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2D Bipolar Devices – Fabrication, Metrology and Measurement

J. H. G. Owen, E. Fuchs, R. Santini and J. N. Randall, Zyvex Labs, Richardson, TX

J. P. Mendez, X. Gao, D. Mamaluy, S. Misra, Sandia National Lab, Albuquerque, NM

R. Misra and S. O. R. Moheimani, UT Dallas, TX

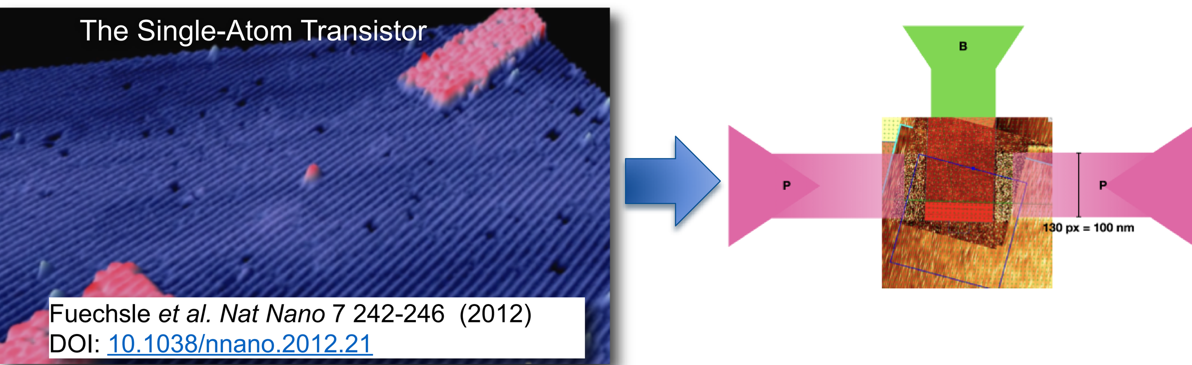
W. P. Kirk, 3D Epitaxial Technologies, Richardson, TX

Atomically Precise Ultra-High Performance 2D Micro Electronics (BJTs)
DE-SC0020817
Zyvex Labs, Sandia National Labs, 3DET

Atomically Precise Scanning Probe Based Analysis of Activated Dopants for 2D Micro Electronics(Dopants)
DE-SC0020817
Zyvex Labs, UT Dallas

Overview

Atomically Precise Advanced Manufacturing



HDL State of the Art – Single Atom Transistor

Our Goal –APAM Bipolar Junction Transistor

Objective is to fabricate and measure the properties of bipolar devices built from patterns of dopant atoms placed with atomic precision. This project is part of a sustained program to develop patterning and device fabrication technologies for Atomically Precise Manufacturing (APM) using STM-based Hydrogen Depassivation Lithography (HDL). This is a rapid commercialization approach because it enables:

Automated, programmable tools.

Premium R&D markets – low-noise high-frequency bipolar analog devices, atomic-scale classical computers.

HDL has been used for placement of P atoms deposited from PH_3, to make P-based spin or charge qubit devices - quantum computers.

Other ultraprecise devices, e.g. Tunnel FETs and Bipolar Junction Transistors, have also been proposed. -Atomically Precise Advanced Manufacturing (APAM)

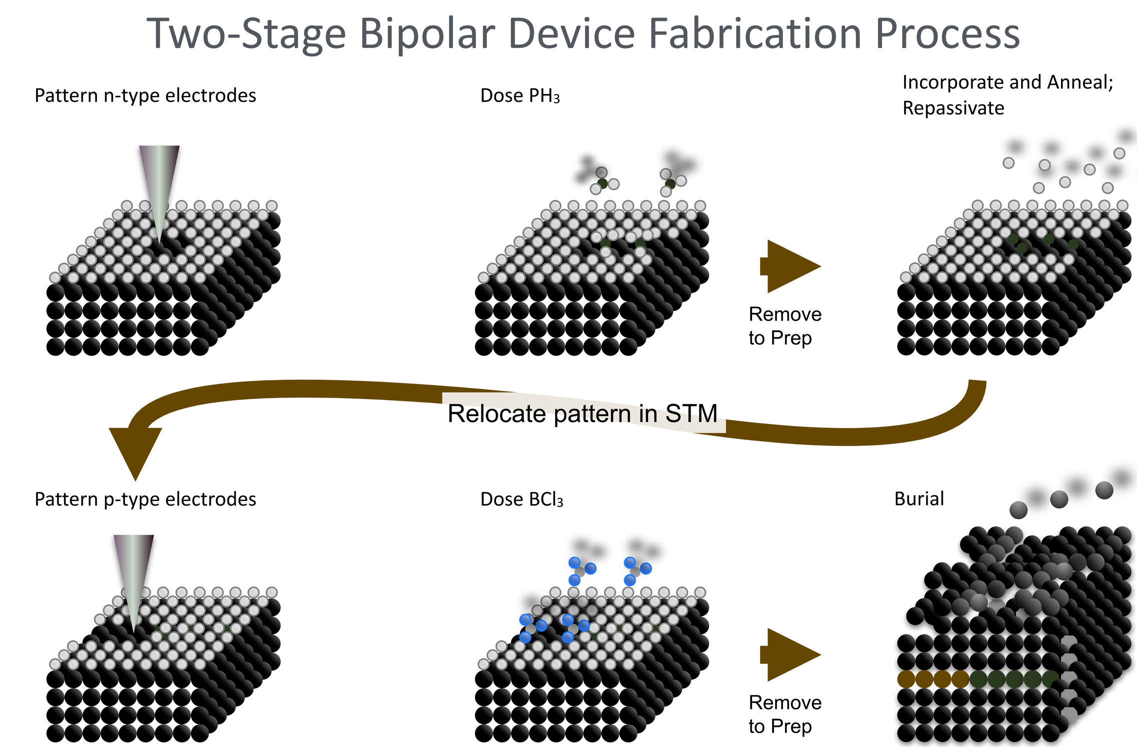
Bussmann, E. *et al.* *Atomic - Precision Advanced Manufacturing for Si Quantum Computing.* MRS Bulletin. 2021, 46, 1–9. DOI: 10.1557/s43577-021-00139-8

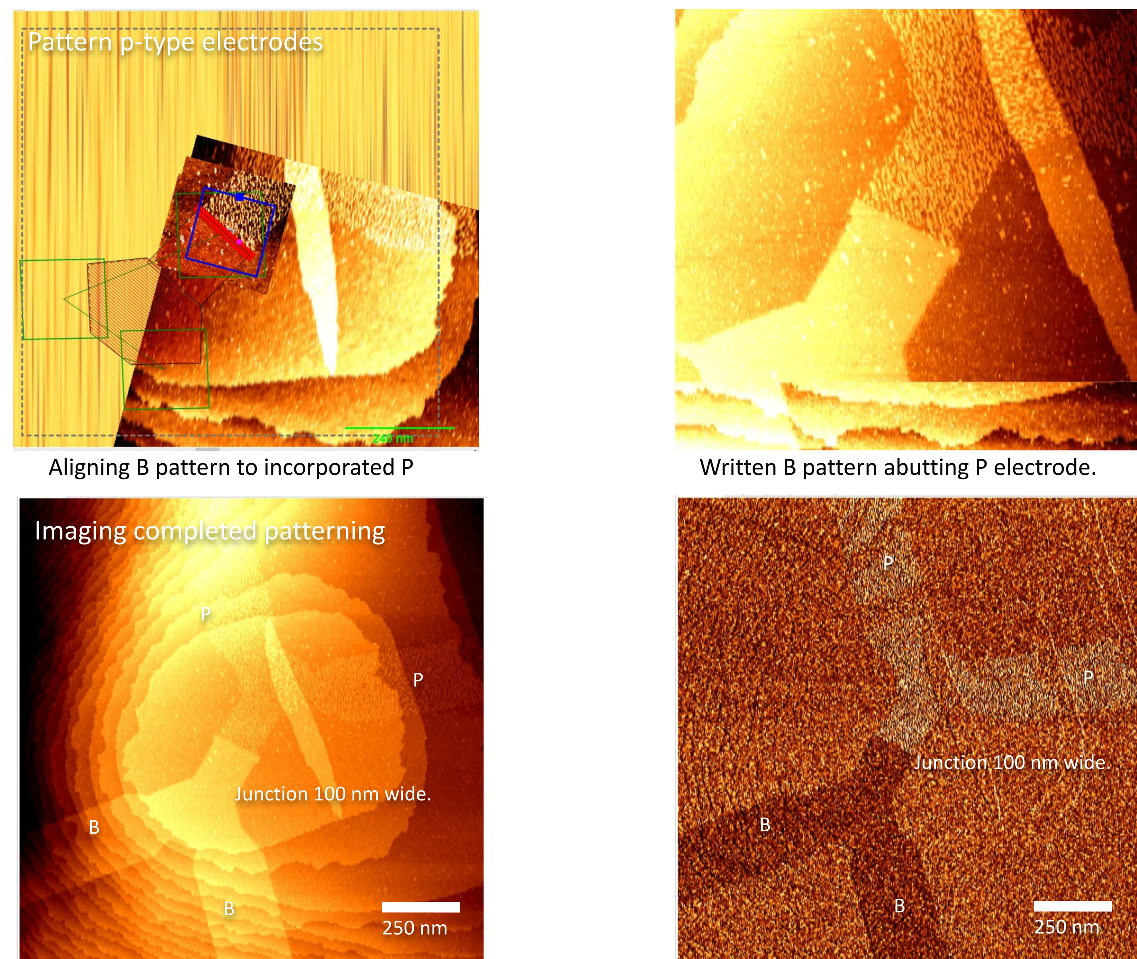
Project Teams and Roles:

- **Zyvex Labs** leads development of automated, atomically-precise lithography. They create dopant-based devices for testing, and write the software for integration of the high-frequency techniques into our lithography software.
- **Zyvex Labs** leads development of automated, atomically-precise lithography. They will create 2D bipolar devices.
- **Sandia National labs** leads on device modelling. They have modelled p-n junctions of various sizes, and are now modelling n-p-n junctions.
- **3DET** is developing a unique UHV alane source as an Al dopant precursor, and provides device contacting and measurement for Zyvex-made devices.
- **University Texas at Dallas** provides the control engineering expertise, developing the spectroscopic imaging methods to image the dopant patches.

Highlights

Two-Stage Bipolar Device Fabrication Process





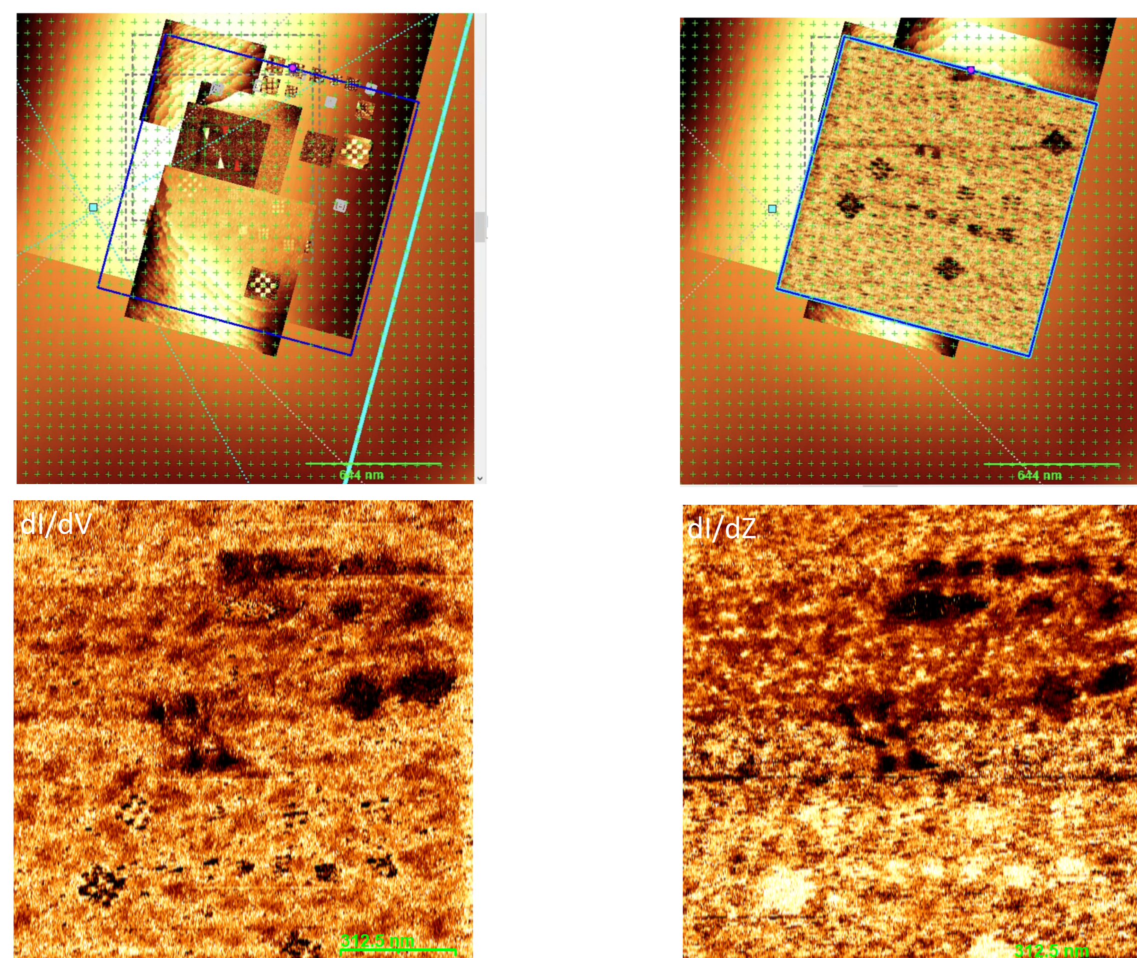
Aligning B pattern to incorporated P

Written B pattern abutting P electrode.

Topo

dI/dZ

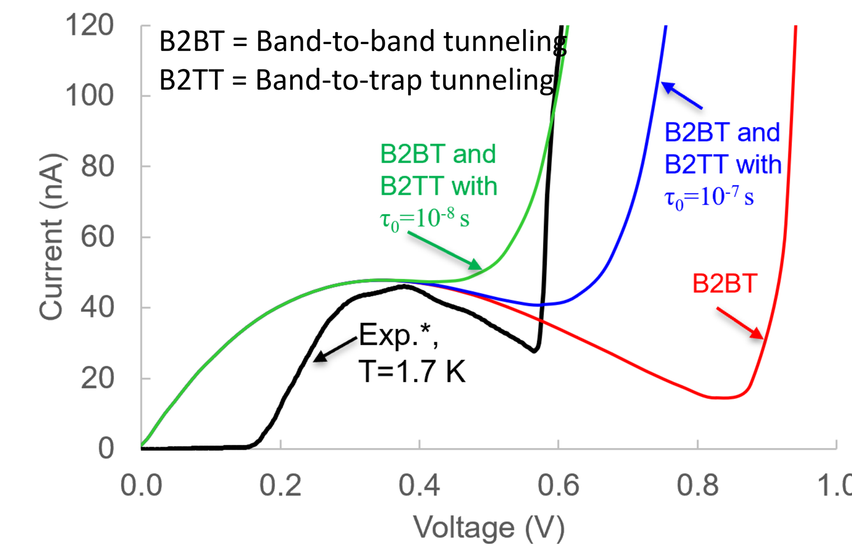
dI/dZ imaging captured simultaneously with topographic image shows strong contrast between patterned and unpatterned areas.



We are exploring the limits of the dI/dV and dI/dZ modes. Here a mixture of B patches and P patches are shown after patterning in Topo mode, and after having been buried with dI/dV mode. In dI/dV imaging, both dopants have the same contrast, with dI/dZ, the contrast is opposite.

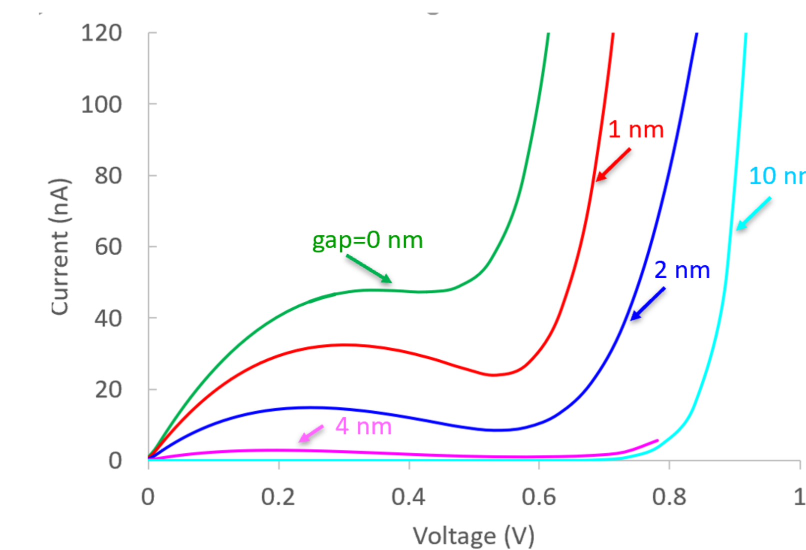
Device Simulations of 2D p-n junction devices

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

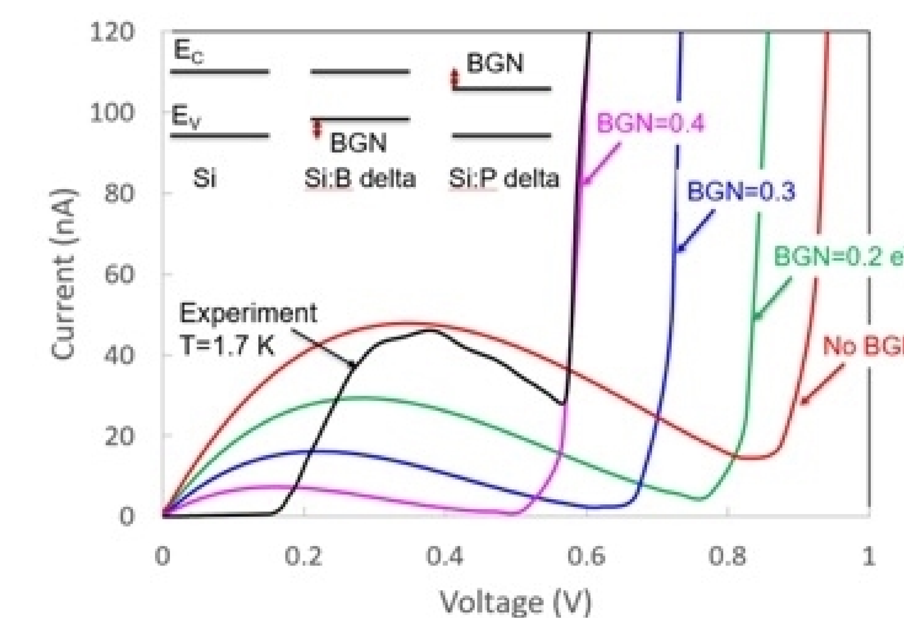


* T. Skereň et al. Nat. Electron., vol. 3, pp. 524–530, 2020.

With B2BT and B2TT, simulation results are in decent agreement with the experimental data except for voltages less than 0.2 Volts.



Simulated current-voltage (I-V) curves for B2BT (band-to-band tunneling) only (red), B2BT and B2TT with different zero-field lifetimes (blue and green) as compared to the experimental data (black). As expected, inclusion of B2BT does not affect the negative differential conductance response but decreases the valley voltage and increases the valley current.



Simulated I-V curves for different band gap narrowing (BGN) values as compared to the experimental data. Inset: schematics showing the locations of BGN for the Si:B (p-type) and Si:P (n-type) delta layers. Due to high doping in delta layers, BGN is expected; but its value depends on process conditions and doping density. The same BGN value was applied to Si:B and Si:P delta layers.

Progress

We are developing STM Lithography for Atomically Precise Advanced Manufacturing.

For bipolar devices, the n-type patterns are written first, dosed with PH_3, and the P incorporated. The p-type patterns are aligned to the P patches to provide atomic-precision gaps between p and n electrodes.

We have successfully created *p-n* junction devices, and we are now working on *n-p-n* devices. Modelling indicates that we need much lower doping in the device channels. Device measurements of *p-n* junctions are being repeated to obtain more consistent results.

dI/dZ and dI/dV imaging simultaneous with topographic imaging provides extra electronic contrast of patterns and incorporated dopants, to make alignment of patterns easier.

The next step will be to fabricate and measure the electrical properties of further devices and compare to the modelling predictions.

The modelling is now exploring 2-D and 3-D models to test the possible effects of background doping on the device performance.

AMMTO linkage

- Fabrication of 2D dopant-based devices using Atomically Precise Advanced Manufacturing (APAM) comprising HDL with dopant placement and burial.
- Fabrication and measurement of 2D bipolar devices, including Bipolar Junction Transistors
- Metrology of surface and buried dopant locations during and after device fabrication is essential to optimize the fabrication process, and confirm the device structure after burial.

- Potential Contributions to EES2 Goal:
  - Lower energy-consumption devices, high-frequency analog devices, allowing for more efficient control of other systems.
  - Continuing to miniaturize computing devices down to the atomic scale thus continuing the Moore's Law trend of reducing energy consumption per computational bit.
  - Developing tools and processes compatible with multiple dopant species to make solid state atomic scale bipolar devices and materials.

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