Electronic Supplementary Information (ESI) for:

# Thermoelectric terahertz photodetectors based on selenium-doped black phosphorus flakes

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## S1- Electrical transport of thin selenium-doped BP flakes: reproducibility.

Here we present the results of electrical characterization performed on three Se-doped BP flakes of similar thicknesses. The three FETs were realized with nominally identical fabrication procedures, but on different substrates. The different results obtained demonstrate that the initial state of the substrate plays an important role, since hydro philia, cleanliness and glue residues can locally alter the flakes integrity [Ref. S1].

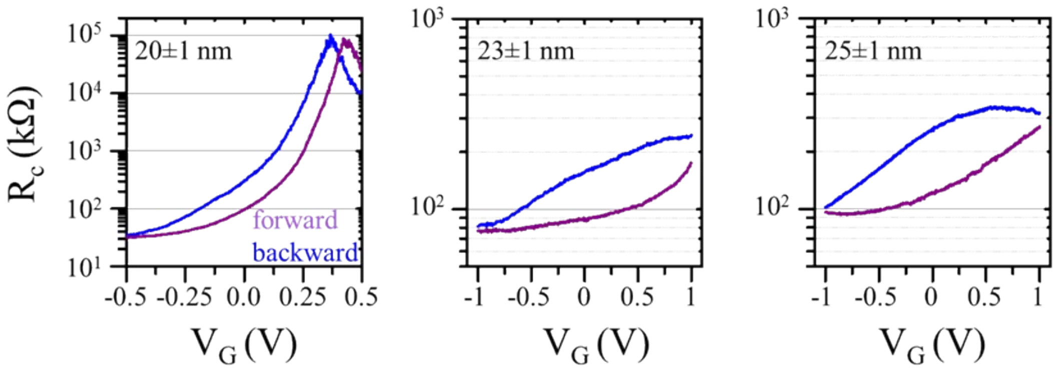


**Figure S1**: Electrical transport characteristics of three selenium doped BP flakes fabricated in three different runs. From left to right the thickness is 20 ± 1 nm, 23 ± 1 nm (corresponding to Sample B in the main text) and 25 ± 1 nm, respectively. The corresponding hole mobility values are 370 $cm^2V^{-1}s^{-1}$, 42 $cm^2V^{-1}s^{-1}$ and 40 $cm^2V^{-1}s^{-1}$. The corresponding $I_{ON}/I_{OFF}$ ratios are 3000, 3, and 3, respectively.

Ref. S1- J.O. Island, G.A. Steele, H.S.J. van der Zant, A. Castellanos-Gomez. *2D Mater.* **2015**, 2, 011002.

## S2- Evaluation of the response time

In order to characterize the response time of the best performing photodetector (Sample *C*), we employed a pulsed QCL. The THz source was driven by a pulse generator giving a waveform with an on-state voltage of -14 V, a pulse duration of 7 µs and a repetition frequency of 6 kHz. The detector signal was measured at the drain contact with no bias applied between S and D and $V_G$ set to 1.4 V. A voltage pre-amplifier with a bandwidth of 200 MHz and gain 100 was used in this experiment. With this setup, the response time should be only limited by the BP-FET itself. The time traces of the QCL driving voltage and of the detector output, collected with a fast oscilloscope, are reported in Figure S2.

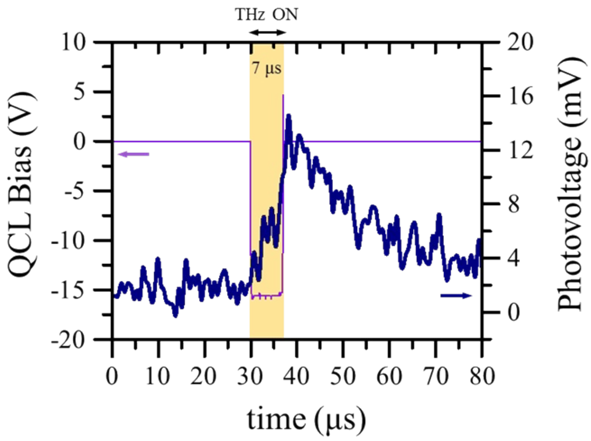


**Figure S2**: sample *C*, photodetection response time. Time traces of the QCL bias (left vertical axis) and of the photoresponse (right vertical axis). The photovoltage trace is recorded with an oscilloscope. The photoresponse plot represents the raw data, after a pre-amplification stage of 40 dB.

The detector signal increases during the THz pulse, with a rise time (from 10% to 90% of the maximum signal) of 6 µs, corresponding to a measured bandwidth (BW) of 60 kHz (BW = 0.35/rise time). After the pulse, the signal decays with a timescale of 17 µs, obtained by an exponential fit to the data. The reported time constant of 6 µs is larger than the ones reported for graphene based detector (few tens of ns, ref.S2). However, it is worth mentioning that it is suitable for the most required terahertz imaging applications.


Ref. S2- S. Castilla, B. Terrés, M. Autore, L. Viti, J. Li, A. Nikitin, I. Vangelidis, K. Watanabe, T. Taniguchi, E. Lidorikis, M.S. Vitiello, R. Hillenbrand, K.-J. Tielrooij, F.H.L. Koppens. Submitted **2018**.