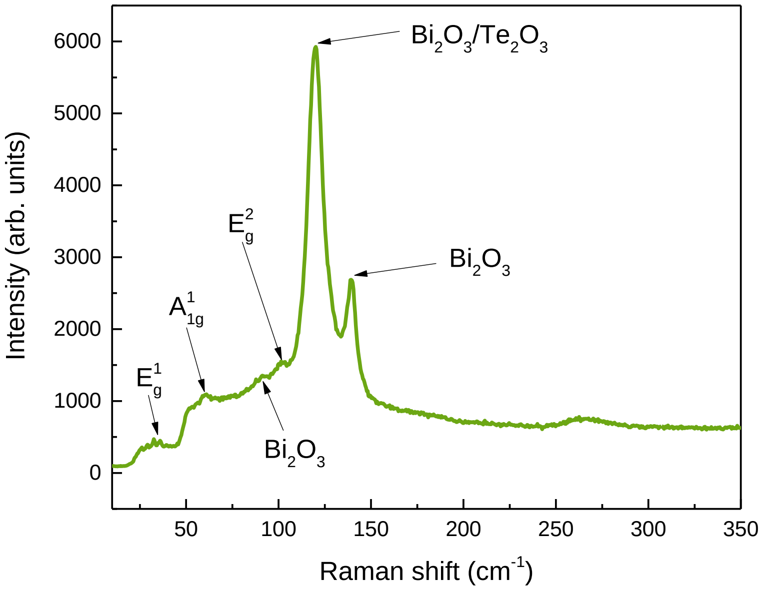

Figure S6: Raman spectra of the nano-wires showing peaks due to the formation of oxides at 91 cm^{-1}, 123 cm^{-1}, and 140 cm^{-1}.