Programmable black phosphorus image sensor for broadband optoelectronic edge computing

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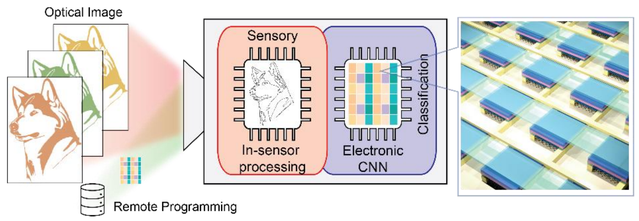
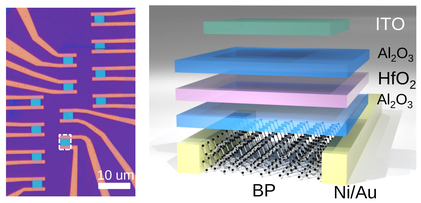
Introduction

- The conductivity of black phosphorus (bP) changes dramatically depending on the charge doping level, and so does the responsivity at wide wavelength ranges from visible to Mid-IR light [1].
- The doping level of the bP channel can be manipulated by concentration of local charges, which can be stored in non-volatile manner by engineering the stack of dielectric layers (AHA) [2].
- As bP-transistors are connected in an array, it can perform basic convolutional neural network tasks in a vision sensor, enabling edge computing [3].



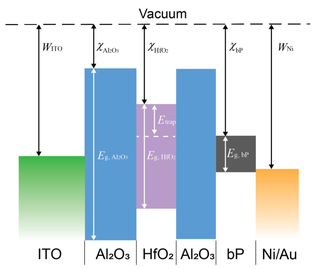
Black Phosphorus Phototransistor Design

BP-Phototransistor structure and the Optical image

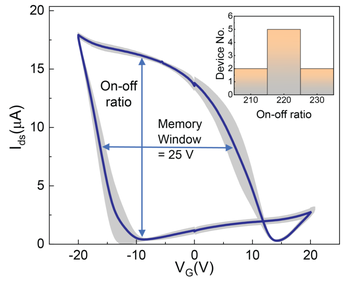


- $Al_2O_3/HfO_2/Al_2O_3$ (AHA) stack of dielectric layers traps charges in the HfO_2 [1]
- ITO for transparent top gate
- BP (11 nm) as a channel material with 200 on-off ratio
- ~8% inter-device variation

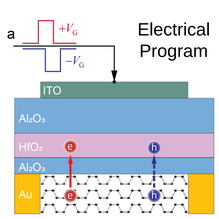
Band alignment

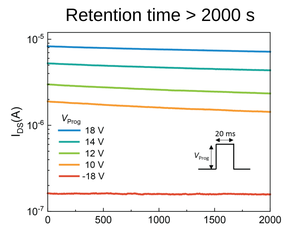


FET-Gate modulation And Device variation

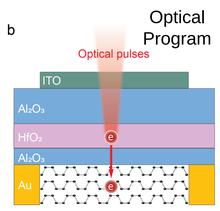


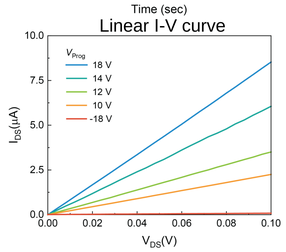
Electrical/Optical Programming and Readout



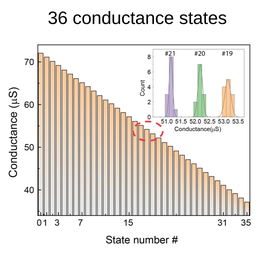


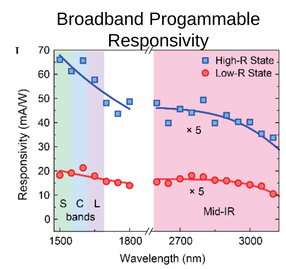
- -18 V top gate pulse makes the BP channel least conductive. (erased)
- Different top gate pulses (10 – 18 V) set the channel conductivity (programmed)
- Each state shows linear I-V characteristics.

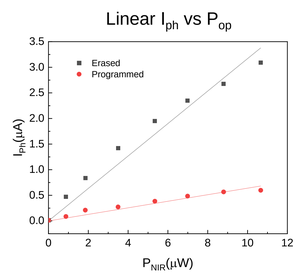




- Optically programmed states:
  Fine control of the states with 36 states.
- Each state separated well in conductivity, and stayed stable > 1000 s.
- Programmable responsivity over broad IR spectra
- Linear dependance of optical power and photocurrents.

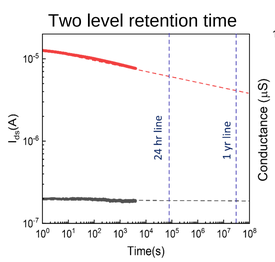


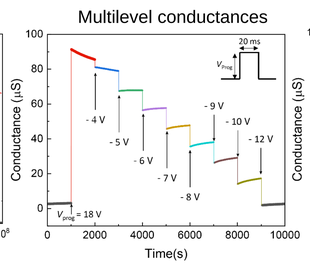


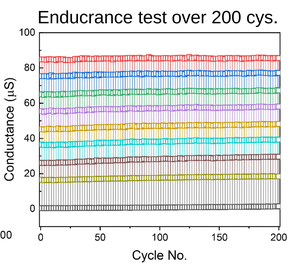


Device retention time, repeatability and durability

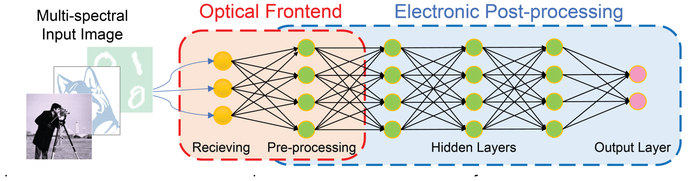
- Electrically programmed states: retention time (30%) ~ 1 year.
- Repeatable conductance states over 200 programming cycles with long retention time >1000s

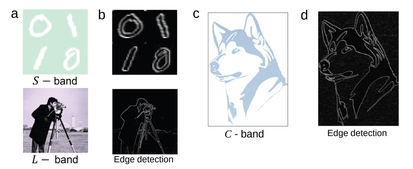






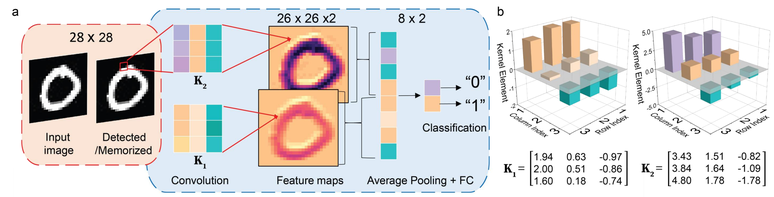
Optoelectronic Edge Detection

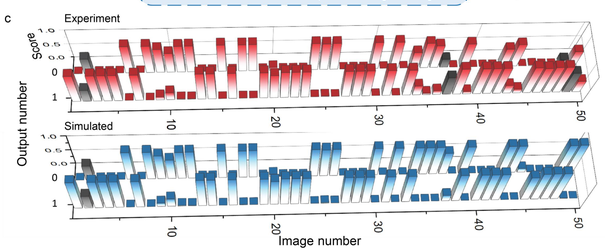


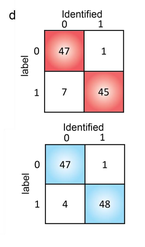


- Different images encoded in difference NIR wavelength regime.
- Optoelectronic convolutional Kernel calculation results in clear edge detection.

Hand-written digit classification







- Input can also be encoded electrically.
- 36 steps, or more than 5 bits of conductivity states enable the computation with more complex kernel matrix.
- MNIST hand-written digits are classified for randomly picked '0' and '1' with 92 % accuracy. [4]

References

[1] Youngblood, N., Chen, C., Koester, S., & Li, M. Waveguide-integrated black phosphorus photodetector with high responsivity and low dark current. Nat. Photon. 9, 247–252 (2015)
[2] Feng, Q., Yan, F., Luo, W. & Wang, K. Charge trap memory based on few-layer black phosphorus. Nanoscale 8, 2686–2692 (2016)
[3] Jang, H., Liu, C., Hinton, H., Lee, M.-H., Kim, H., Seol, M., Shin, H.-J., Park, S. & Ham, D. An Atomically Thin Optoelectronic Machine Vision Processor. Adv. Mater. 32, 2002431 (2020)
[4] Lee, S., Peng, R., Wu, C. & Li, M. Programmable black phosphorus image sensor for broadband optoelectronic edge computing. Nat. Comm. in press (2022)

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