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Modeling and Design of Atomic Precision Advanced Manufacturing (APAM) Enabled Bipolar Devices

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Atomic Precision Advanced Manufacturing (APAM)

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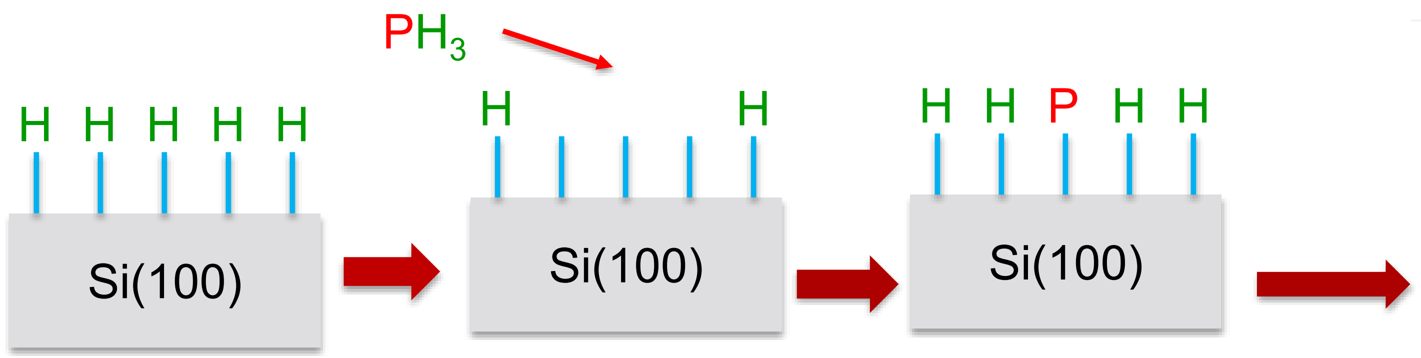
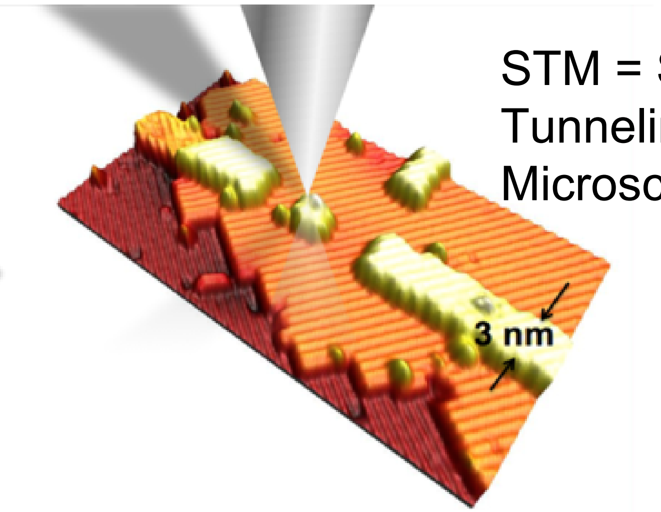
APAM is a process of area-selective dopant incorporation at the atomic scale



H-terminated surface

STM patterning with PH_3 precursor

P incorporation at atomic scale



STM = Scanning Tunneling Microscope

APAM key properties (vs. standard processing)

- Atomic precision
- Extremely high density of dopants

APAM is widely used for making qubits[1] which operate at cryogenic temperatures.

Unique opportunity in microelectronic from the atomic physical limit

[1] Y. He *et al.*, “A two-qubit gate between phosphorus donor electrons in silicon,” Nature, vol. 571, pp. 371-375, 2019.

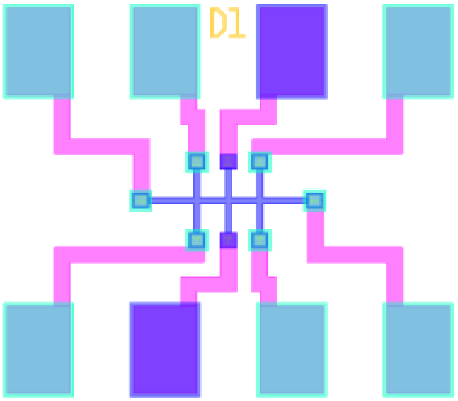
Sandia APAM Achievements Toward Microelectronic

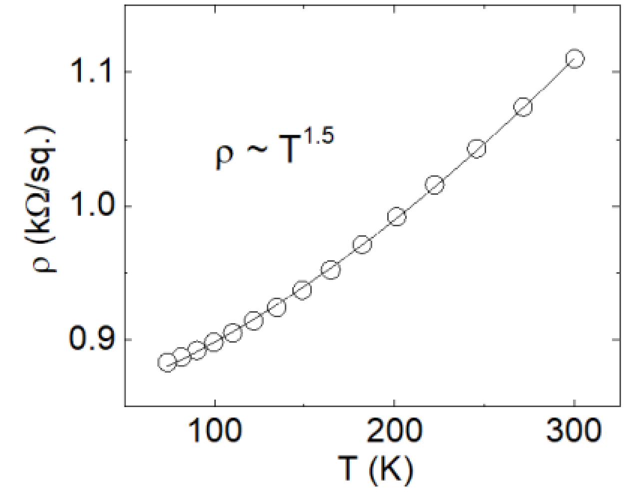
Sandia National Laboratories

- ❑ Room-temperature operation

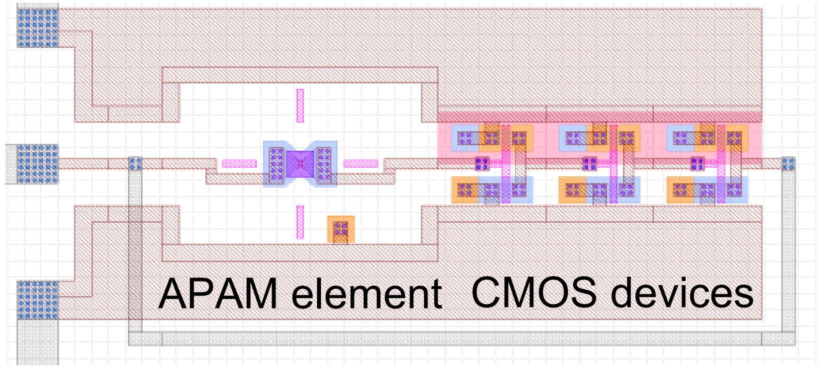
  X. Gao, et al., Modeling Assisted Room Temperature Operation of Atomic Precision Advanced Manufacturing Devices, presented at 2020 SISPAD.

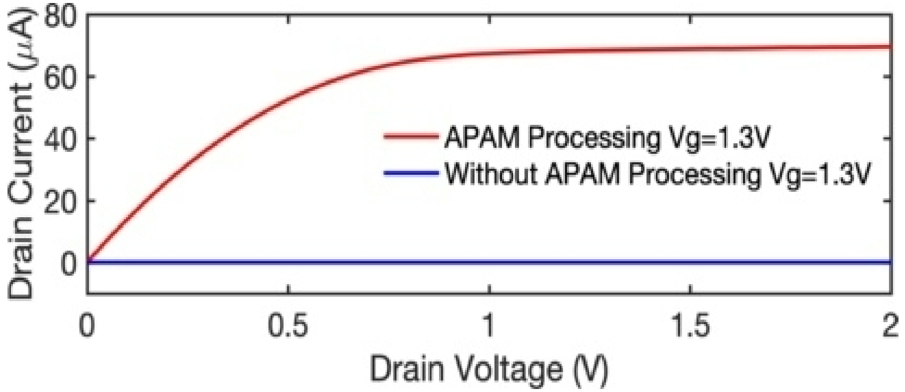
APAM Hall bar geometry





- ❑ APAM-CMOS Integration





Paper in preparation

US Patent Application 17/360,284

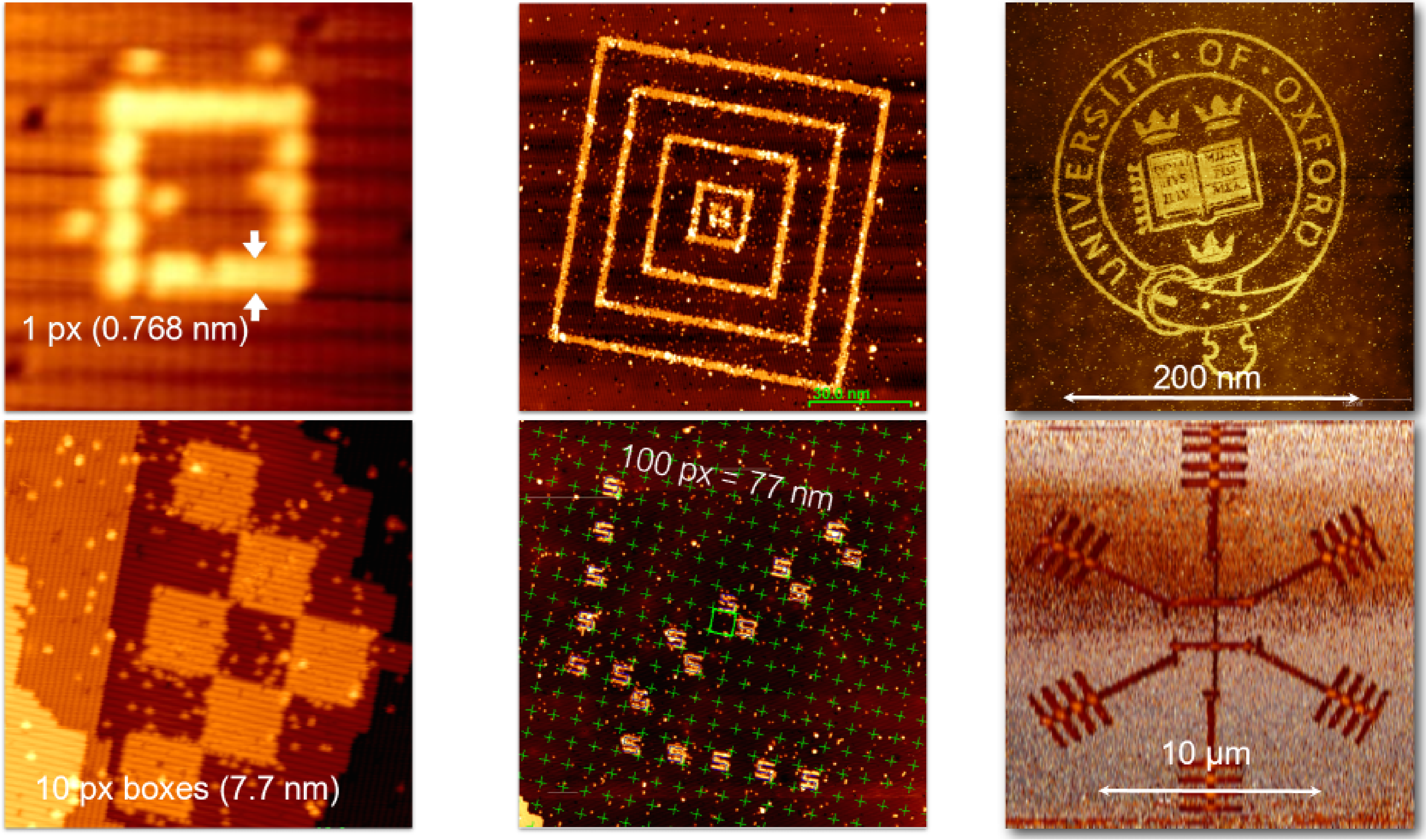
- ❑ APAM enabled VTFET [2] and bipolar devices

[2] X. Gao *et al.*, Modeling and Assessment of APAM Enabled Vertical Tunneling Field Effect Transistor, SISPAD 2021.

Automated Lattice-Aligned APAM Patterning

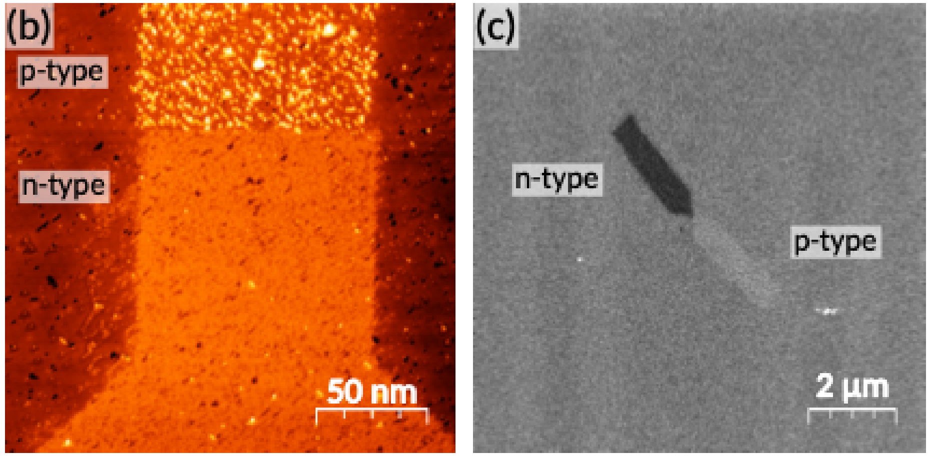
Sandia National Laboratories

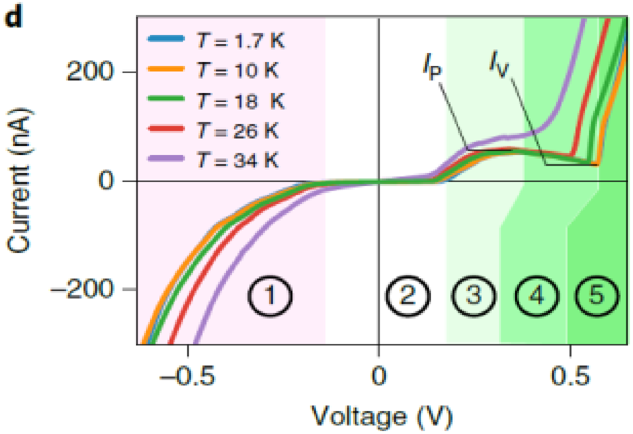
Zyvex Labs LLC developed tools for automated, lattice-aligned APAM patterning.



APAM Enabled Bipolar Devices

First APAM bipolar device was published by T. Škereň et al. [3]

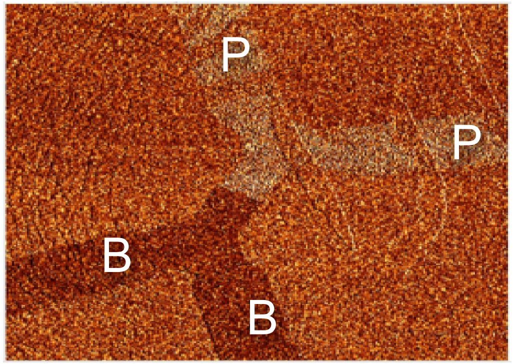


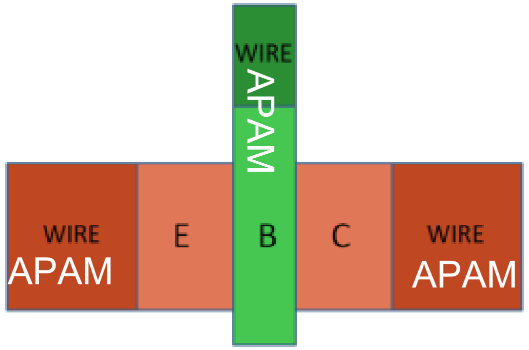


Clear negative differential conductance (NDC) in the forward bias region

Goal of the Zyvex/Sandia collaboration project:

- Design and fabricate working APAM pn junction
- Explore the path to design and fabricate

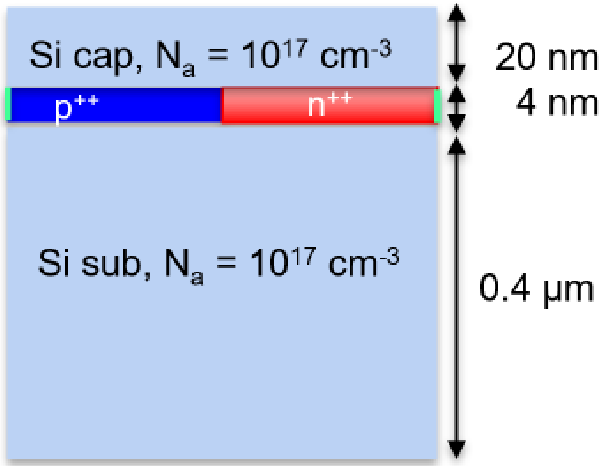




This work utilizes Charon TCAD simulations to understand the operation of APAM bipolar devices and to facilitate their designs.

[3] T. Škereň *et al.*, "Bipolar device fabrication using a scanning tunneling microscope," Nat. Electron. **3**, 524-530 (2020).

APAM PN Junction Simulation: B Parameter Effect

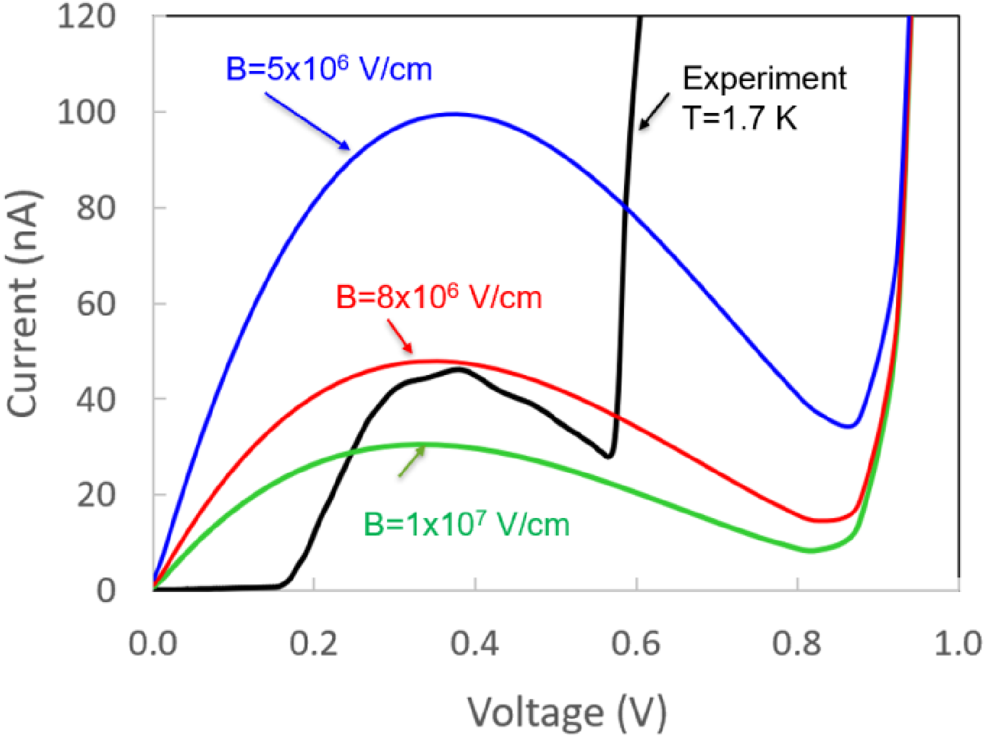


https://charon.sandia.gov/

Simulations were done using Charon, an open-source TCAD code developed at Sandia National Labs.

- δ-doping = 3×10^{20} cm^{-3}, to produce 1.2×10^{14} cm^{-2} as in Skeren's paper.
- Electron mobility was taken from the paper.
- Band-to-band tunneling (B2BT) is modeled as

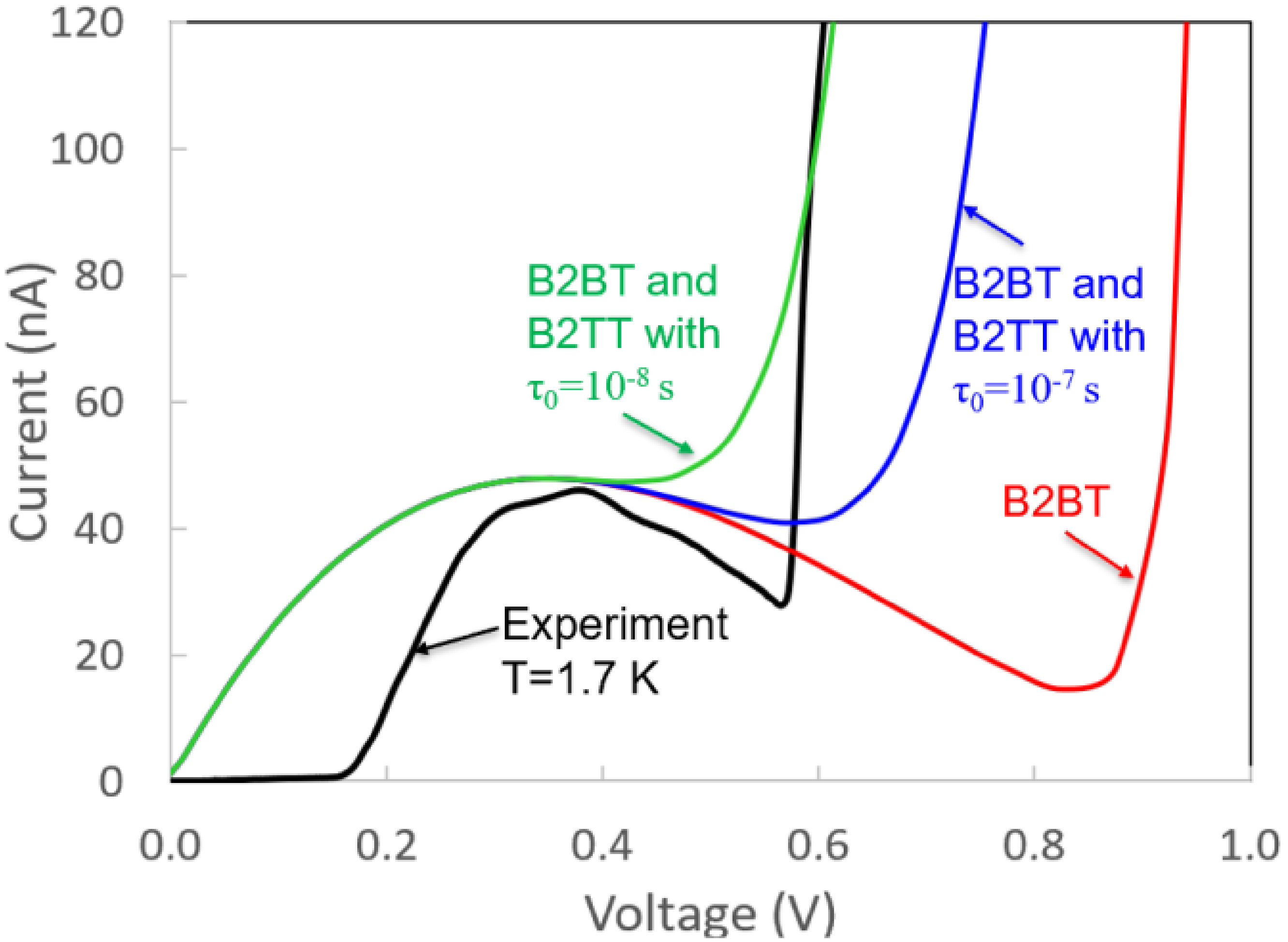
$$G_{bbt} = \pm \left(\frac{|F - F_0|}{F_0} \right)^{\beta} A F^{\gamma} \exp\left(-\frac{B}{F} \right)$$



The B parameter, a threshold field for B2BT, shows a dominant effect in determining the NDC peak current.

APAM PN Junction Simulation: Determine Valley Voltage

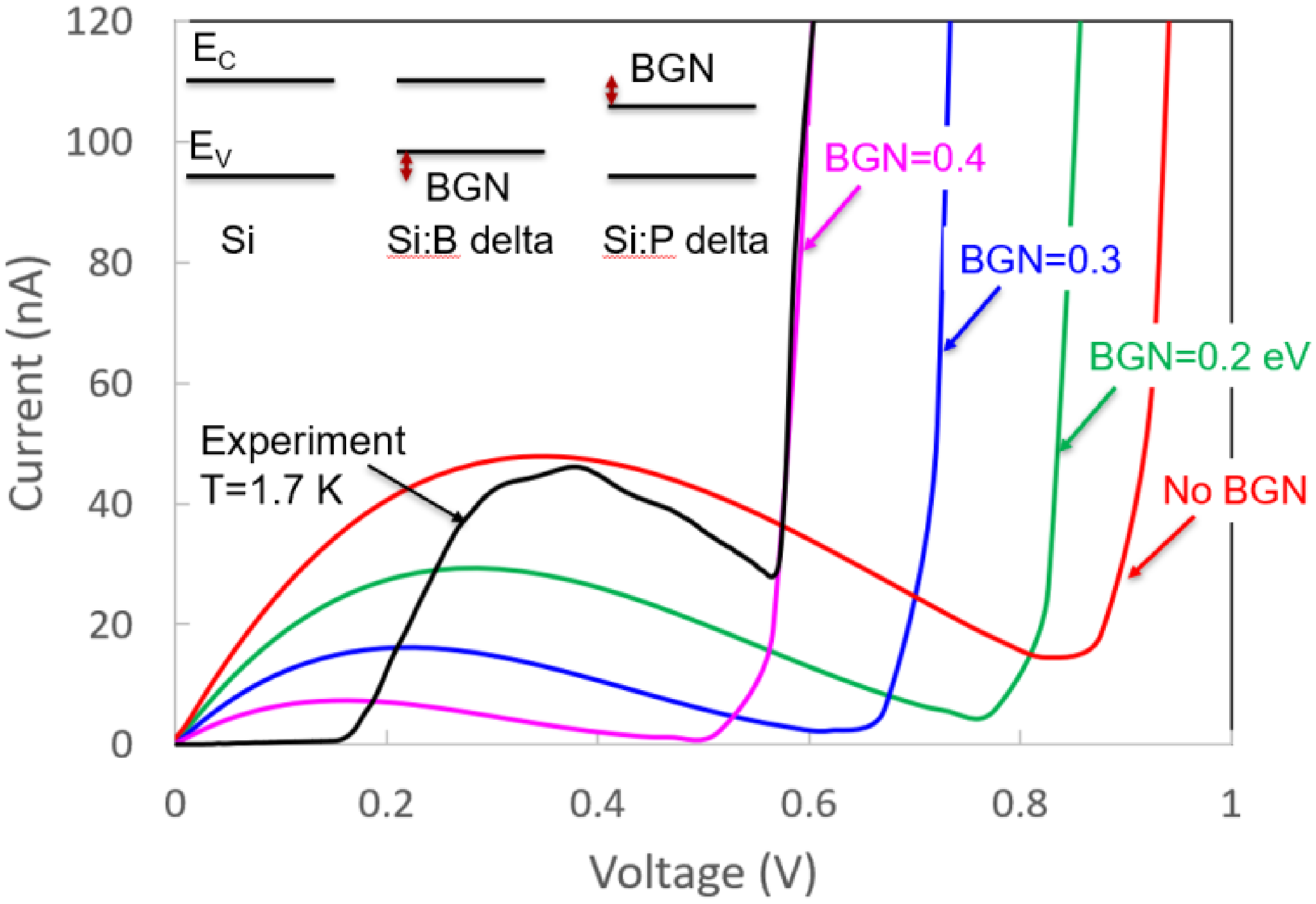
Effect of band-to-trap tunneling (B2TT) on valley voltage



Band-to-trap tunneling indeed significantly reduces the valley voltage.

APAM PN Junction Simulation: Determine Valley Voltage

Effect of band gap narrowing (BGN) due to high doping on valley voltage

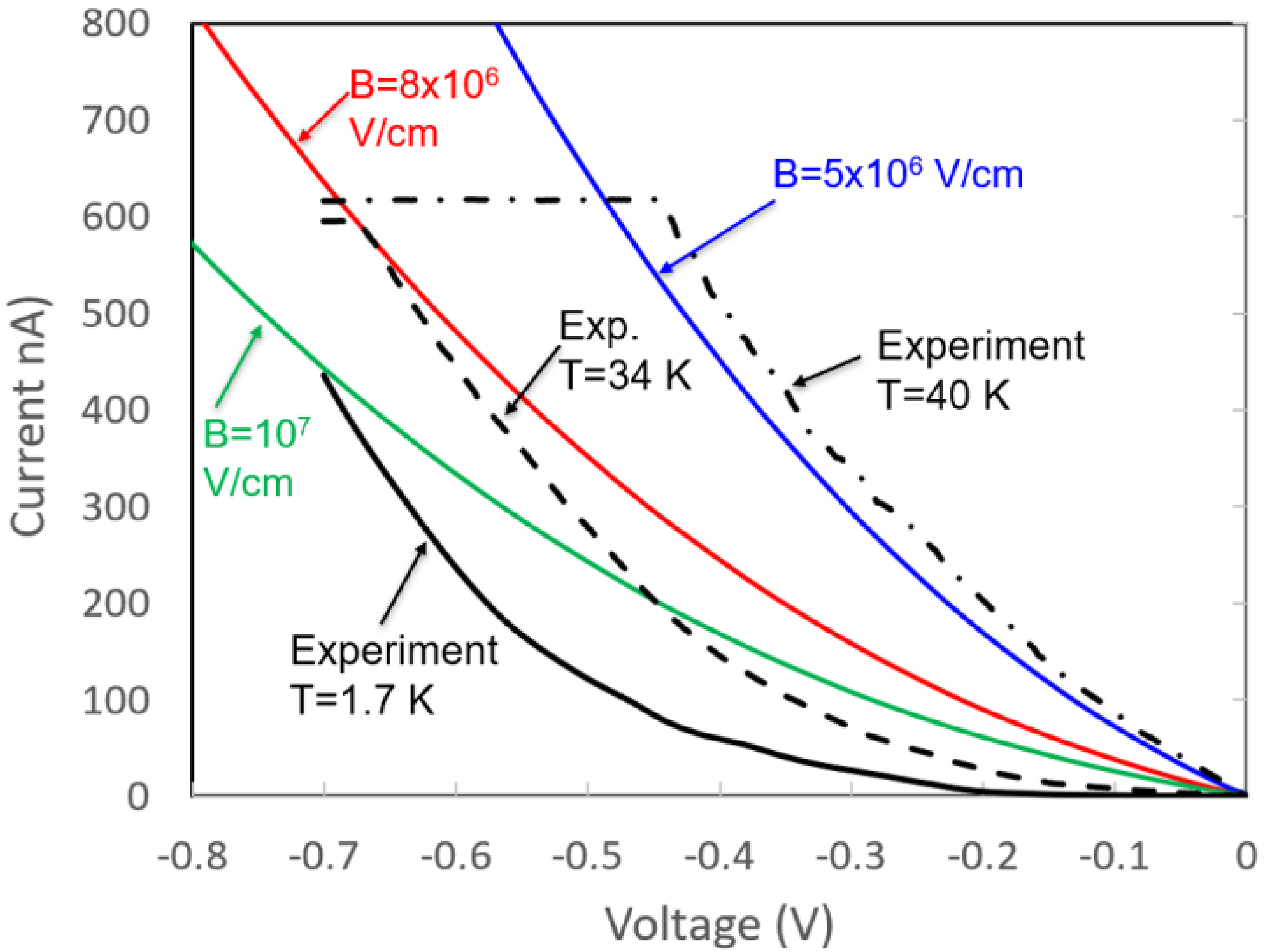


High delta-doping induced BGN can also reduce the valley voltage.

A combination of B2BT and BGN effects may be responsible for the small measured valley voltage.

The near-zero current response for voltages < 0.2 V needs further study.

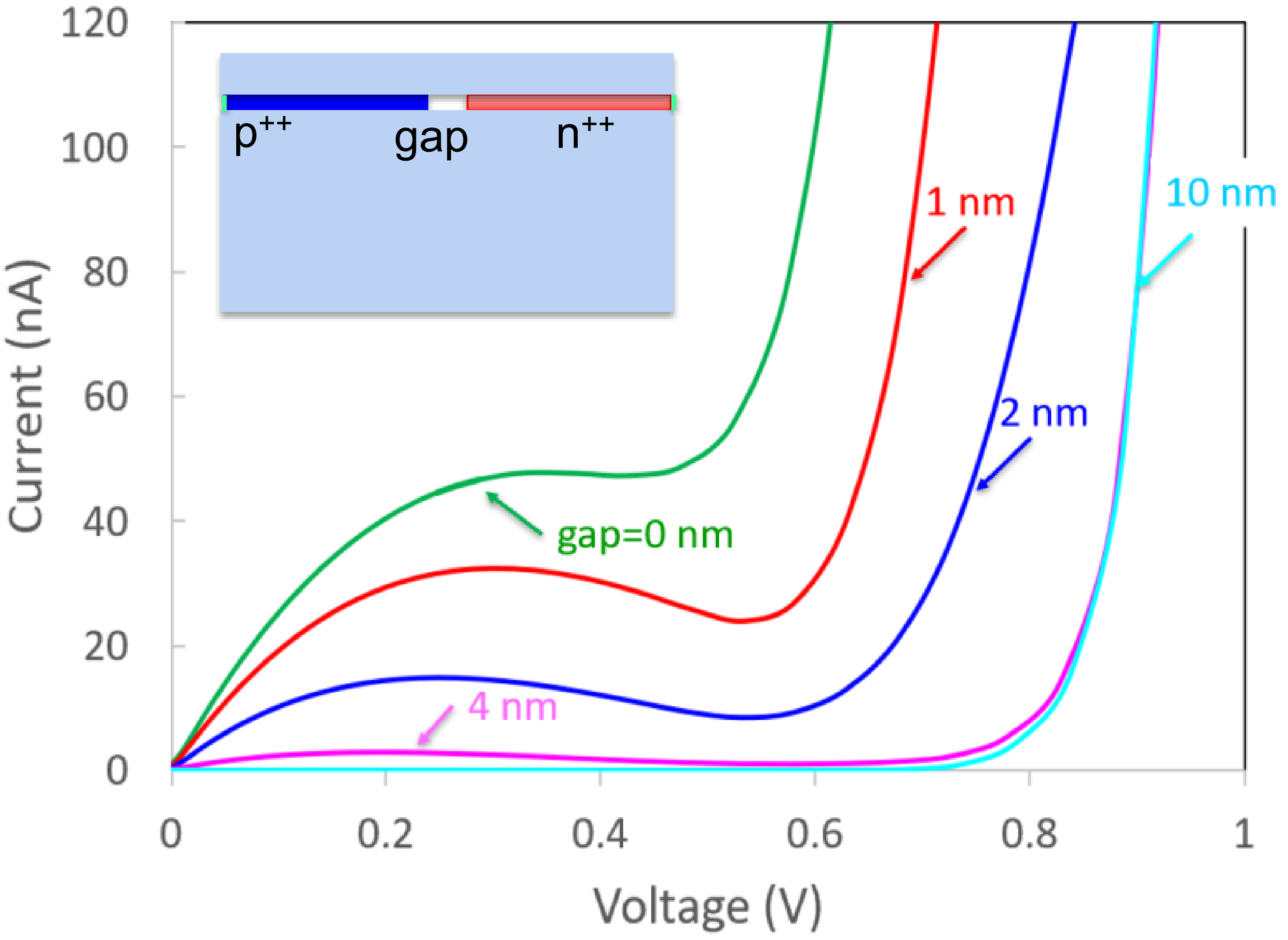
APAM PN Junction Simulation: Reverse Response



Band-to-band tunneling with an adjustable field parameter can model the main feature of the measured reverse I-V response.

TCAD simulation with B2BT is able to capture the main features of APAM PN I-V responses.

APAM PN Junction Simulation: Gap Width Dependence

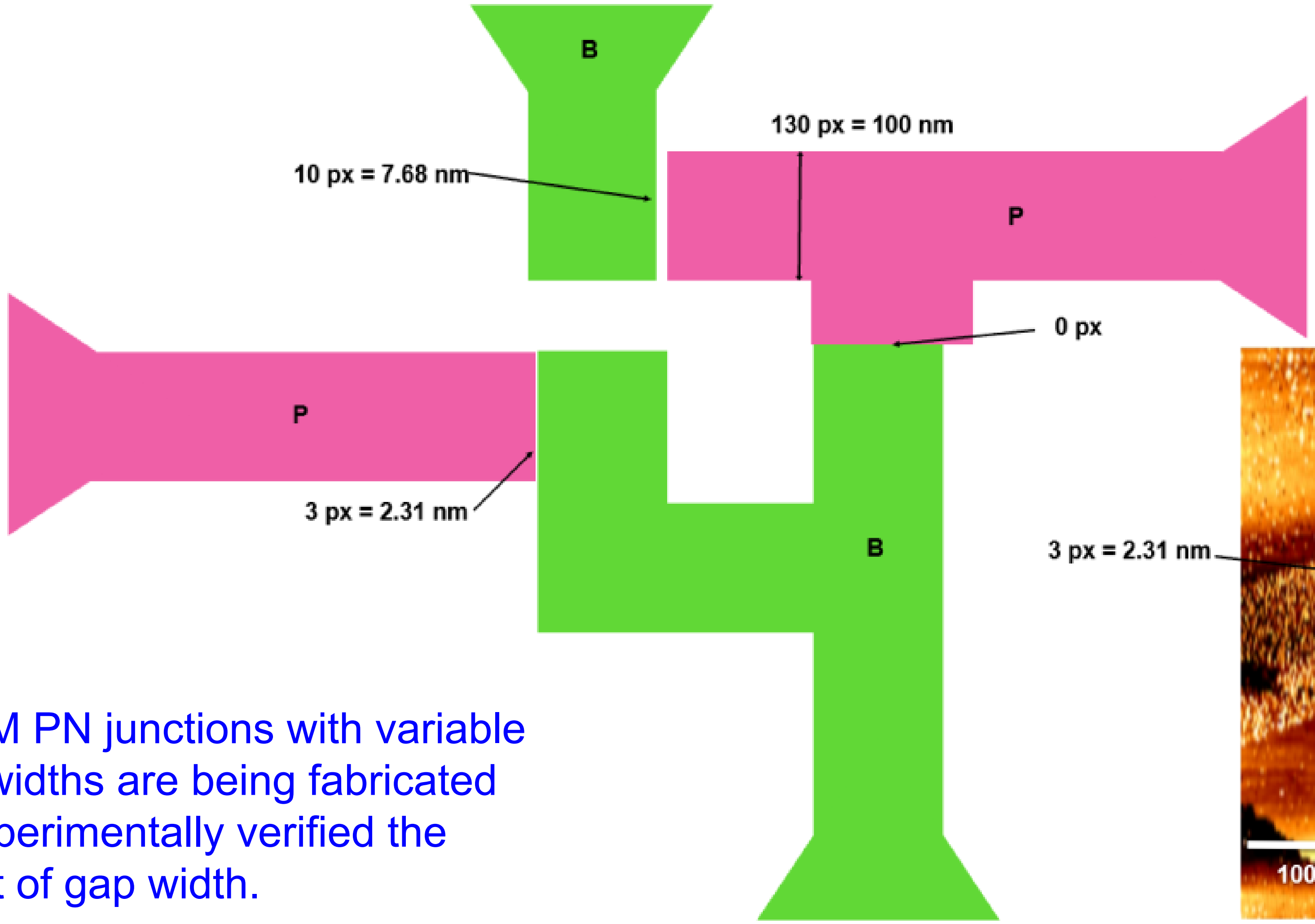


How does a controlled gap between two delta layers affect the I-V response?

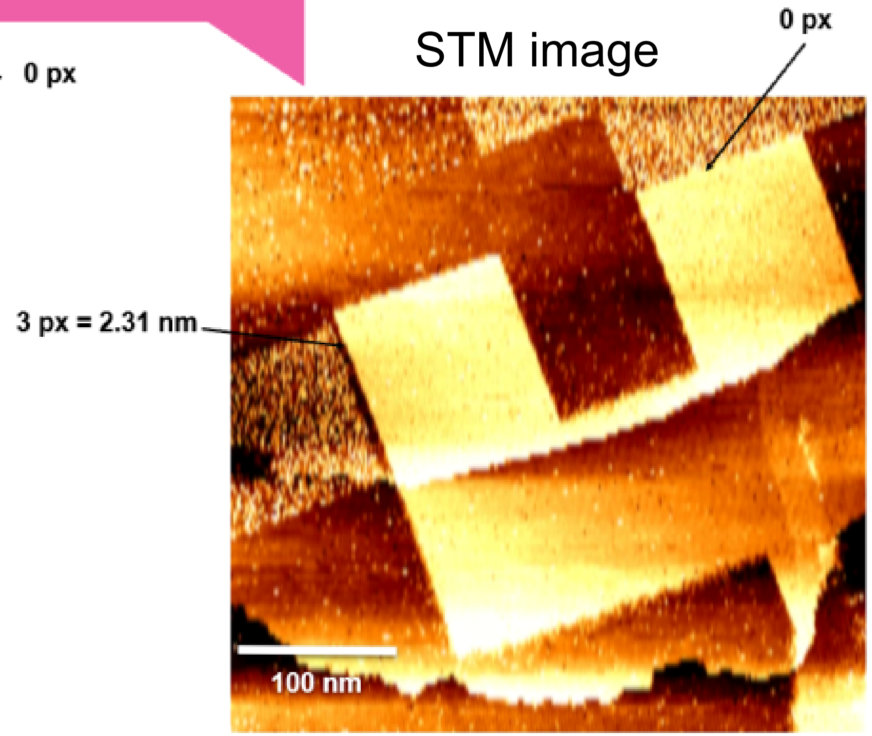
Forward I-V response depends significantly on the gap width.

When the gap is 4 nm or larger, the NDC behavior is diminished.

Fabrication of APAM PN with Variable Gap Width



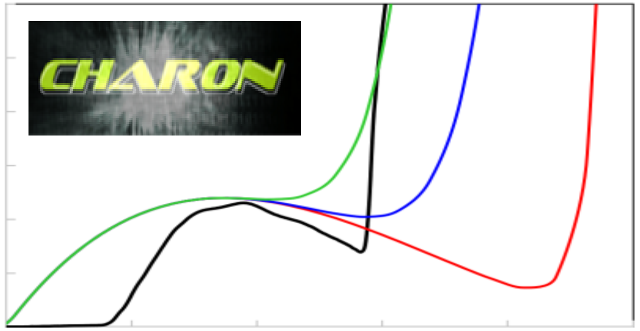
STM image



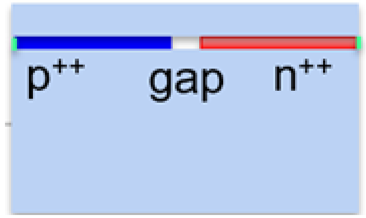
APAM PN junctions with variable gap widths are being fabricated to experimentally verified the effect of gap width.

Summary

❑ Charon TCAD simulations with B2BT and B2TT was shown to **capture the main features** of APAM PN I-V responses.



❑ Modeling results of gap width effect on APAM PN junction response **motivated the experimental design** of PN junctions with various gap widths.



❑ Future work: **model potential APAM BJT designs** and explore parameter space in search of good BJT performance; compare simulation results with experimental data when available.