SAND2024-12521C

Sandia National Laboratories

Atomic Precision Advanced Manufacturing (APAM) devices for quantum sensing

Juan P. Mendez and Denis Mamaluy

Sandia National Laboratories, Albuquerque, New Mexico

2023 WINDS, December 3-8, 2023

U.S. DEPARTMENT OF ENERGY NNSA

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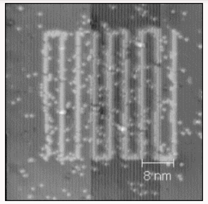
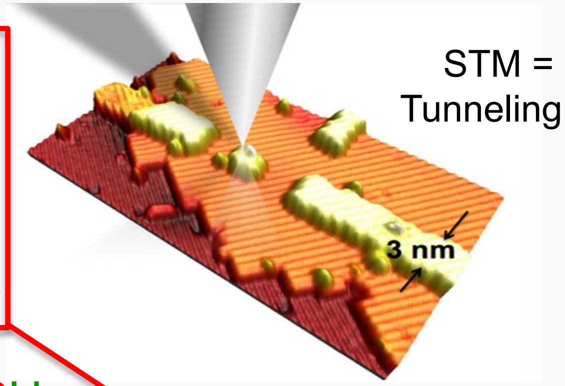
Atomic Precision Advanced Manufacturing (APAM)

APAM

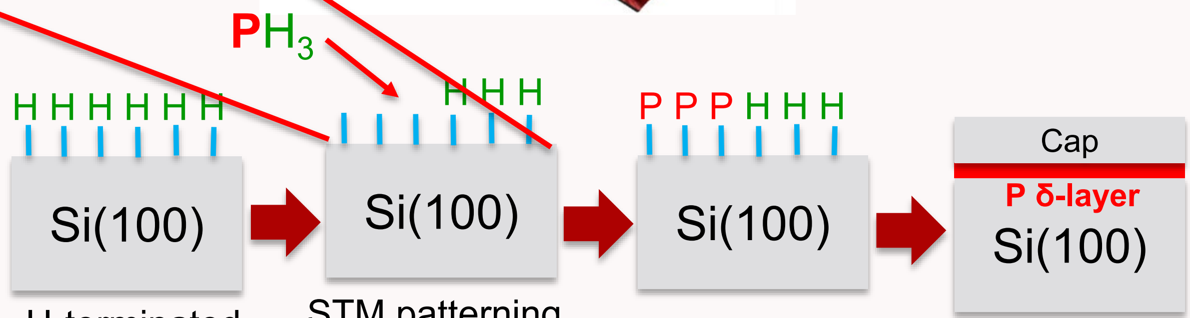
Manufacturing process of dopant incorporation with atomic precision to create planar structures (δ-layers) in semiconductors



STM image. Swartzentruber, Hamers, Lyding, Shen, Avouris



STM = Scanning Tunneling Microscope



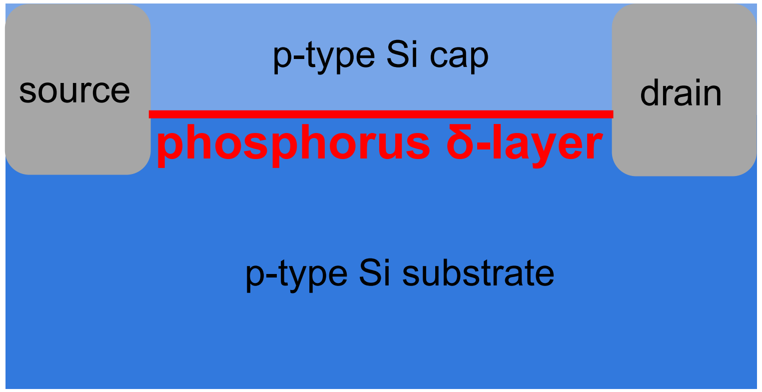
H-terminated surface

STM patterning and PH_3 dosing

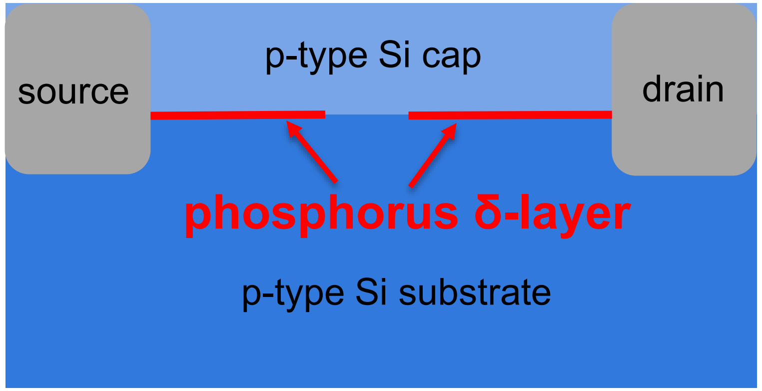
P incorporation

Locking layer & encapsulation

APAM devices



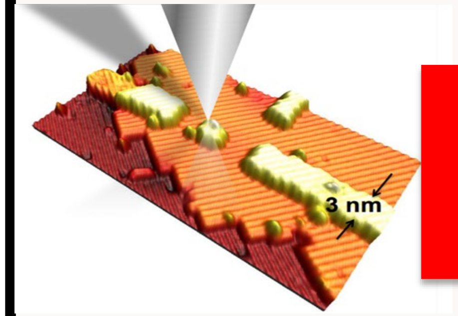
Phosphorus δ-layer wire



Phosphorus δ-layer Tunnel Junction

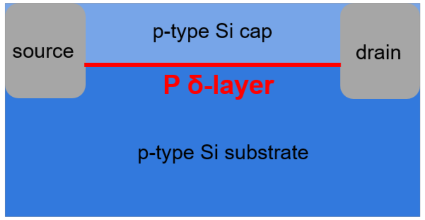
Atomic Precision Advanced Manufacturing (APAM)

APAM

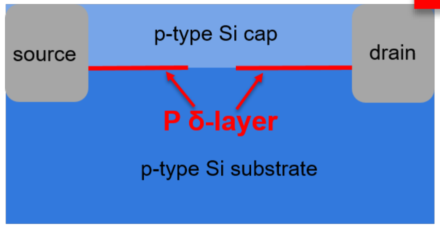


STM = Scanning Tunneling Microscope

APAM devices



Si: P δ-layer wire



Si: P δ-layer Tunnel Junction

APAM Applications

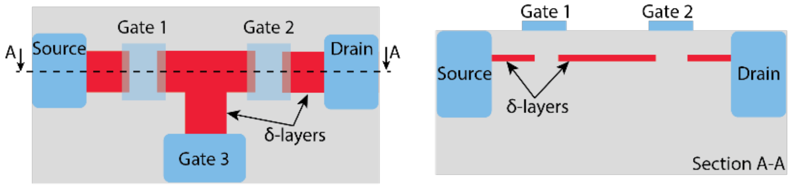
- **Beyond Moore Computing**

NANO LETTERS

pubs.acs.org/NanoLett — Letter

Monolithic Three-Dimensional Tuning of an Atomically Defined Silicon Tunnel Junction

Matthew B. Donnelly,* Joris G. Keizer, Yousun Chung, and Michelle Y. Simmons



δ-layer tunnel junction FET

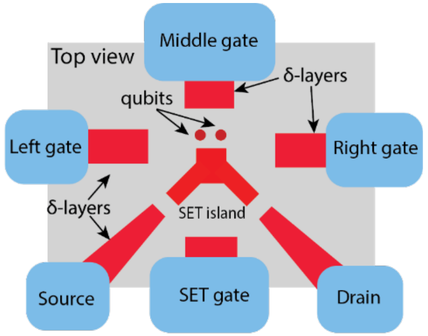
- **Quantum Computing**

LETTER

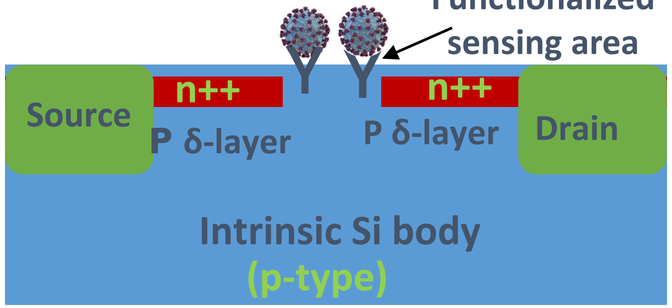
https://doi.org/10.1038/s41586-019-1381-2

A two-qubit gate between phosphorus donor electrons in silicon

Y. He[1,2], S. K. Gorman[1,2], D. Keith[1], L. Kranz[1], J. G. Keizer[1] & M. Y. Simmons[1]*



- **Novel quantum sensing**



FET-based sensors

Advantages of FET-based sensors:

- Label-free electrical detection
- Small size and weight
- Low-cost mass production
- Possibility of on-chip integration

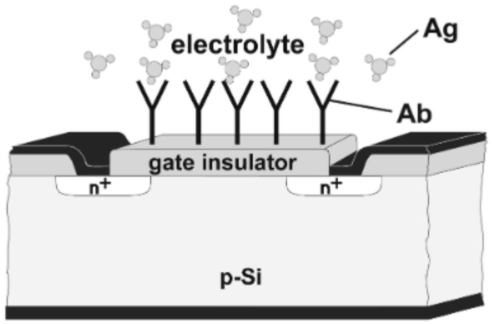


Fig. 6 Schematic structure of an ImmunoFET with immobilised antibody (Ab) molecules. Ag, antigen molecules.

Recent advances in biologically sensitive field-effect transistors (BioFETs)

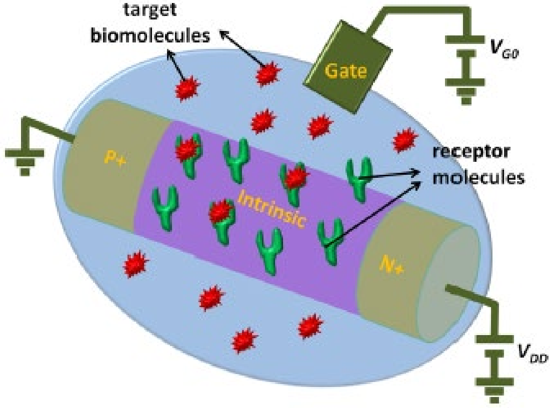
Michael J. Schöning[*ab] **and Arshak Poghossian**[b]

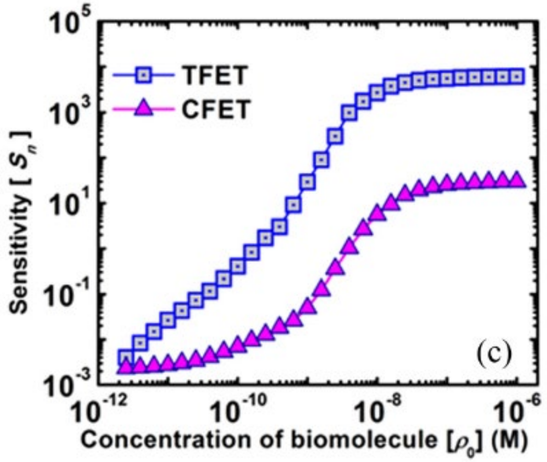
[a] *University of Applied Sciences Aachen, Ginsterweg 1, D-52428 Jülich, Germany*
[b] *Institute of Thin Films and Interfaces, Research Centre Juelich GmbH, D-52425 Jülich, Germany. E-mail: m.j.schoening@fz-juelich.de. E-mail: a.poghossian@fz-juelich.de; Fax: +49 2461612940; Tel: +49 2461612973*

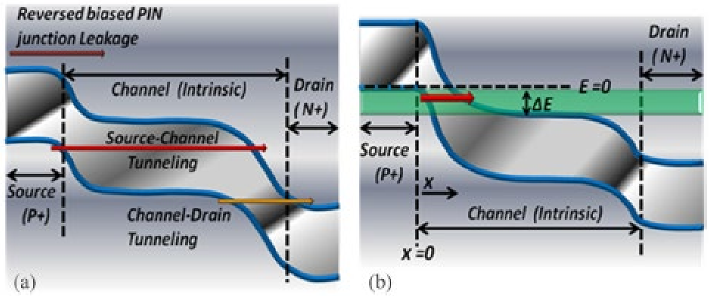
APPLIED PHYSICS LETTERS **100**, 143108 (2012)

Proposal for tunnel-field-effect-transistor as ultra-sensitive and label-free biosensors

Deblina Sarkar[a)] and Kaustav Banerjee[a)]
Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106, USA



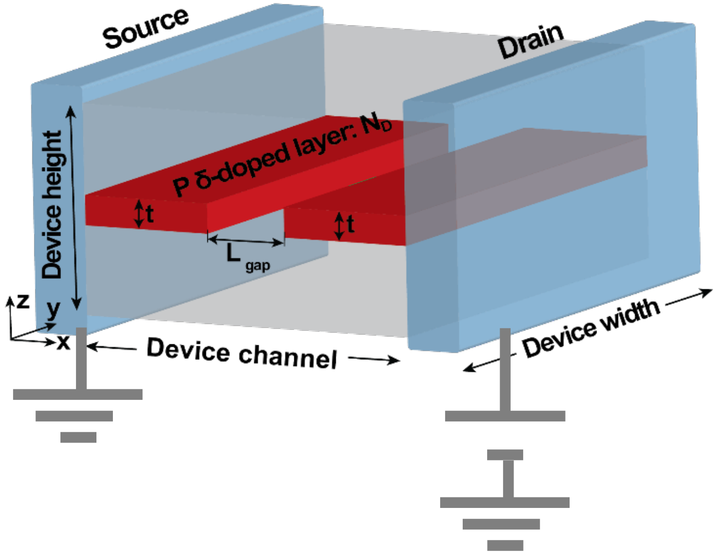




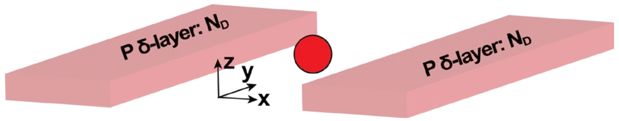
TFET based-sensors can reach a sensitivity of up to 1000, but for molar concentration higher than 10^{-8} mol/L

Tunneling current is strongly affected by impurities

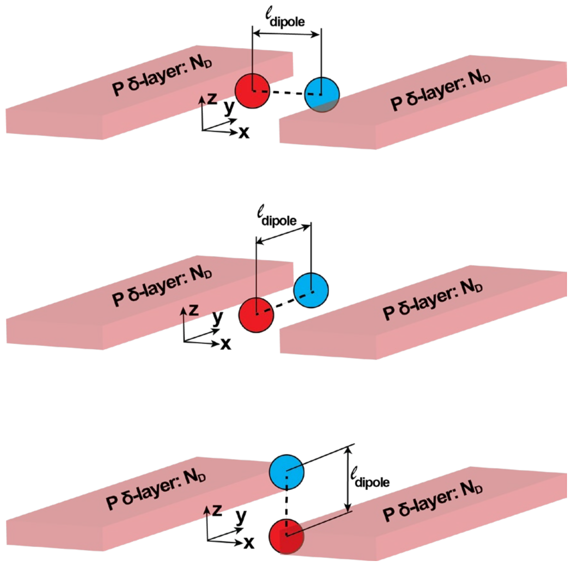
Si: P δ-layer tunnel junction



Single impurity



Electric dipole



- tunneling current can increase up to 60 times higher (L_{gap} =12 nm) !!

PHYSICAL REVIEW APPLIED **20**, 054021 (2023)

Influence of imperfections on tunneling rate in δ-layer junctions

Juan P. Mendez,* Shashank Misra, and Denis Mamaluy†
Sandia National Laboratories, Albuquerque, New Mexico 87123, USA

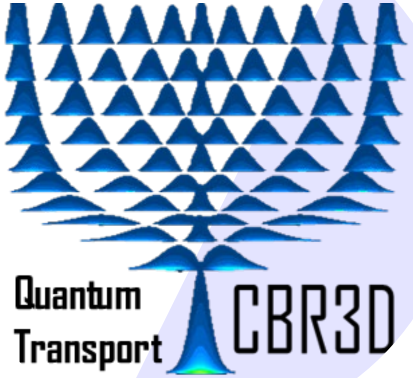
- high-moment dipoles exhibit anisotropic behavior !!

arXiv > cond-mat > arXiv:2310.06704
Condensed Matter > Mesoscale and Nanoscale Physics
[Submitted on 10 Oct 2023 (v1), last revised 11 Oct 2023 (this version, v2)]

Uncovering anisotropic effects of electric high-moment dipoles on the tunneling current in δ-layer tunnel junctions

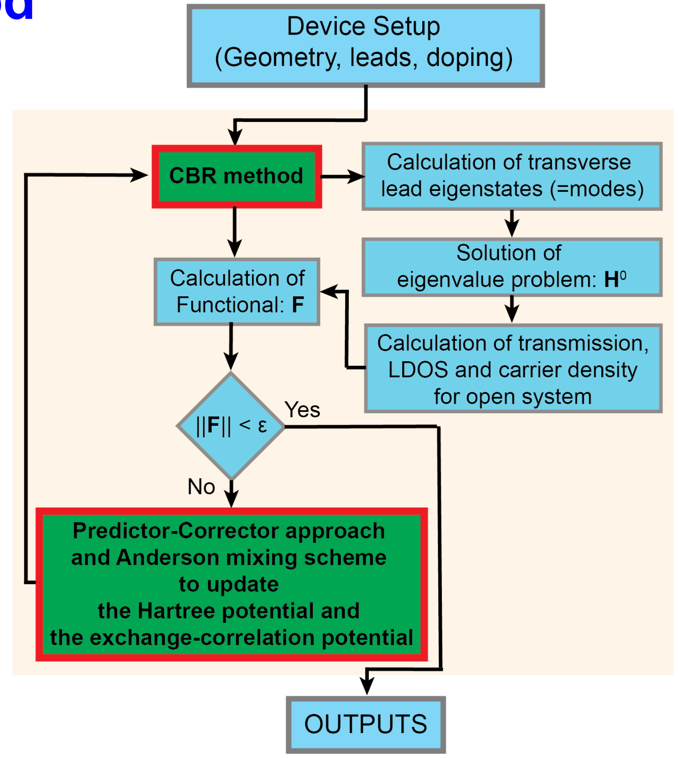
Juan P. Mendez, Denis Mamaluy

Open-system quantum transport simulator

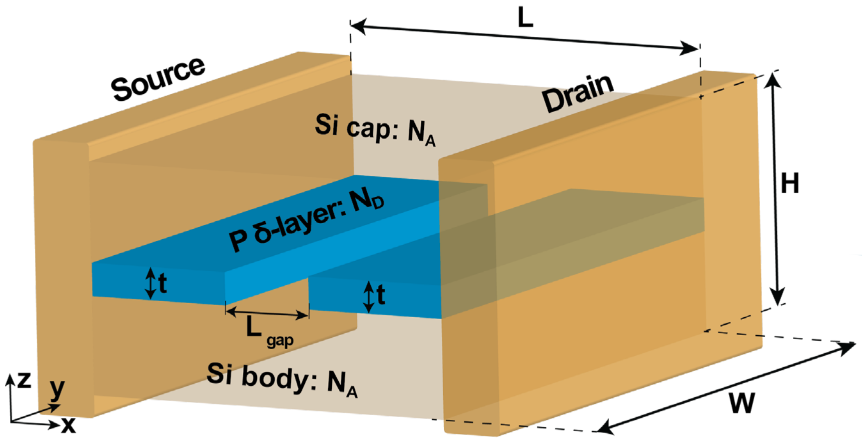


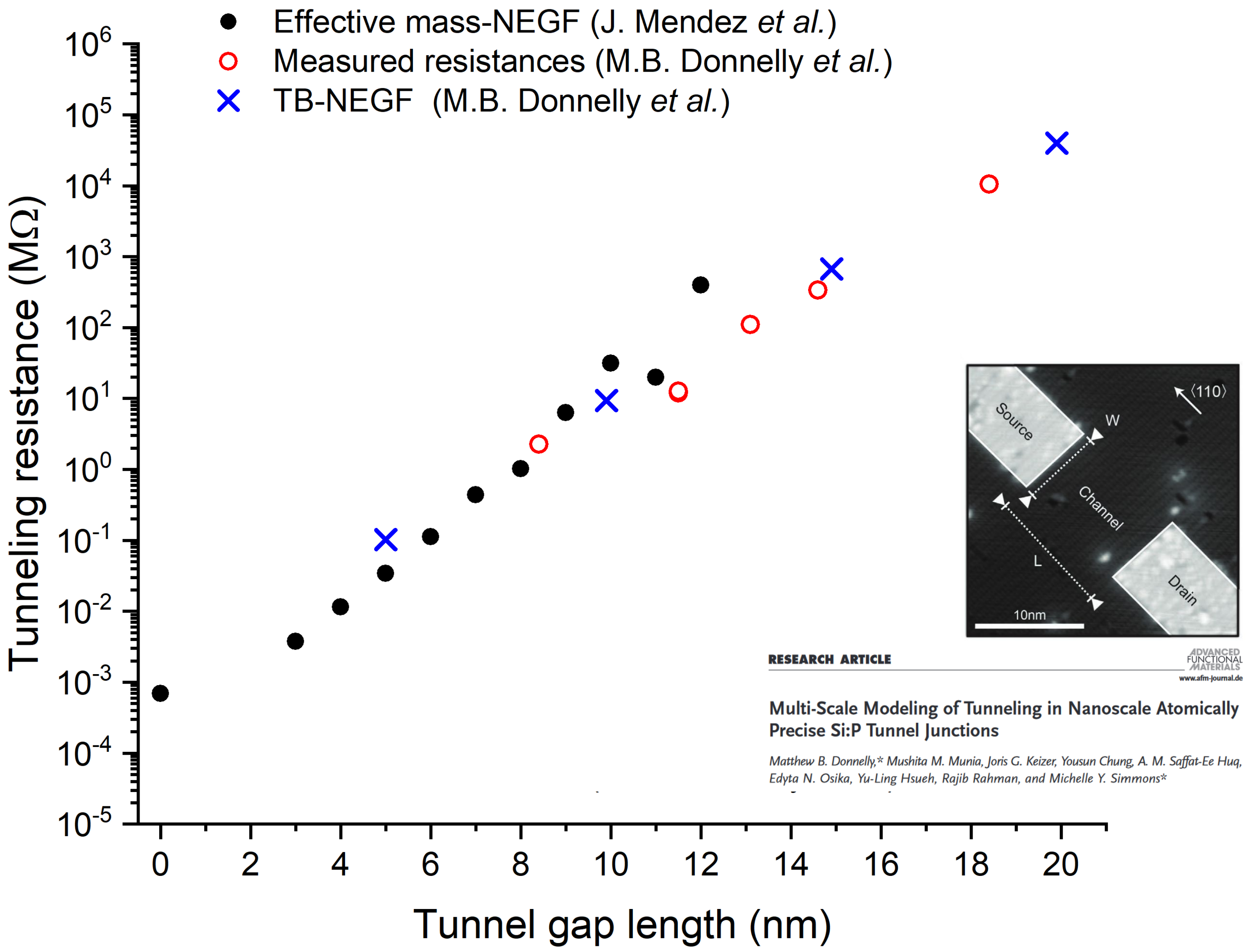
- Our quantum transport simulator is based on **Non-Equilibrium Green's function** (NEGF) formalism
- **Contact Block Reduction (CBR) method** for fast numerical efficiency
- Fully charge self-consistent solution of Poisson-open system Schrödinger equation
- Predictor-corrector approach and Anderson mixing scheme

Quantum transport simulator

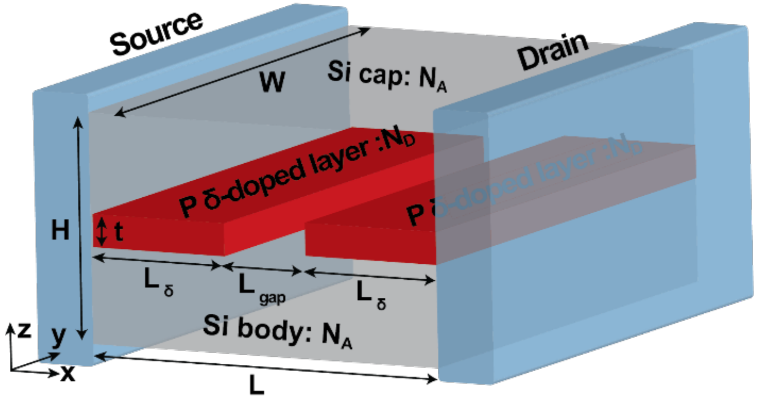


Excellent agreement with experiments!

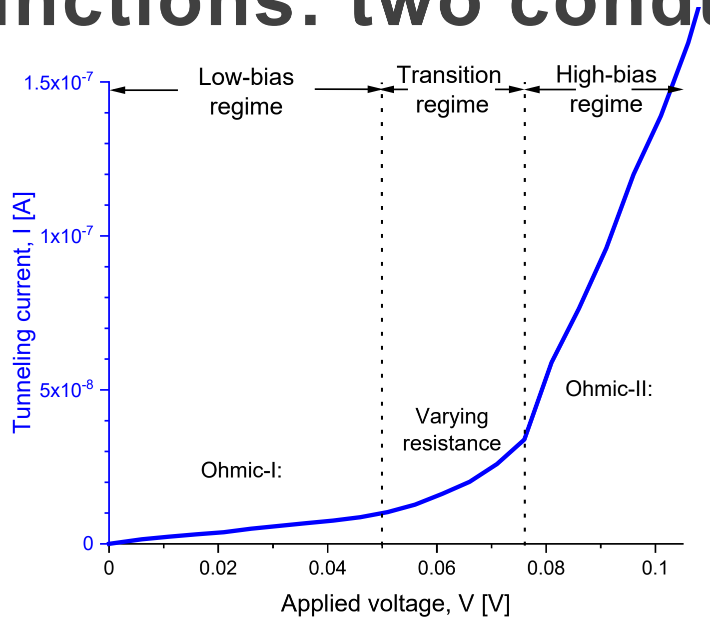




δ-layer tunnel junctions: two conductivity regimes



N_D=1.0×10^{14} cm^{-2},
N_A=5.0×10^{17} cm^{-3},
t=1.0nm, L_{gap}=10nm



scientific reports

OPEN

Check for updates

Conductivity and size quantization effects in semiconductor δ-layer systems

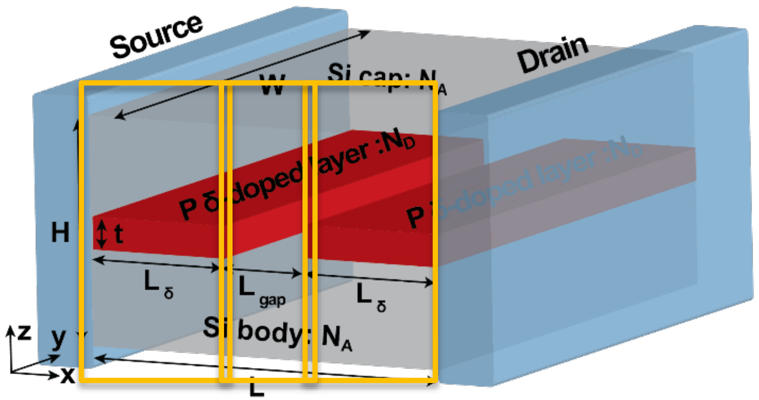
Juan P. Mendez & Denis Mamaluy

PHYSICAL REVIEW APPLIED 20, 054021 (2023)

Influence of imperfections on tunneling rate in δ-layer junctions

Juan P. Mendez,* Shashank Misra, and Denis Mamaluy†
Sandia National Laboratories, Albuquerque, New Mexico 87123, USA

δ-layer tunnel junctions: two conductivity regimes



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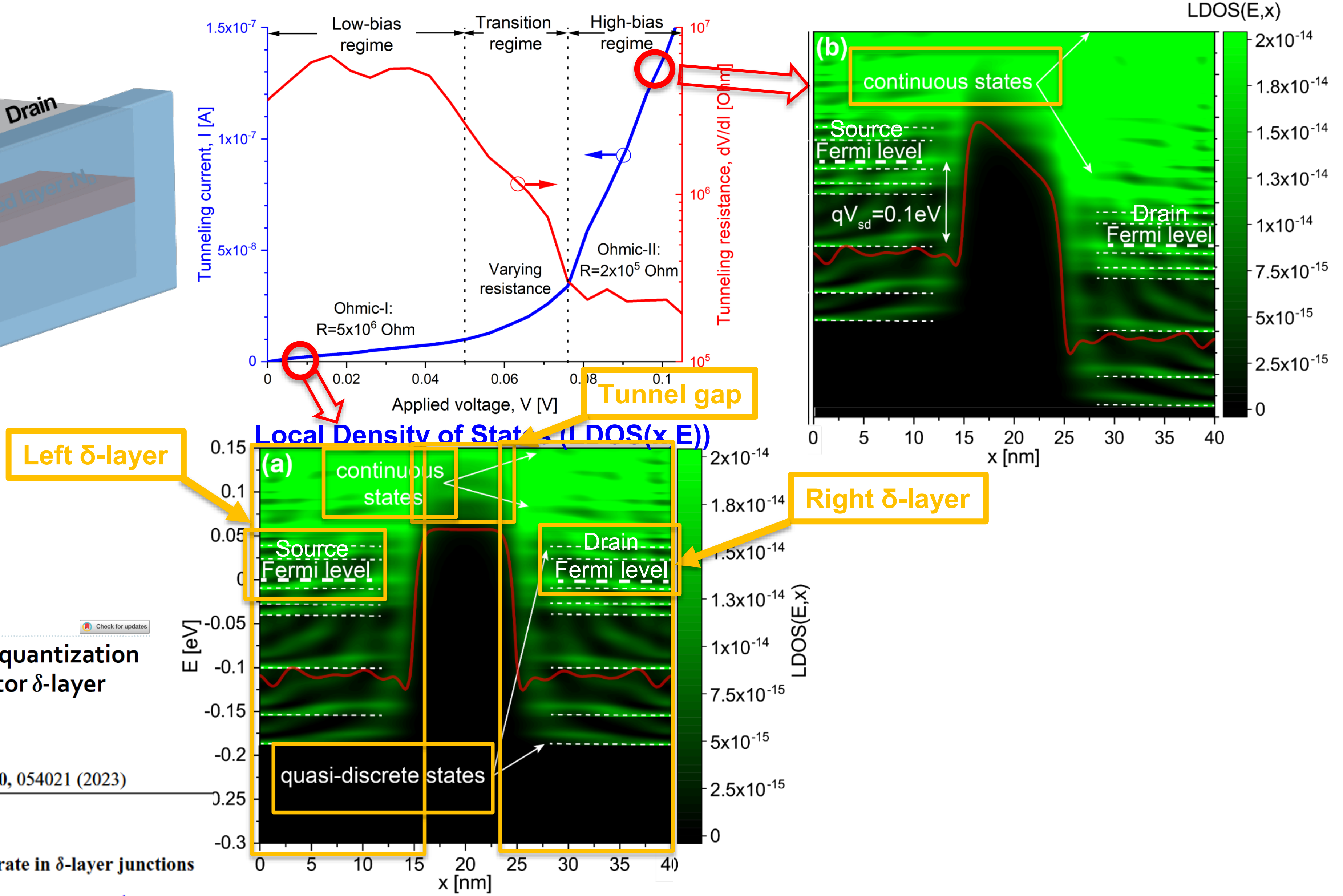

scientific reports

OPEN **Conductivity and size quantization effects in semiconductor δ-layer systems**

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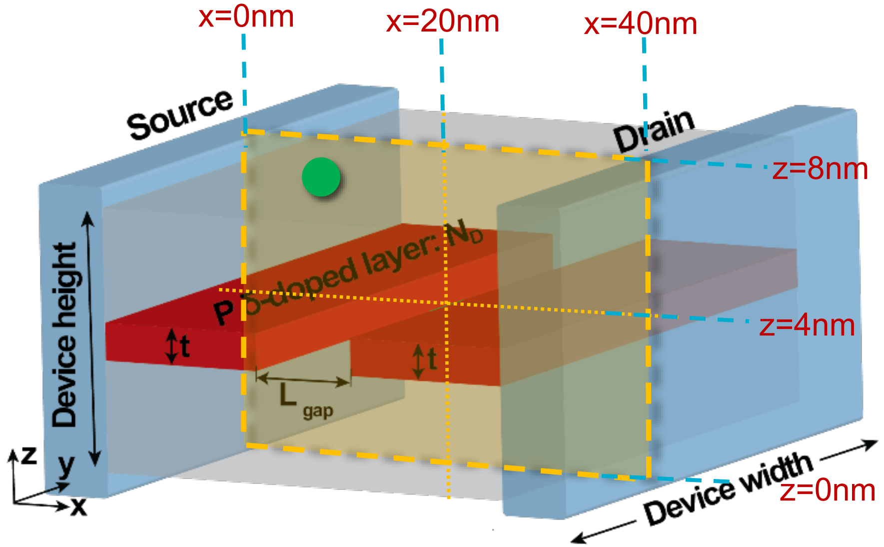
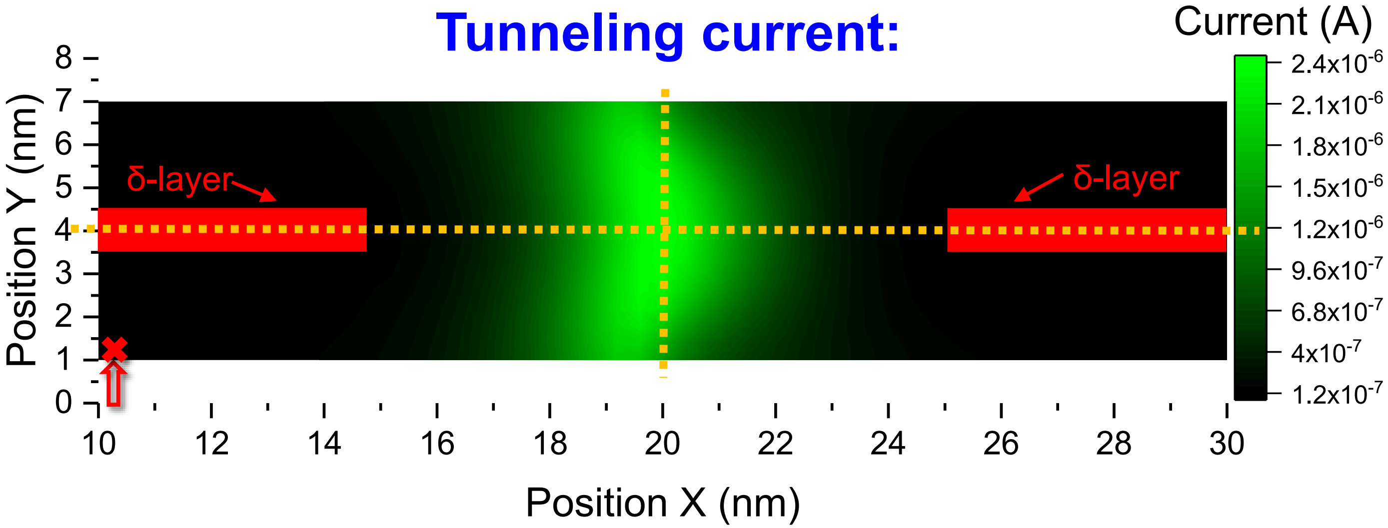
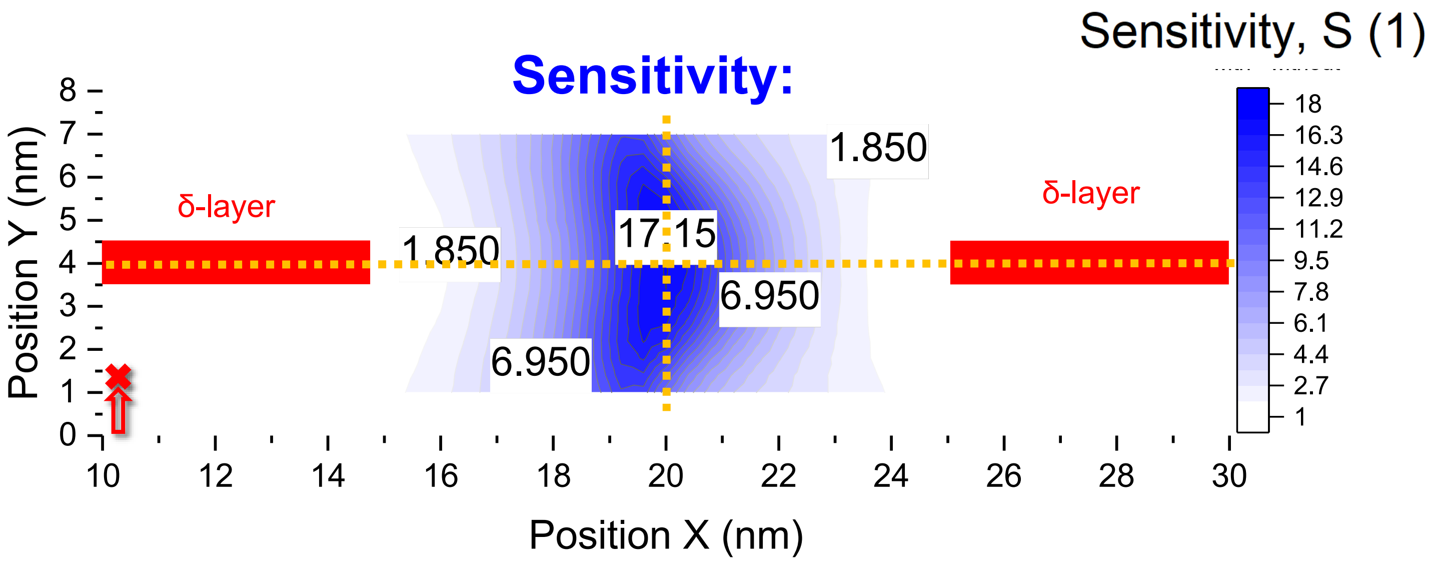
δ-layer TJs are ultrasensitive to charges!



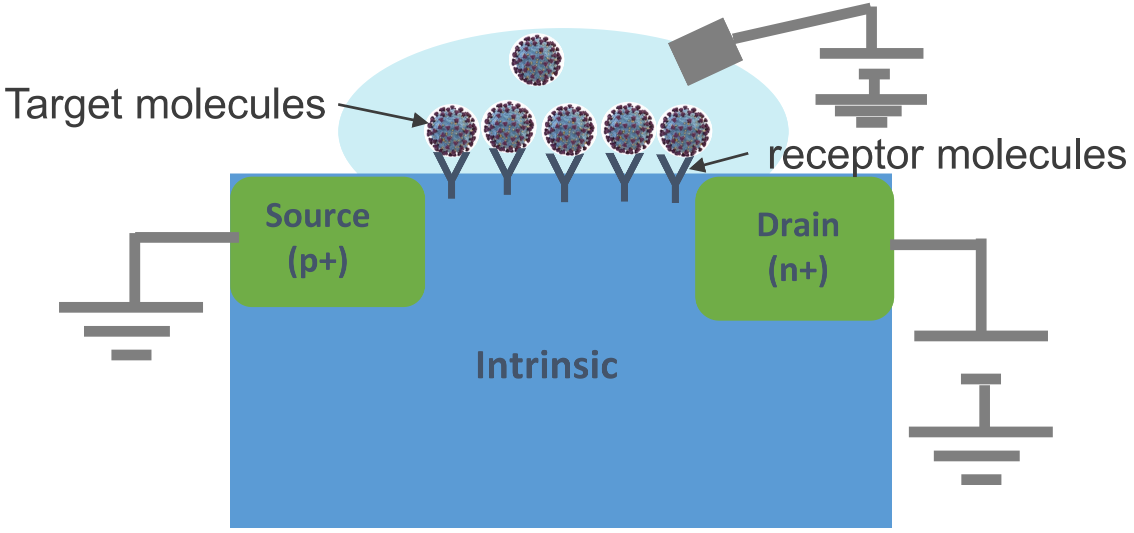




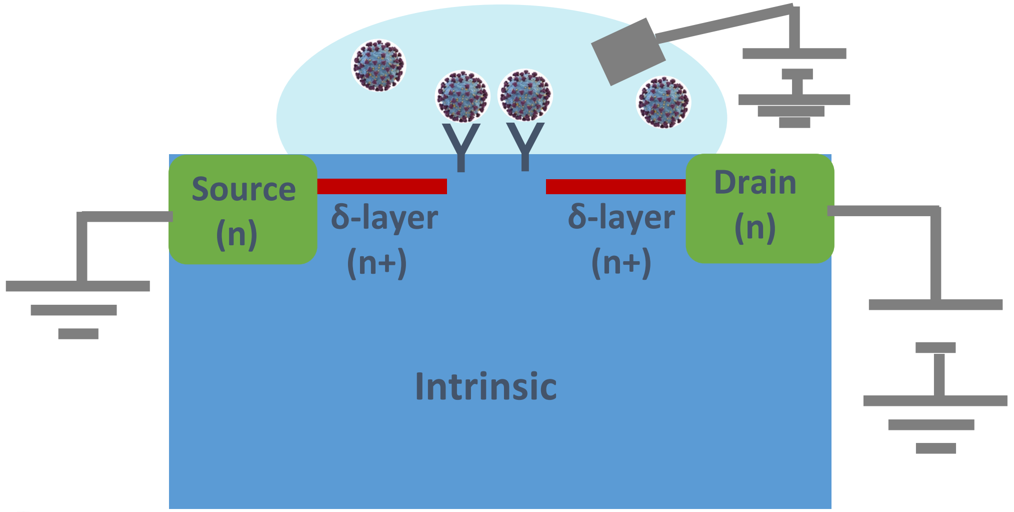
$$Sensitivity,\ S = \frac{I_{with\ charge} - I_{without\ charge}}{I_{without\ charge}}$$

Why is a δ-layer based FET highly sensitive to charges?

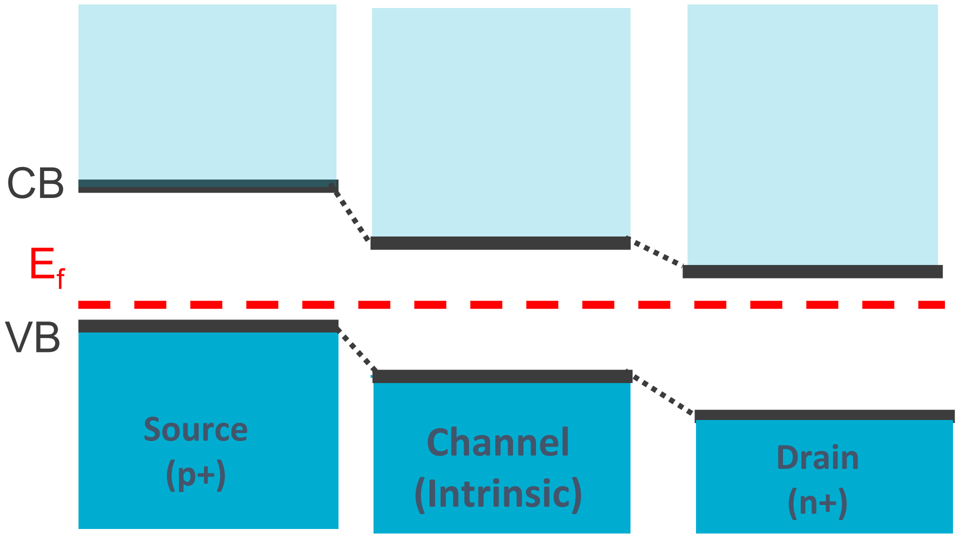
TFET-based sensor

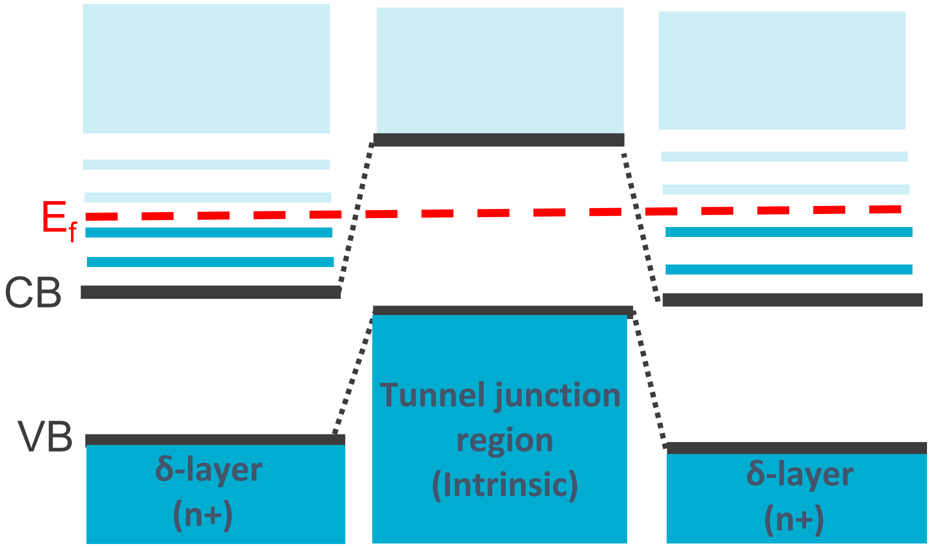


δ-layer based FET sensor

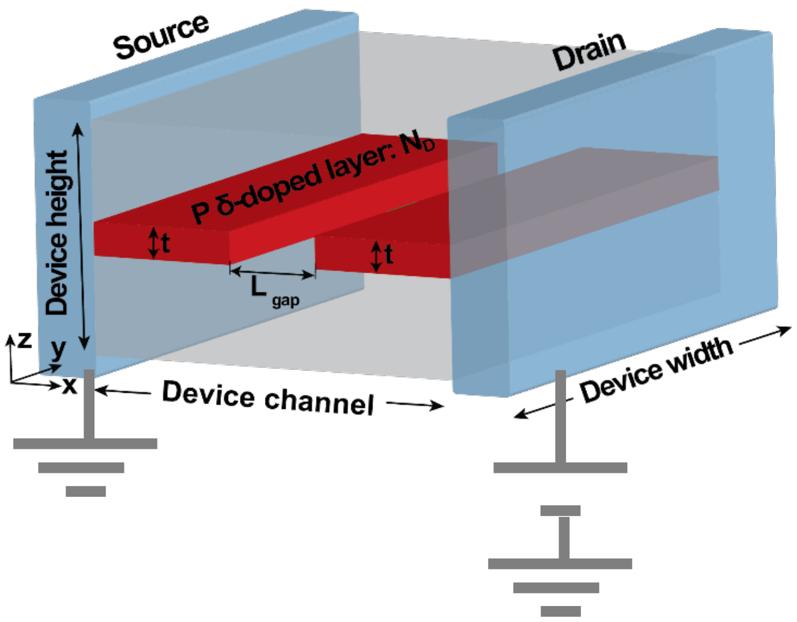


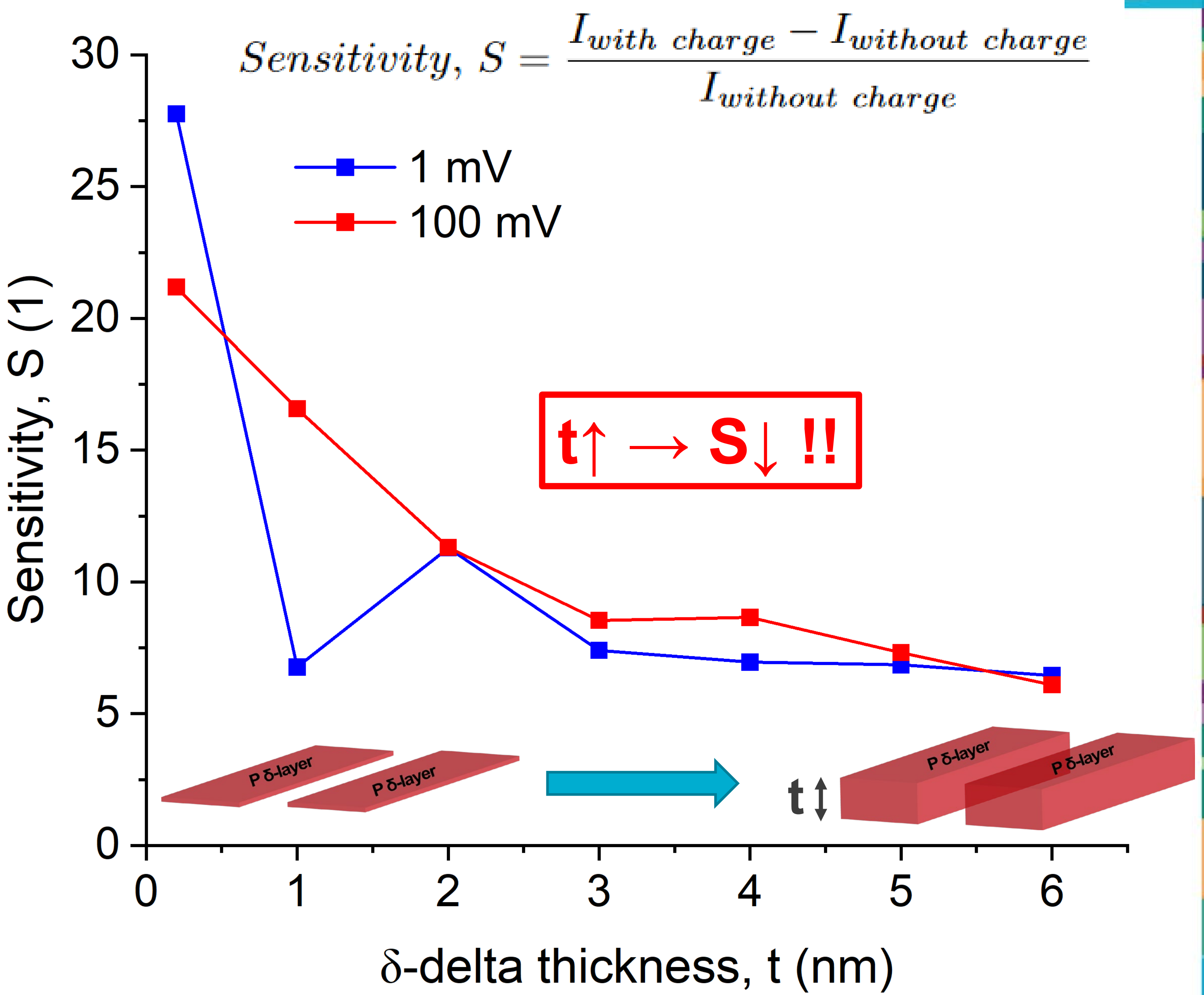
versus





Influence of the δ-layer thickness





- The thinner δ-layer, the more sensitive to the presence of charges

Final remarks

- Atomic Precision Advanced Manufacturing (**APAM**) opens new opportunities to fabricate nanoscale devices for charge sensing
- We have used our **Quantum Transport Simulator** (based on NEGF+Contact Block Reduction method) to investigate FET sensors based on δ-layer tunnel junctions
- We have found that the presence of a single charge near the tunnel junction results in a significant variation of the tunneling current
- FETs based on δ-layers could detect small signals, thus significantly enhancing sensitivity for low concentrations compared to TFET-based sensors
- Applications: chemical/biological detection, gas detection, and radiation detection

THANK YOU

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