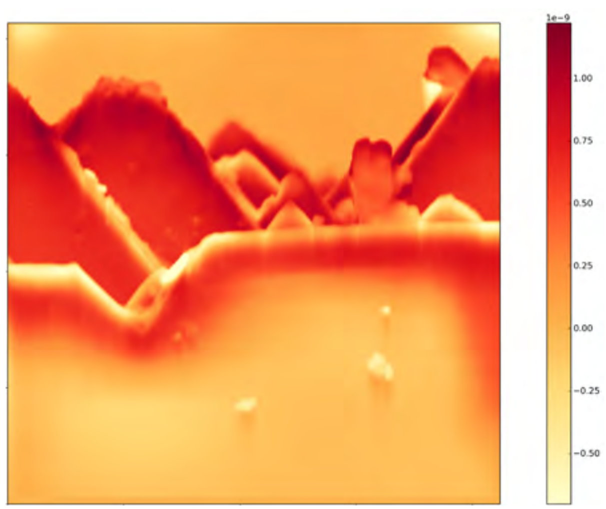
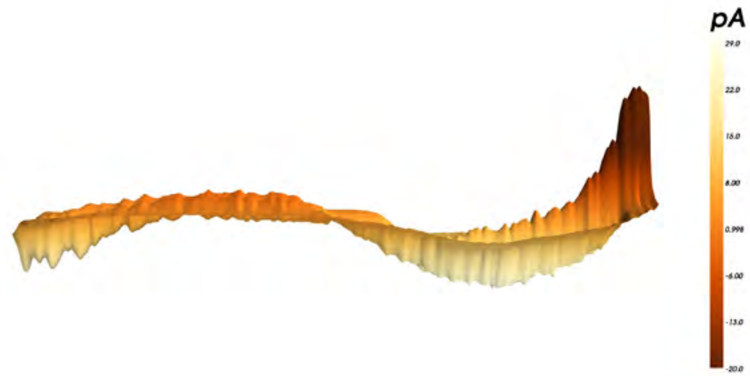
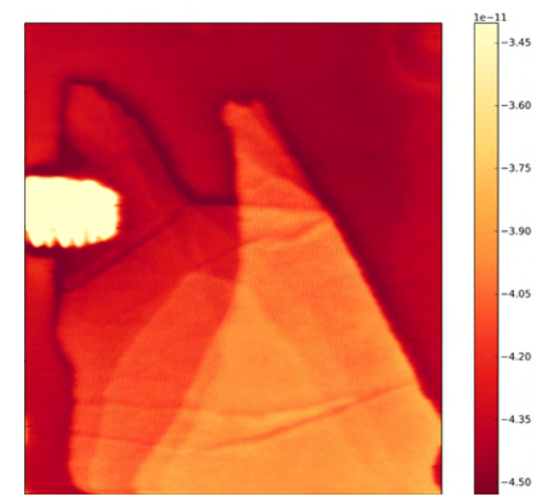
EPHEMERON LABS INC.

Exploring the Electronic Landscape at Interfaces and Junctions in Solid State Devices with Subsurface Local Probing of Carrier Dynamics with Electron Beam Induced Current (EBIC).

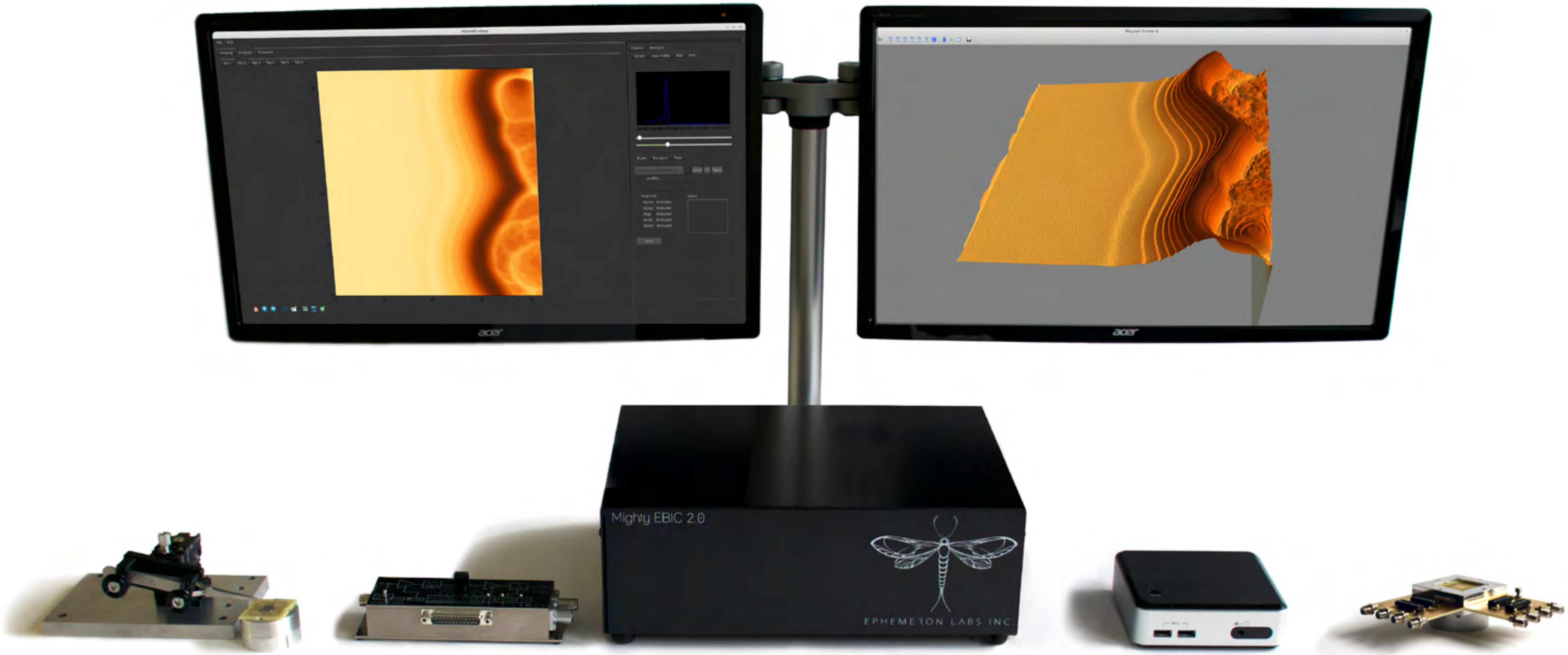
Dr. Terrence McGuckin



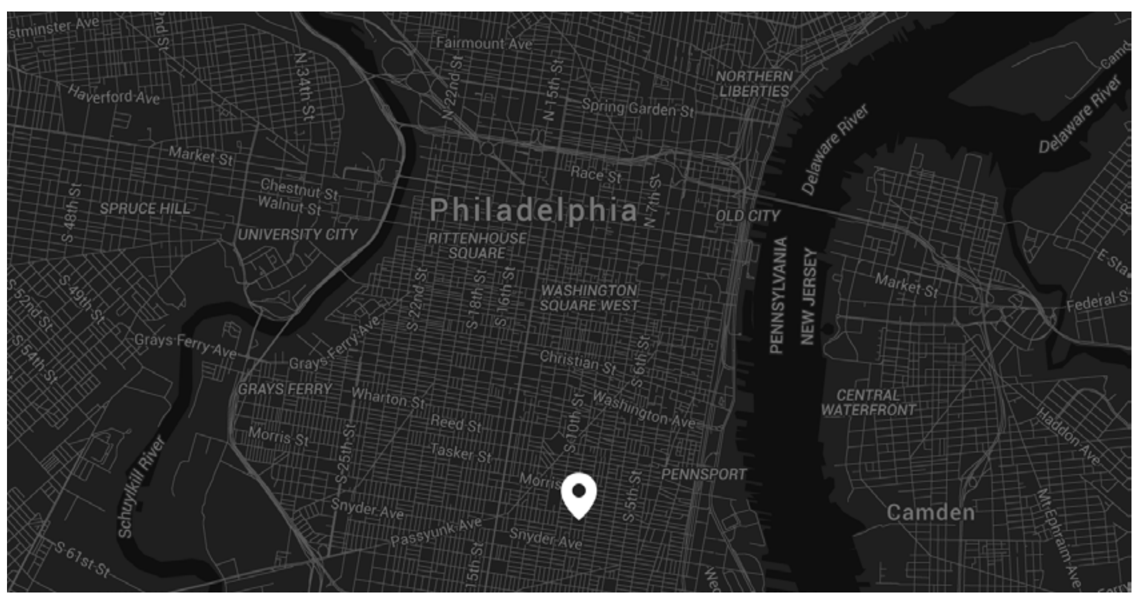




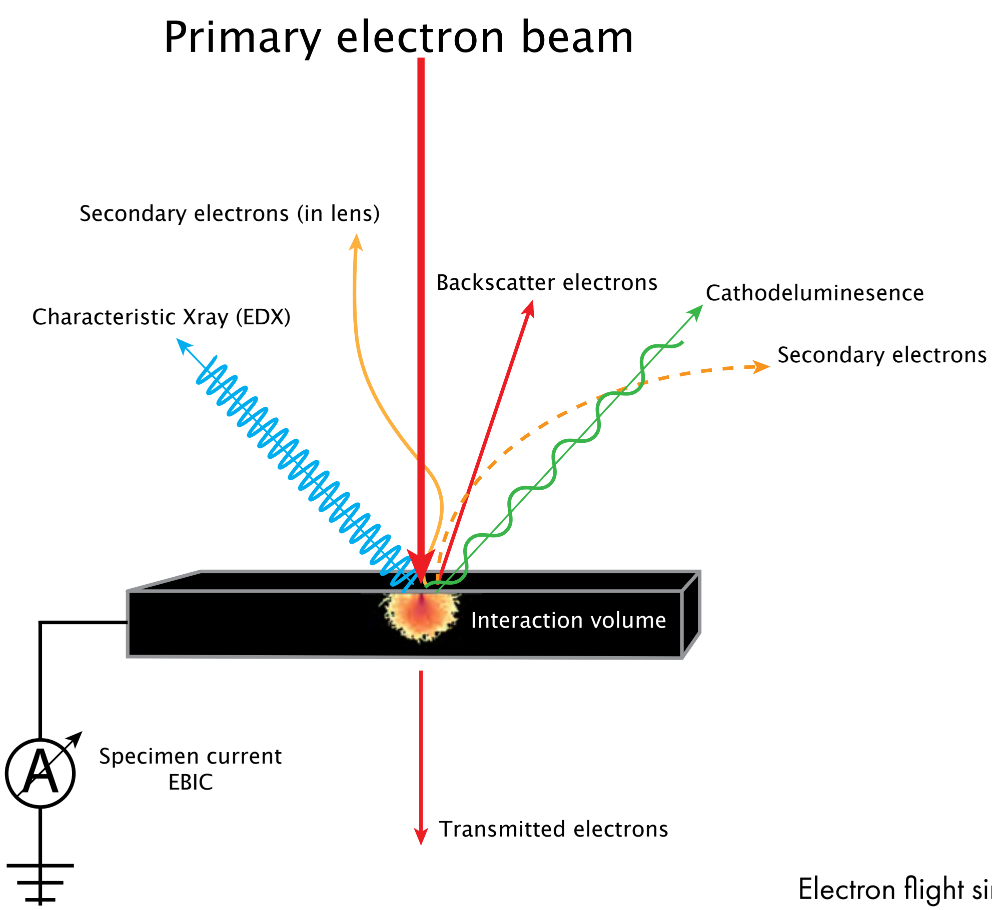
We make quantitative electron beam induced current (EBIC) imaging systems



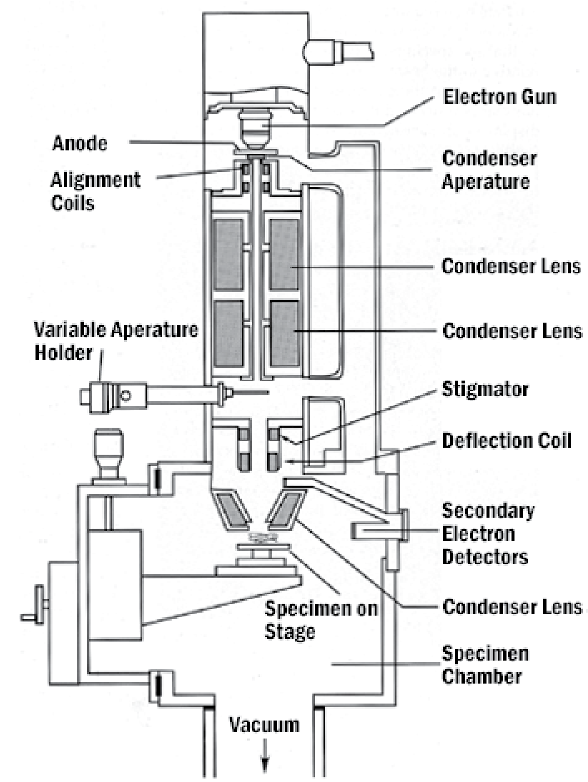
Ephemeron Labs is a Philadelphia based company. Our products are design and assembled at our South Philadelphia site, located in the historic Bok building.



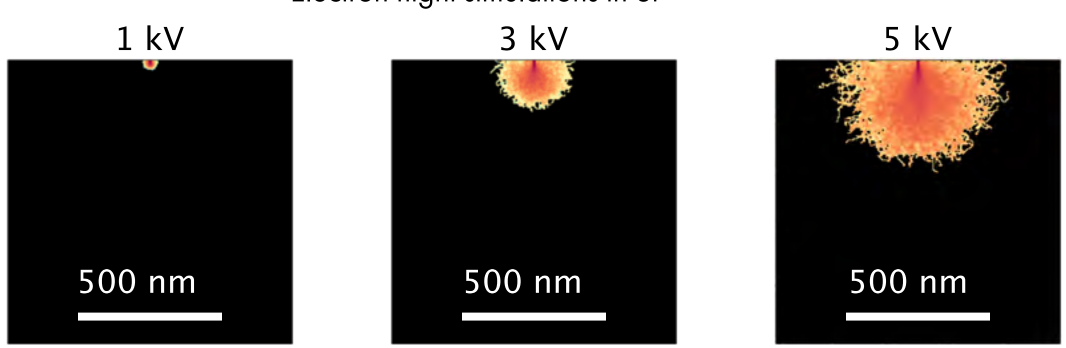
In EBIC we are using the electron beam as a local probe to measure transport properties.



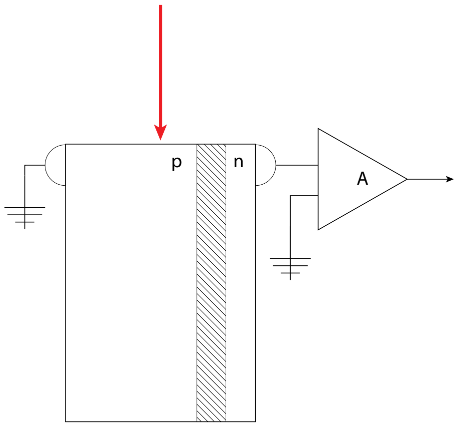
Schematic of scanning electron microscope

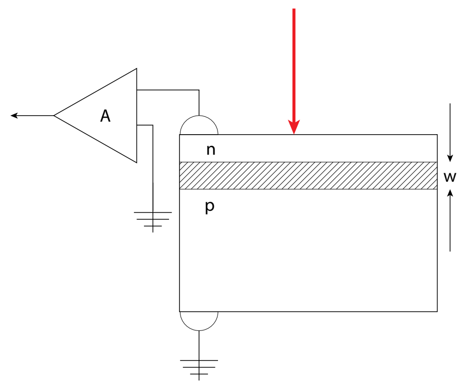


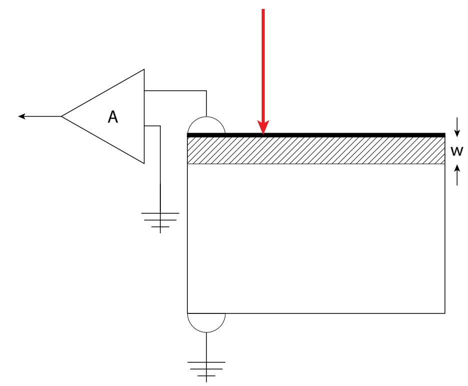
Electron flight simulations in Si

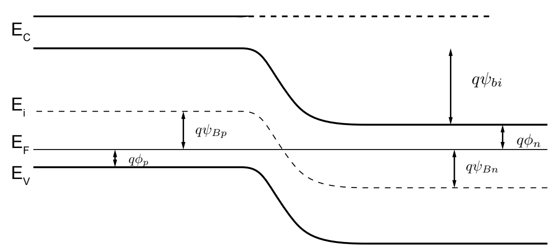


EBIC signal is dependent on the circuit and device configuration. In diodes, providing two separate conduction paths for electrons and holes can lead to large induced signals and image junctions.

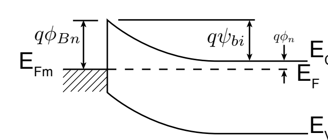


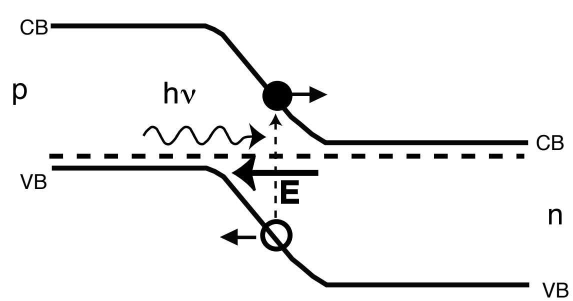




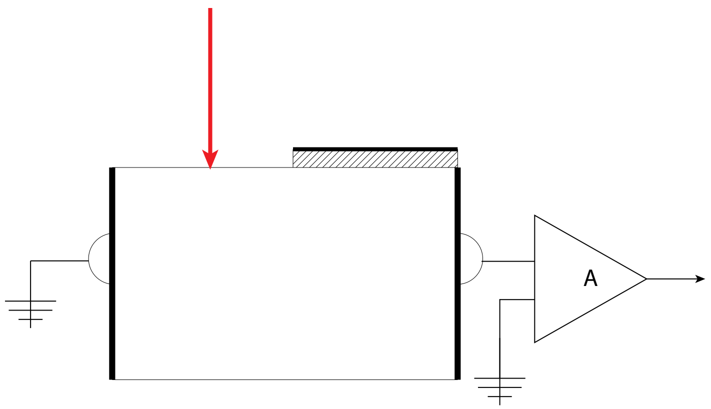


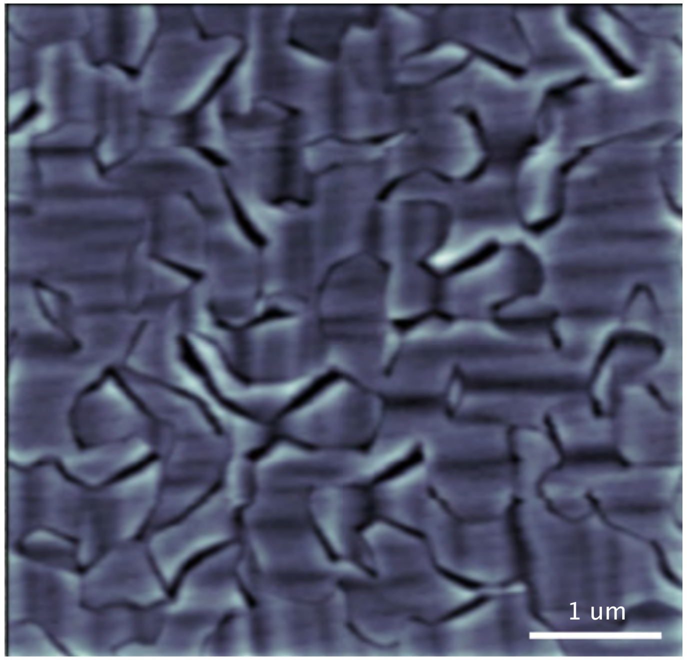
n-type semiconductor

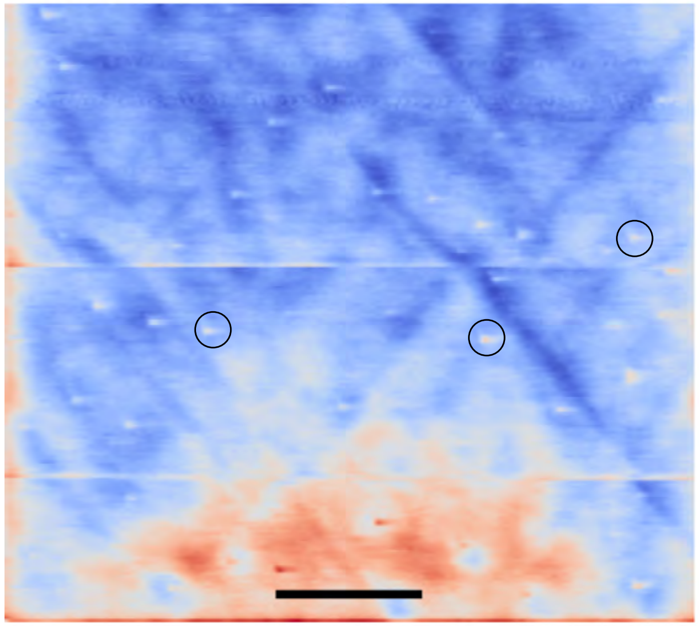




In the absence of a junction in the imaging region, you can measure local differences in fields and defects. With two contacts enables resistive contrast imaging.





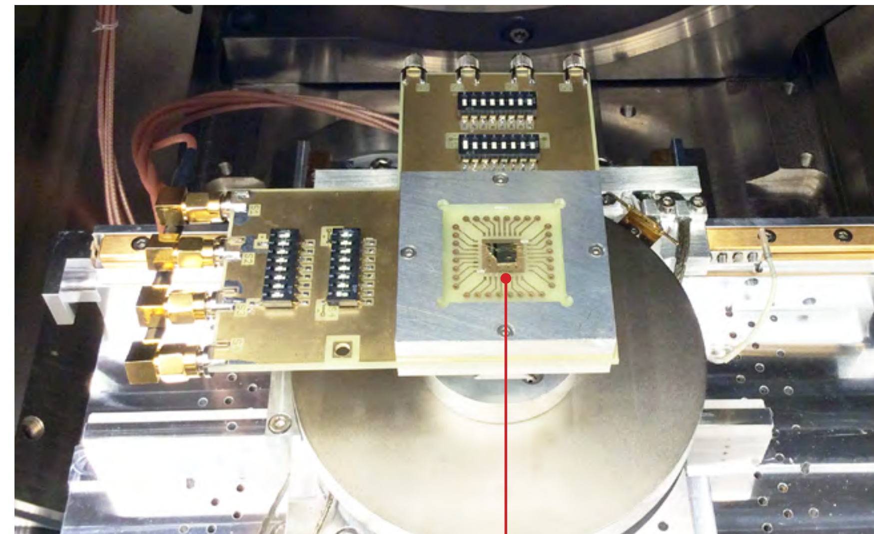


Our system can work with almost any SEM. This is our system installed at Brookhaven National Laboratory Center for Functional Nano-materials.

Helios Dual Beam FIB Center for Functional Nanomaterials

Clean room selfie

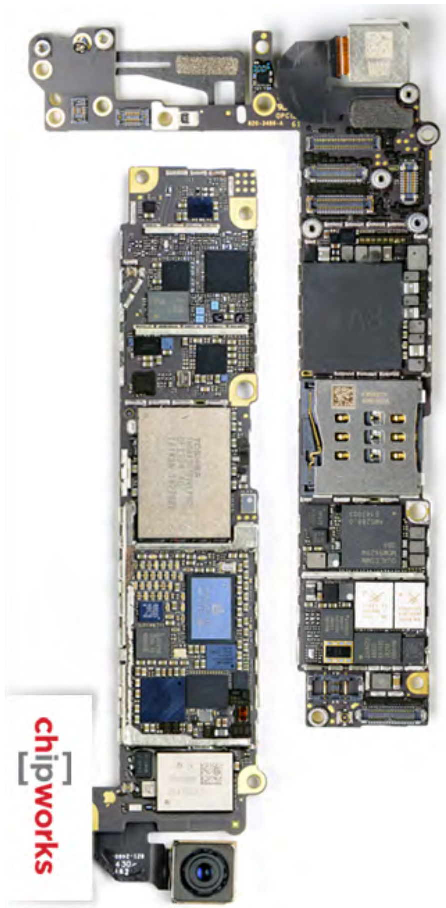
Yes, that is our system!



And our samples

Transimpedance amplifier

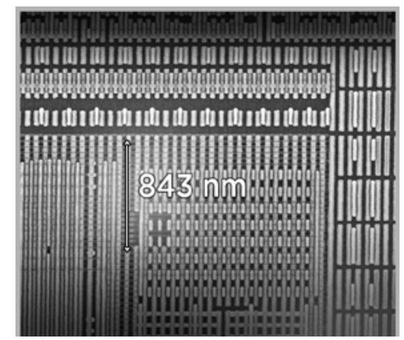
Solid state devices and the materials and interfaces that make up their basic building blocks are at the heart of the technology that enables how our society functions today.



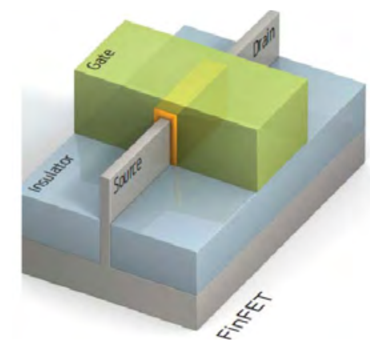
Logic Board

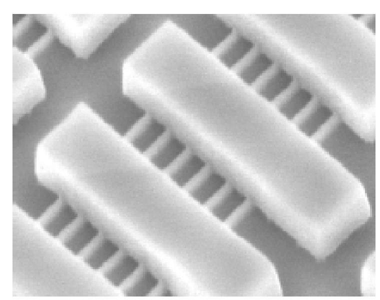
Apple A8 processor

Logic Gates

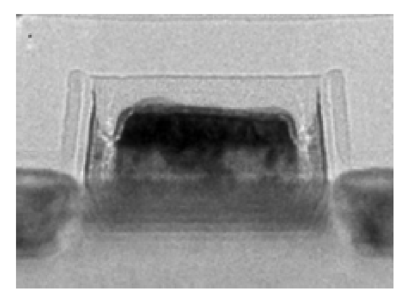


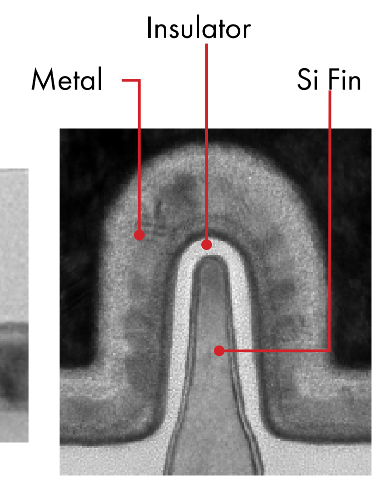
Field effect transistor





SEM of FinFET

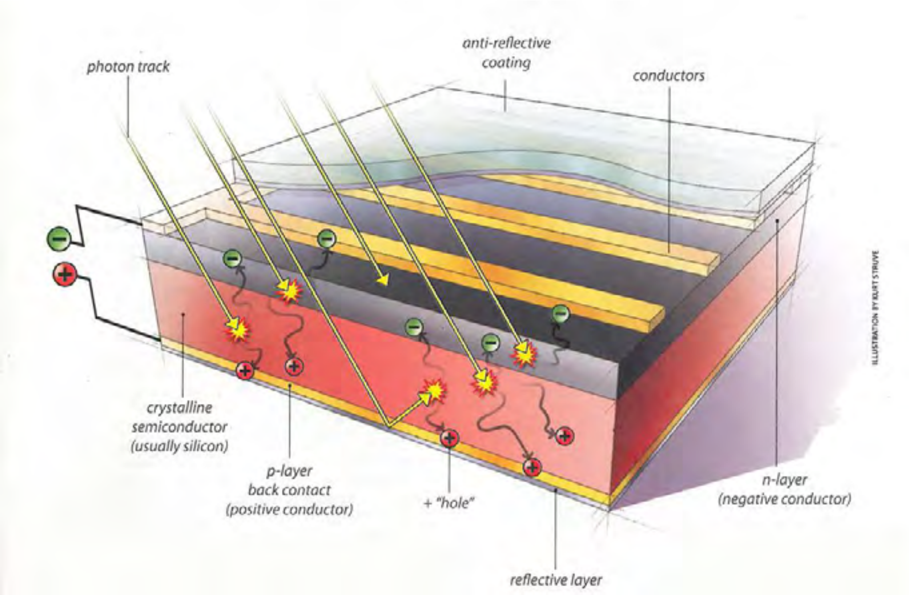




Cross section of FinFET

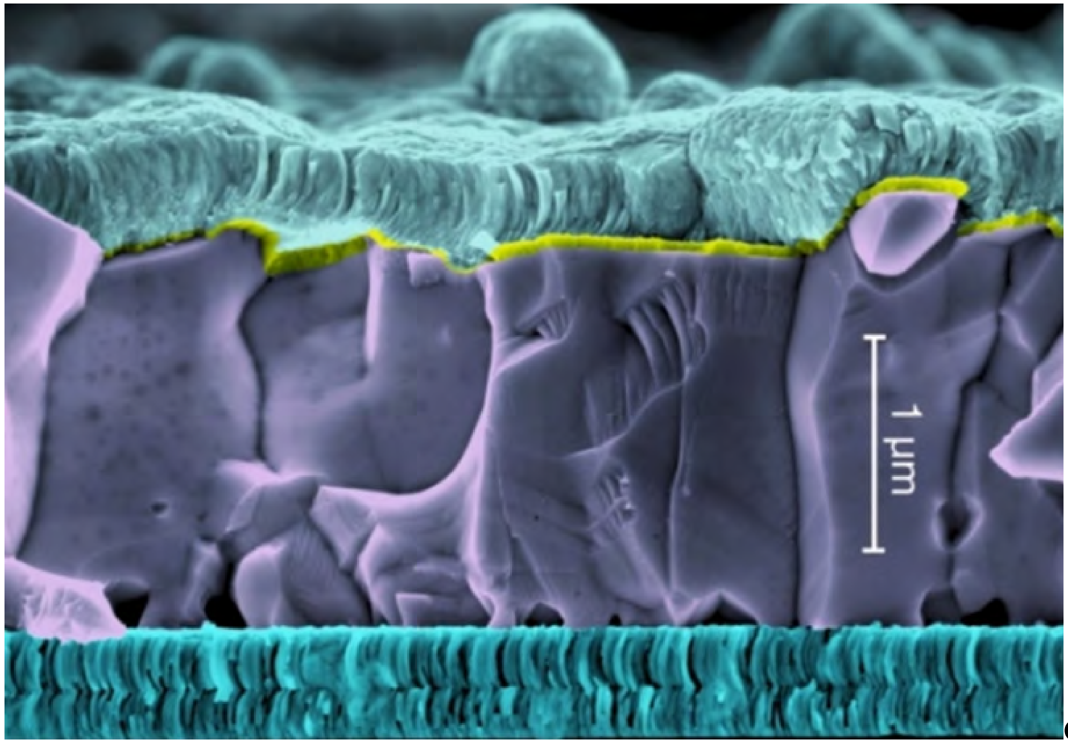
Solar Cells are solid state devices with built in electric fields that separate electrons and holes, created form absorbing light .

Largest roof top solar array in the world.



When we look inside a solar cell, we find it is made up of interfaces between materials.

The   junctions with in this device are what gives rise to electric fields that allow us to separate electrons and holes.



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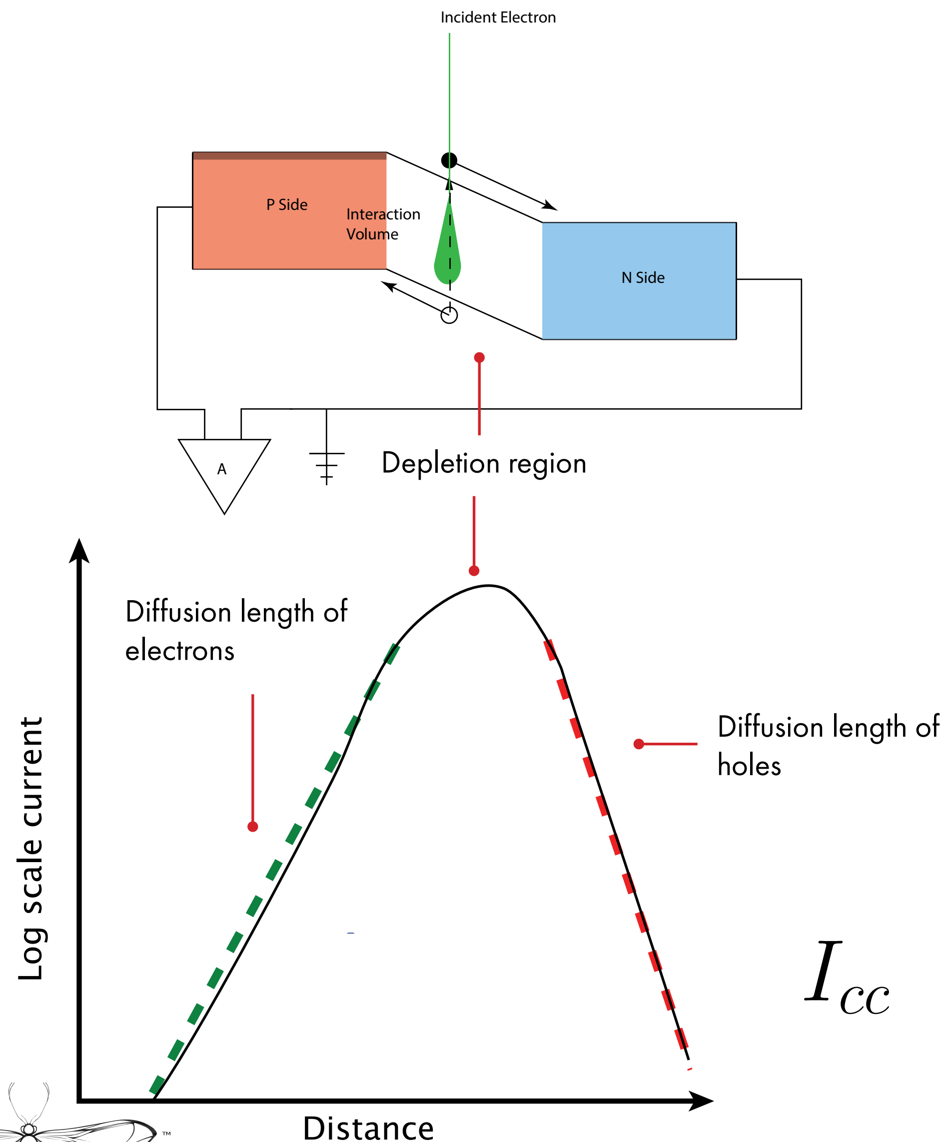
EBIC signal is due to the difference in generation and recombination rates and the processes of drift and diffusion of carriers.

Ebic signal is greatest in the presence of a junction.
Inside the depletion region all carriers are collected.



Generation of carriers

Incident Energy

$$G_e = \frac{E - E_{th}}{Ei} \frac{I_p}{e} (1 - \eta) \frac{1}{volume}$$

Mean Excitation Energy

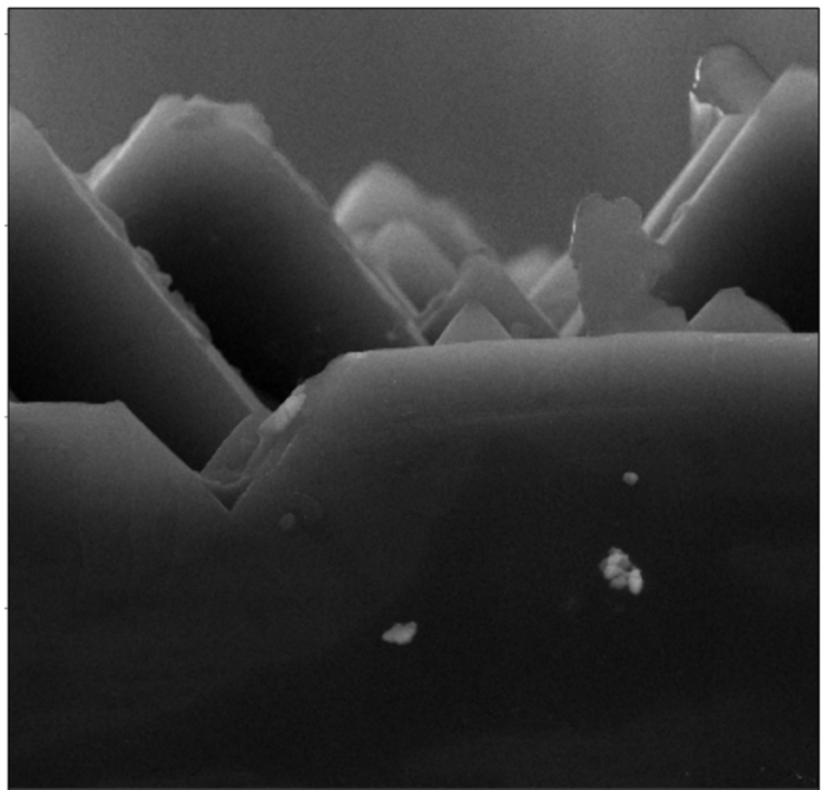
$$G_{e,h} = \frac{E_d}{3E_g}$$

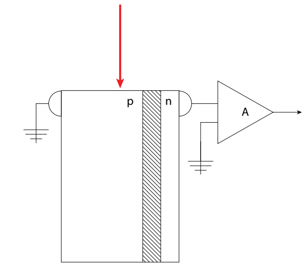
Simplified to Energy dissipated divided by 3 Eg. To account for light,heavy holes, and split off band

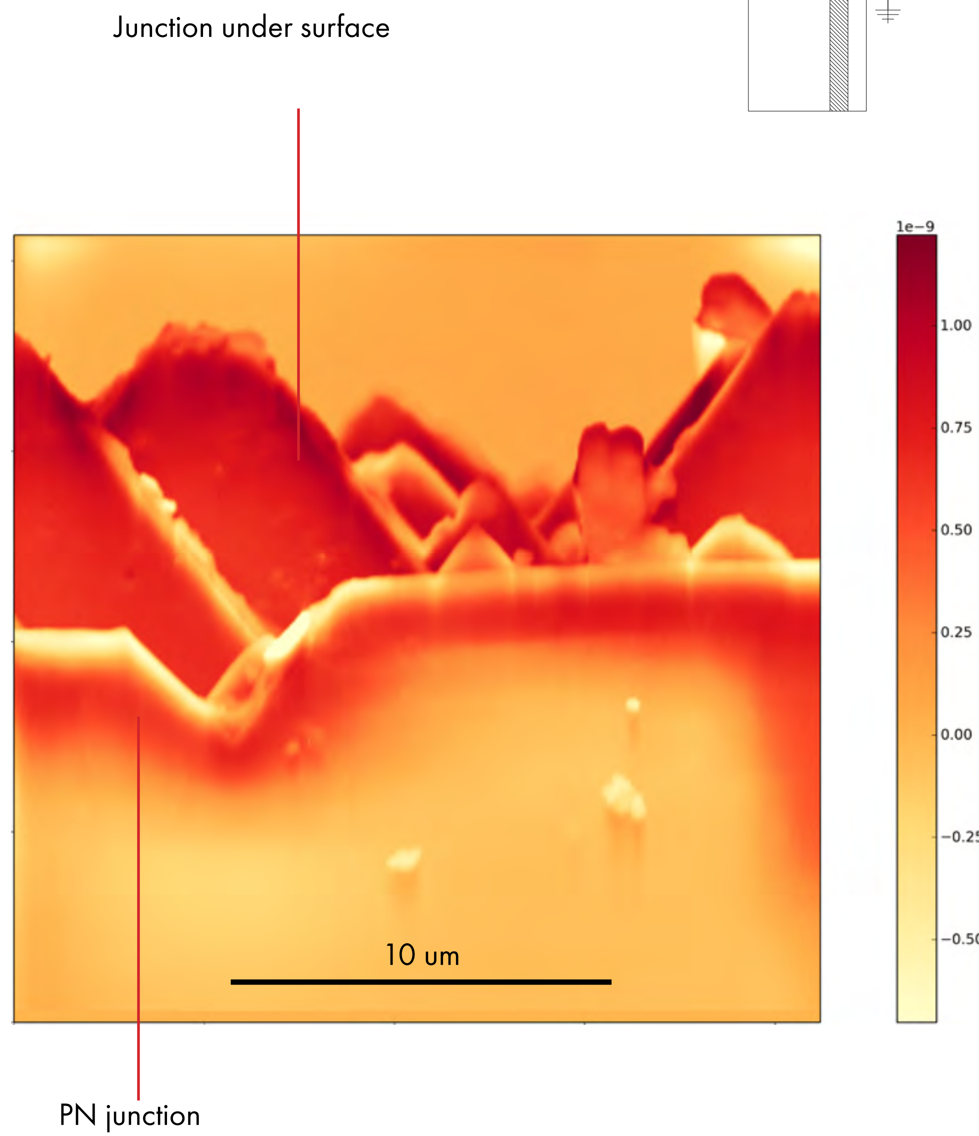
$$I_{cc} \propto exp^{(\frac{-x}{L})}$$

Integrating on one side of the junction gives the expression for the current as a decay exponential as the beam moves away from the junction.

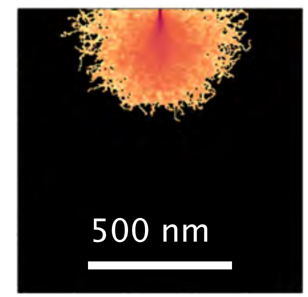
Imaging the cross-section of a Si solar cell. At 20kV the interaction volume is large enough to excite the exposed PN junction and the non-exposed junction.

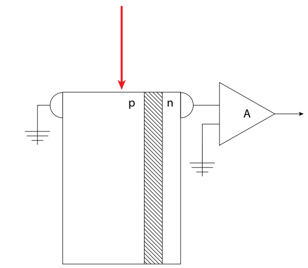


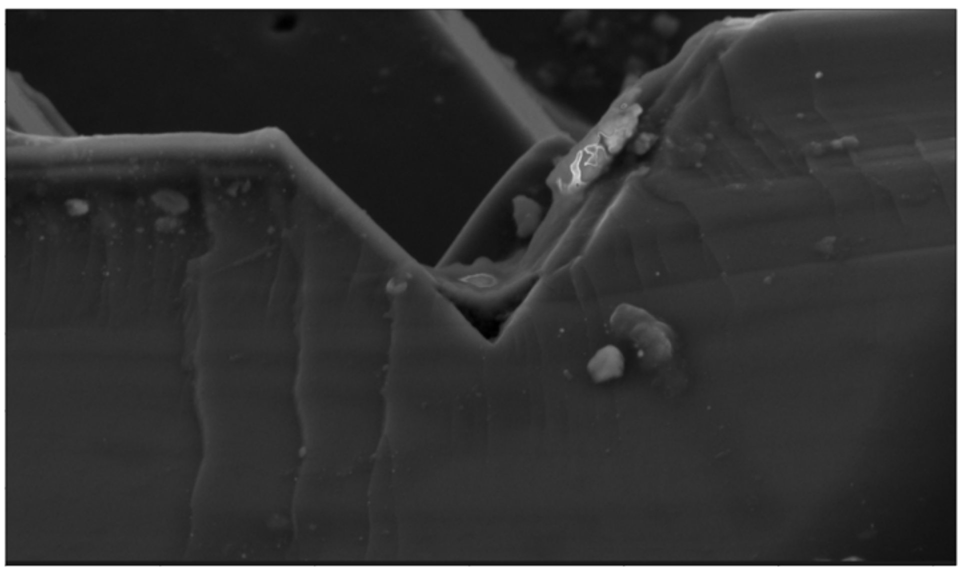


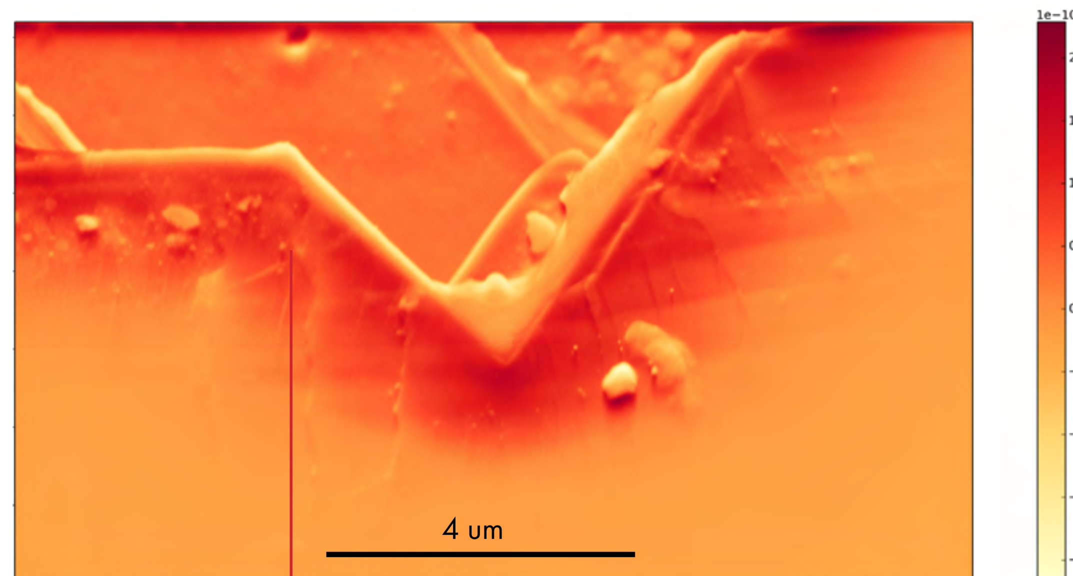


At an acceleration voltage of 5 kV, we can see more of the surface effects and less from the non exposed junction. The interaction volume becomes much smaller only 500 nm across.



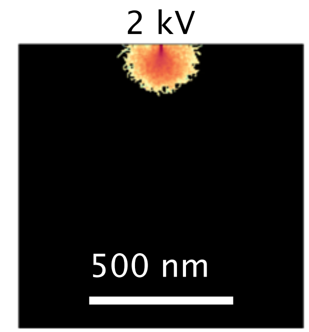


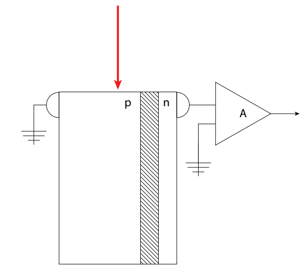


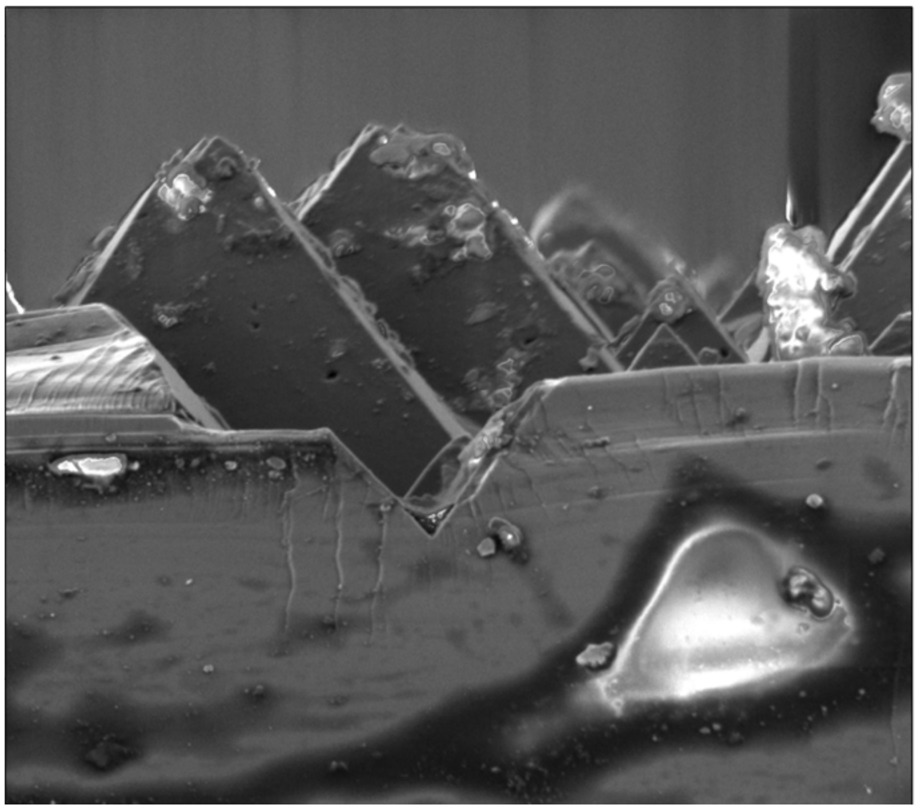


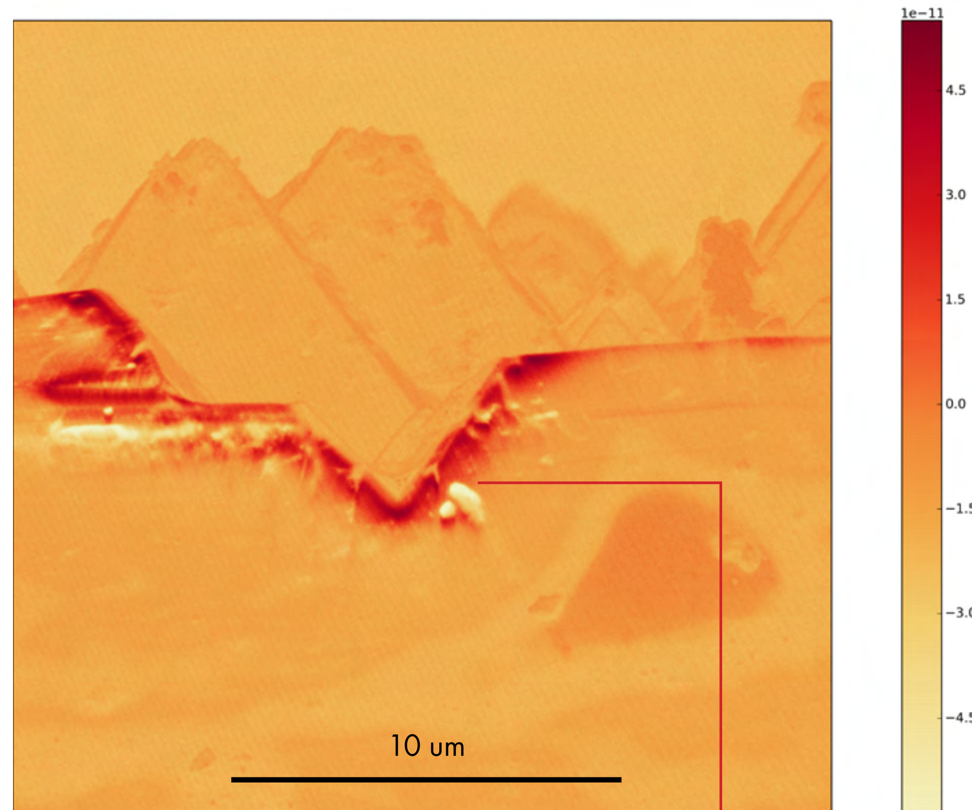
Exposed junction

At 2kv, the beam is interacting exclusively with the surface this is evident in both the secondary electron and EBIC images. The smaller interaction volume means that surface recombination shortens the diffusion length.





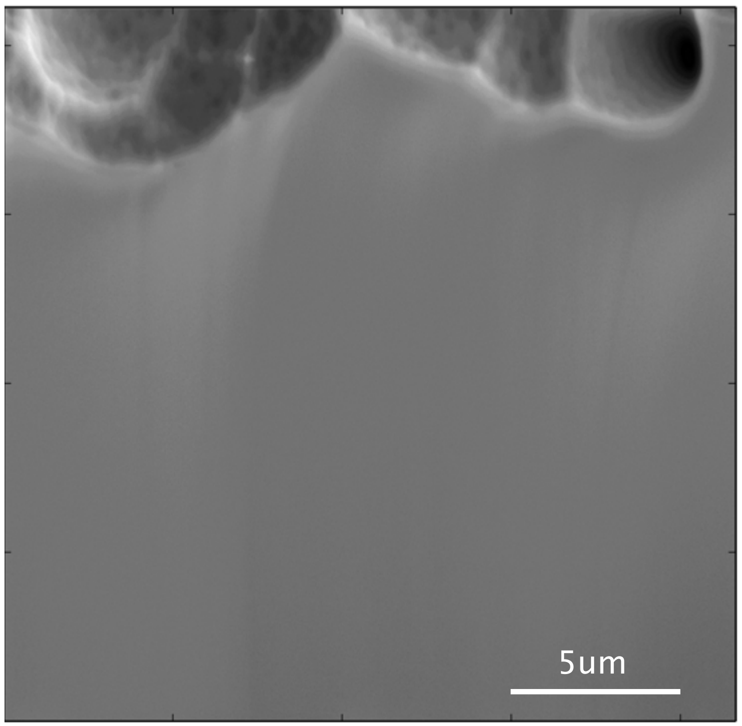


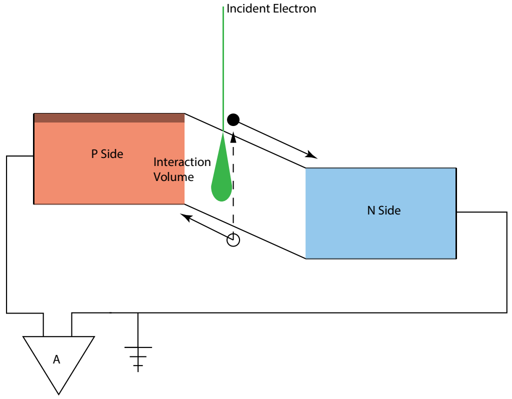


Depletion region

Secondary electron and EBIC images of commercial silicon solar cell cross-section taken simultaneously.

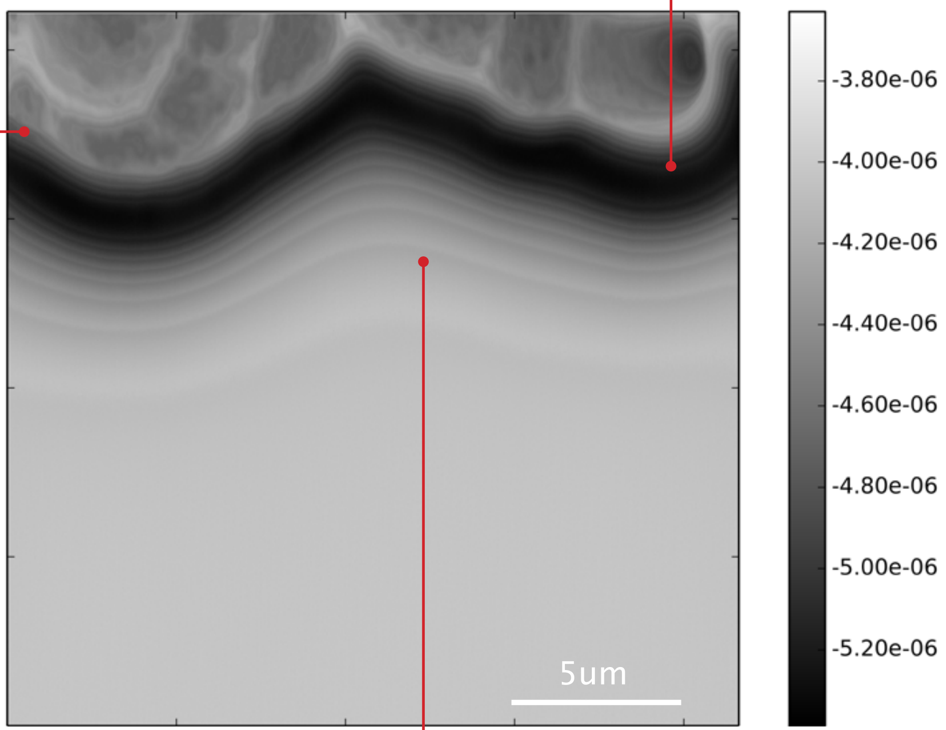
Secondary electron





EBIC

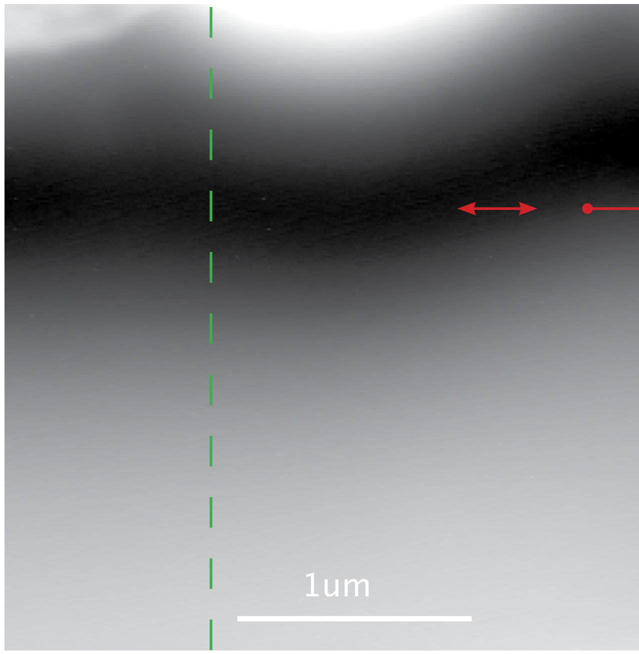
Depletion Region



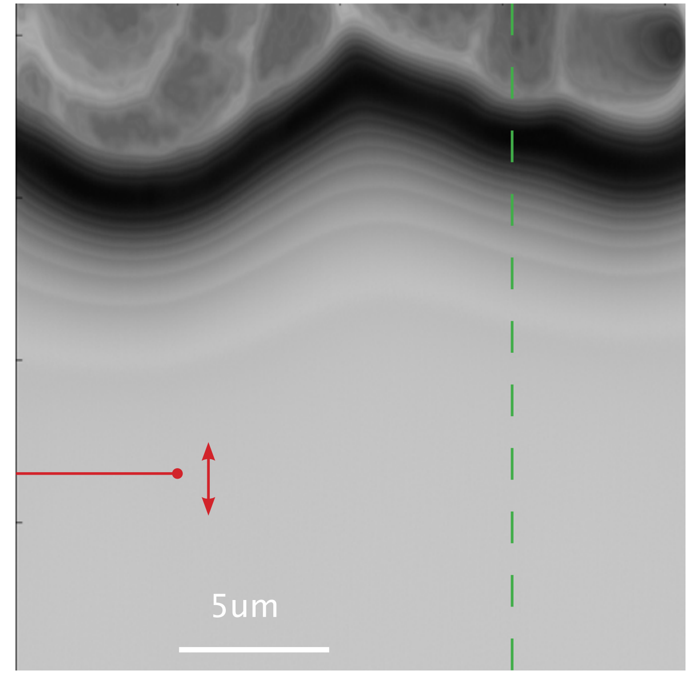
Bands below and above depletion region appear to be from doping profile gradient.

Comparison of Home built EBIC at Brookhaven CFN to Mighty EBIC.

Home Built using a pre-amp and NPGS 14 bit ADCs, 300 x 300 pixels



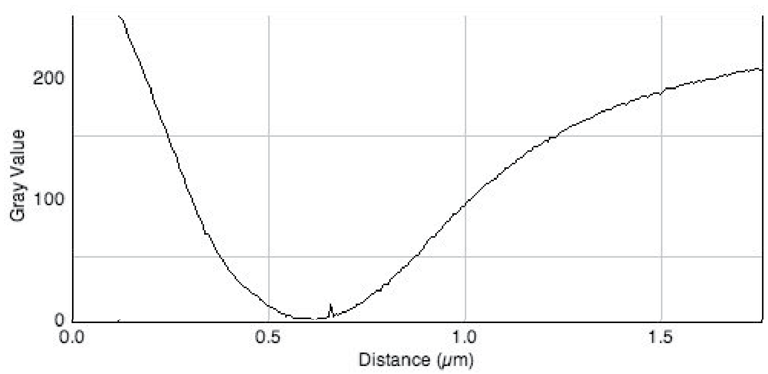
Mighty EBIC 18 bit ADCs, 2000 x 2000 pixels



Scan parallel to junction

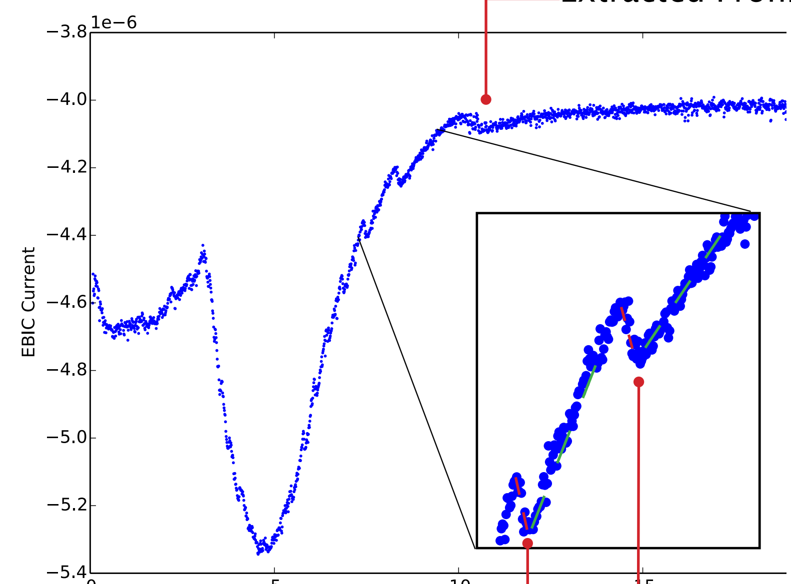
Scan perpendicular to junction

Extracted Profile



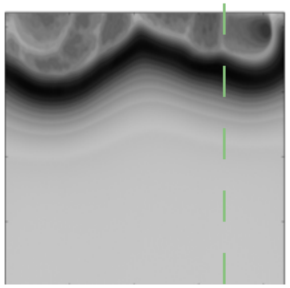
Diffusion lengths, but no bands observed of doping gradient

Extracted Profile

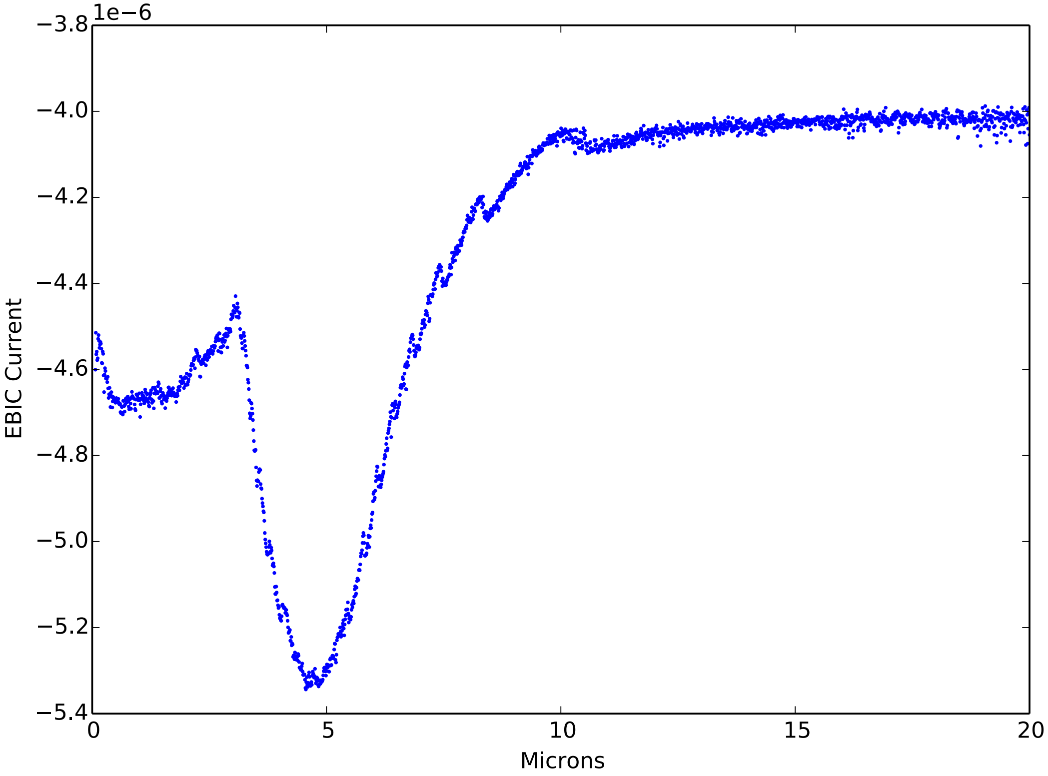


Doping gradient and compensation between dopants observed

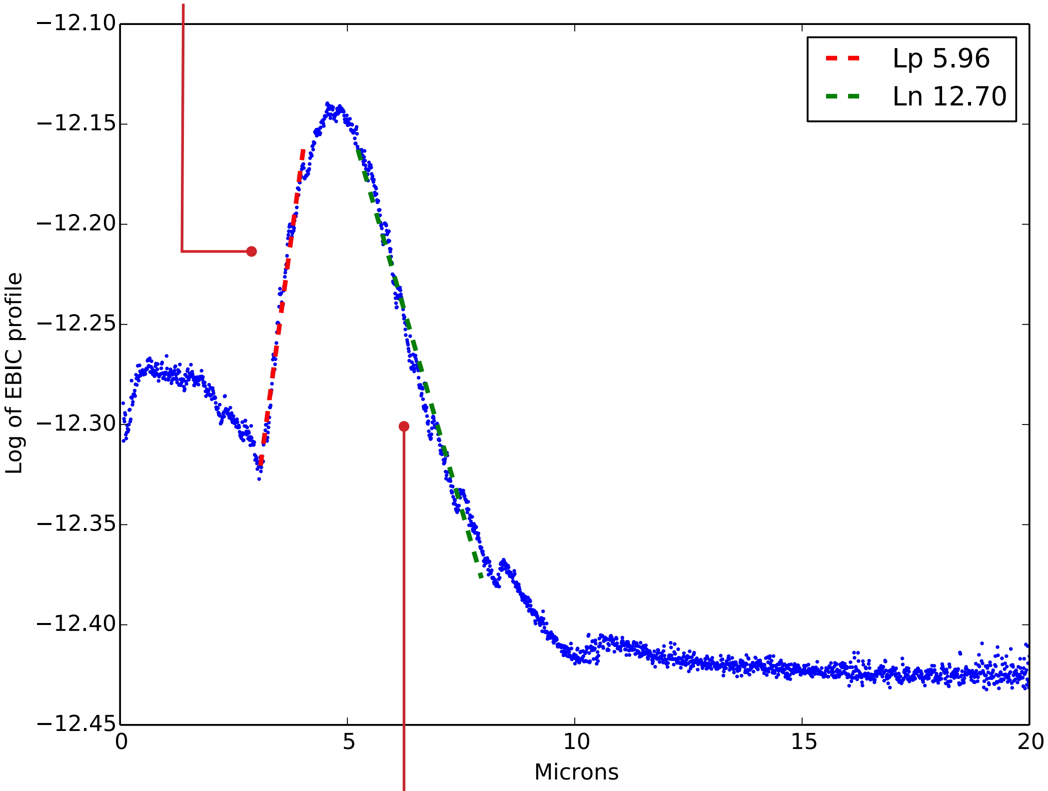
On either side of the junction we can extract the diffusion length.



Green line denotes extracted profile location.



Diffusion Length of holes



Diffusion Length of electrons

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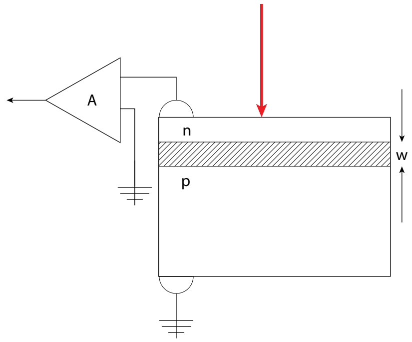
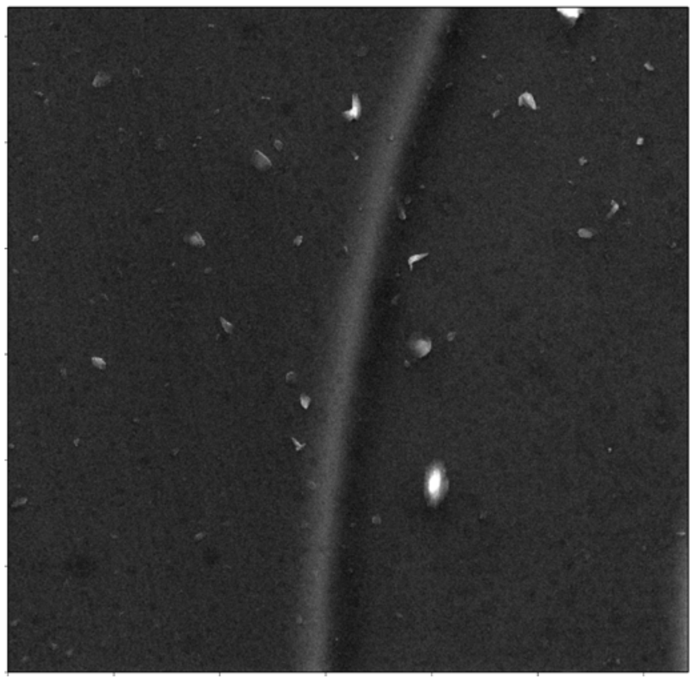
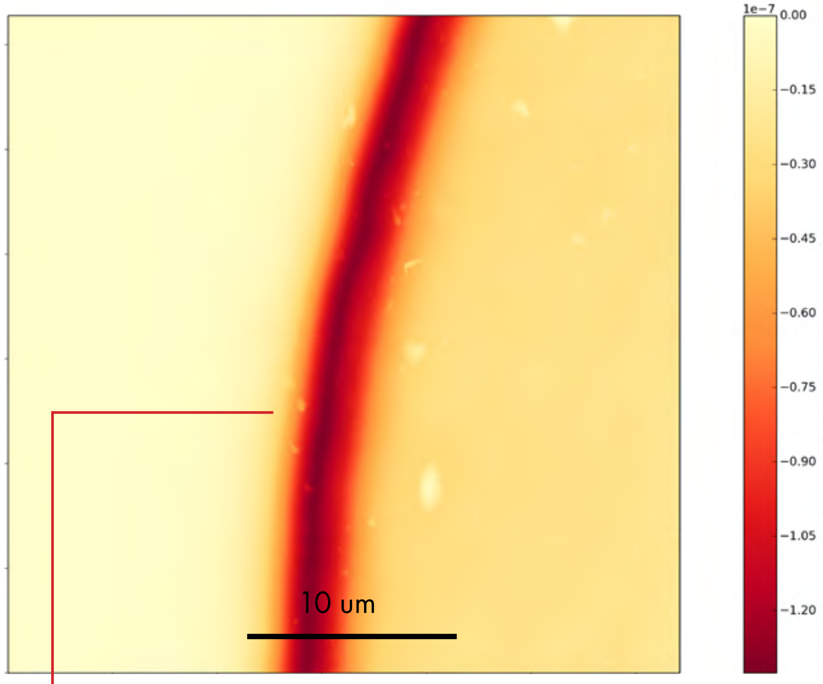
To image buried junctions, the incident energy needs to be great enough to penetrate to the layers of interest. These images of a Zener diode are taken at 20 kV.

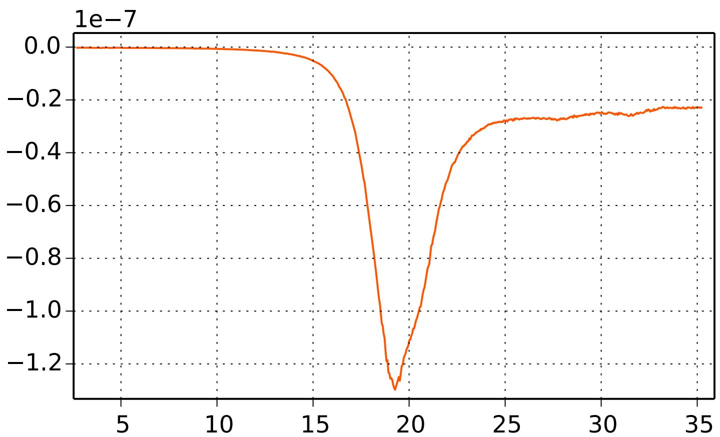


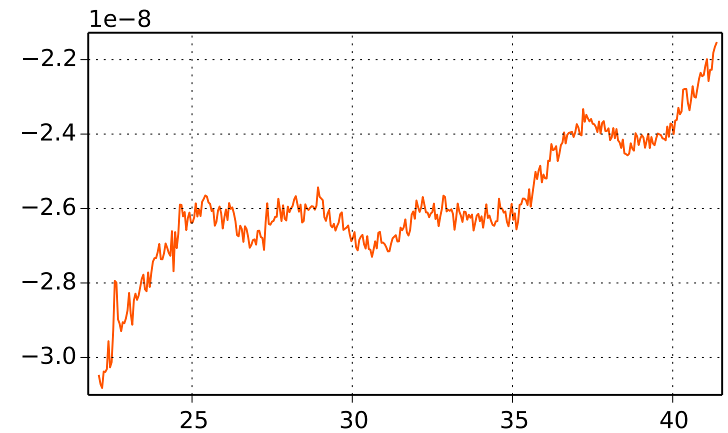


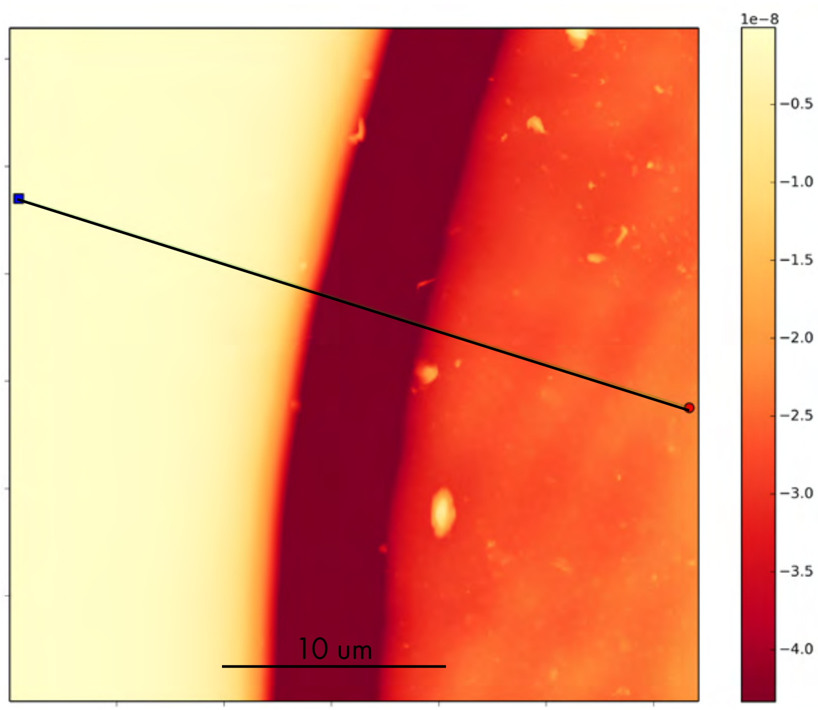


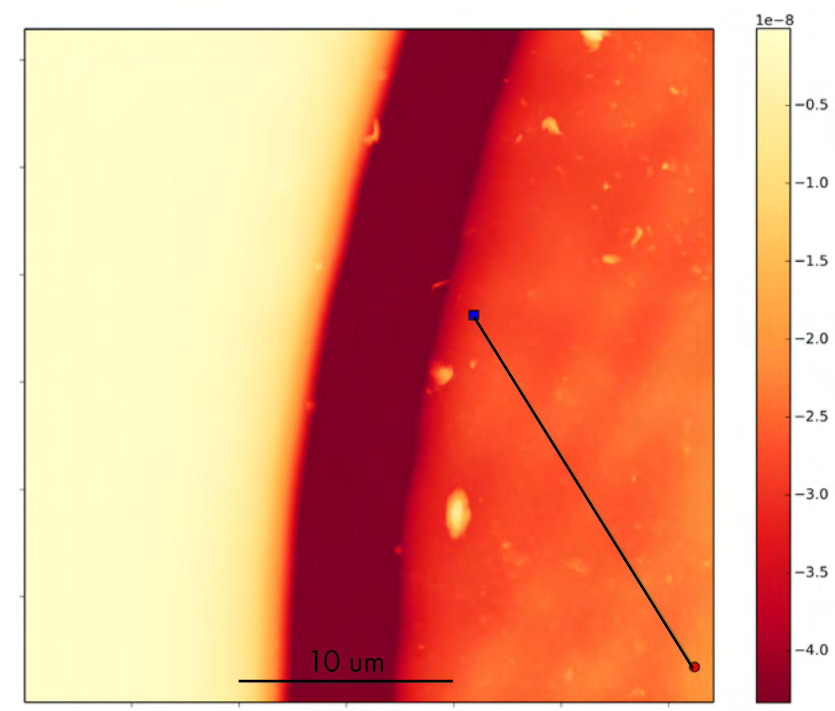
PN Junction.

The line profile across the junction reveal the diffusion lengths of carriers. Outside of the depletion region variations in EBIC signal indicate differences of doping concentrations, an artifact of the fabrication process.

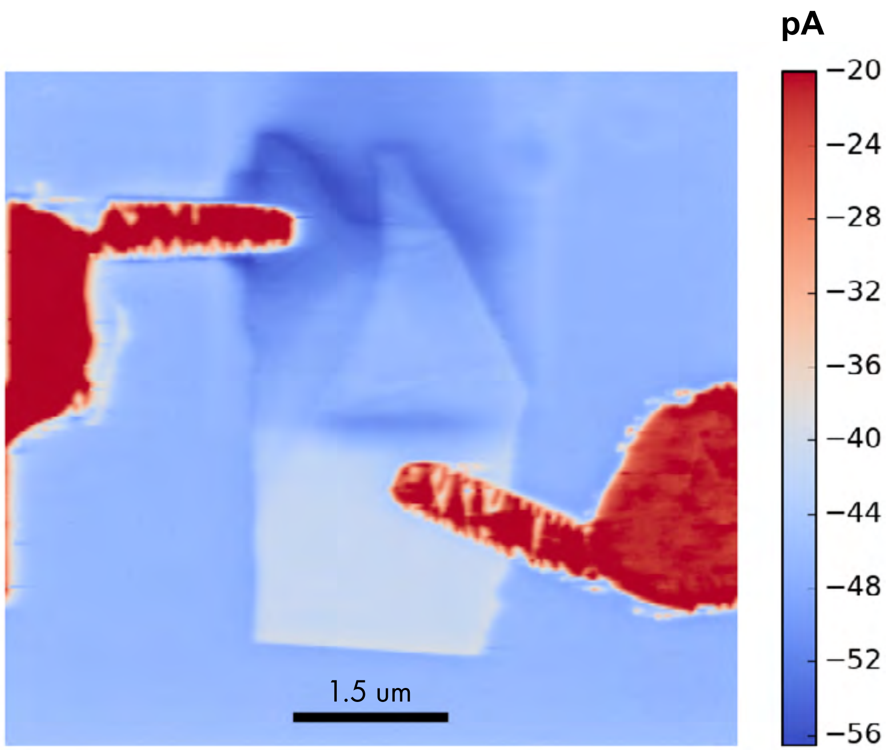




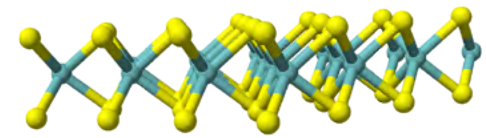


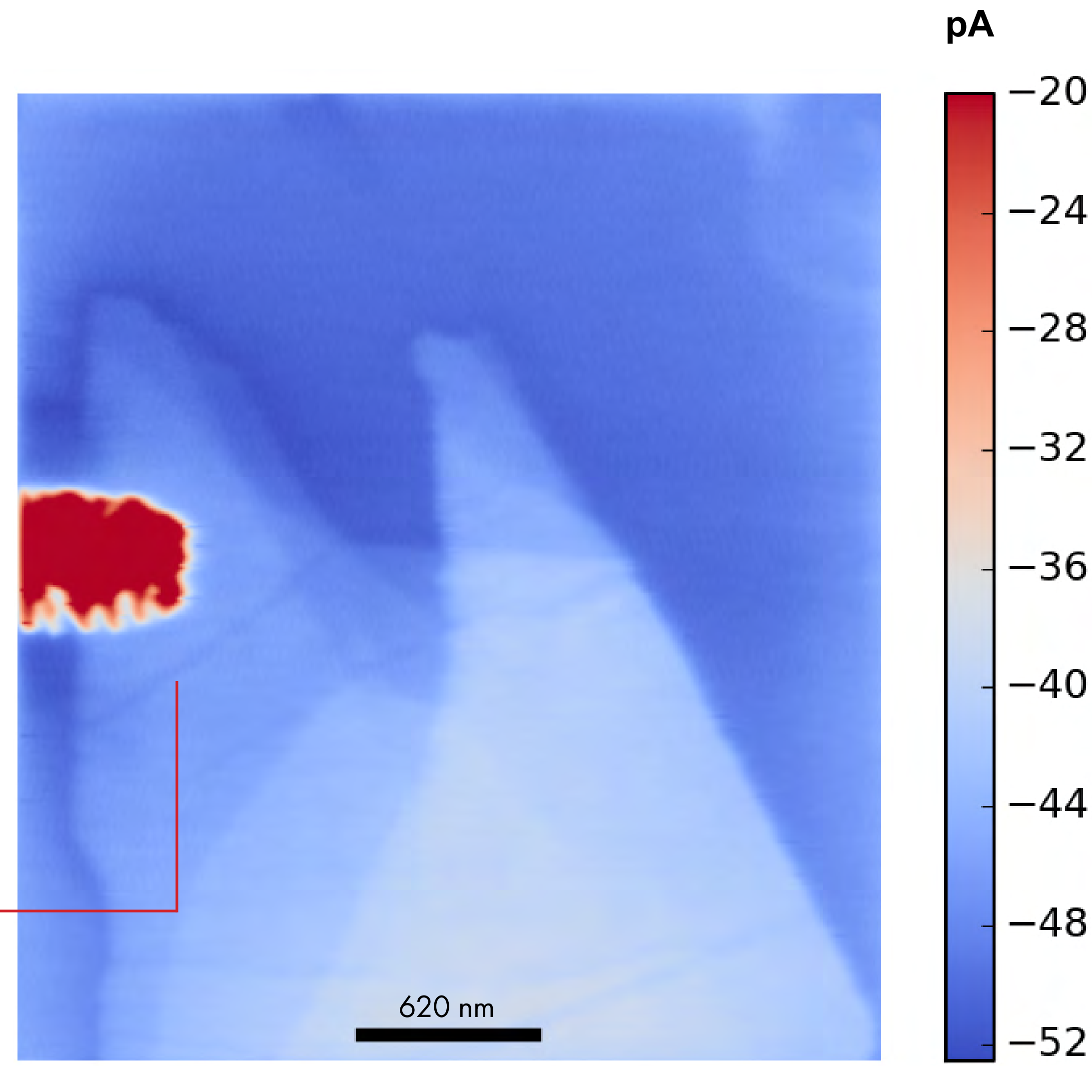


Transport properties in 2D semiconductor devices imaged with EBIC



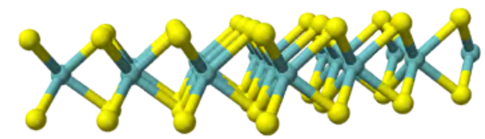
MoS2 device with contacts

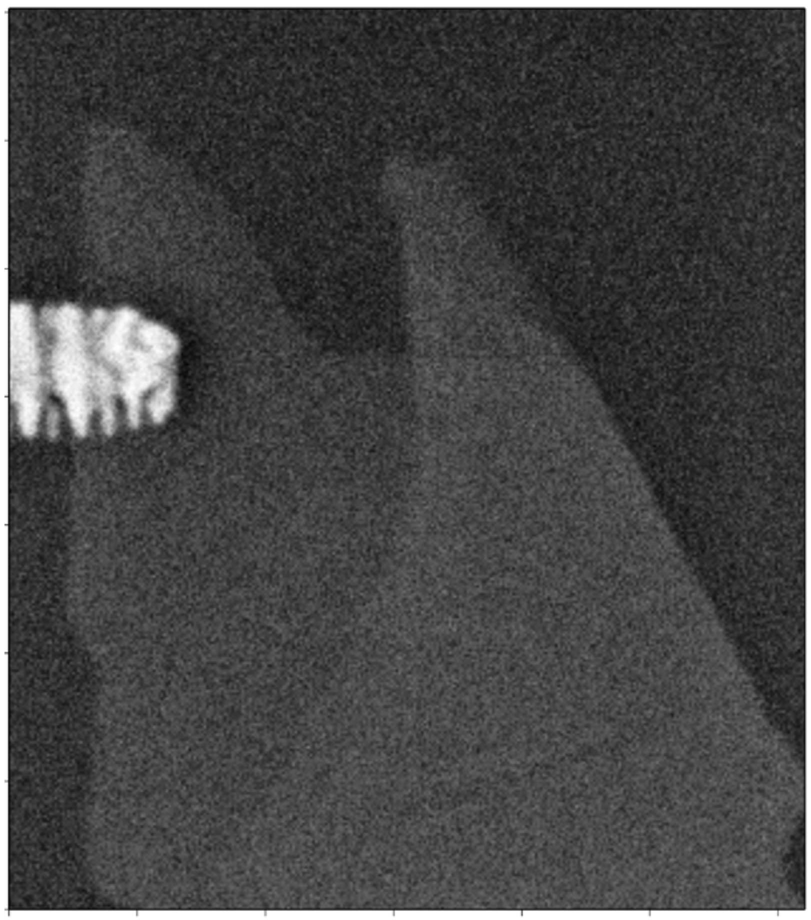




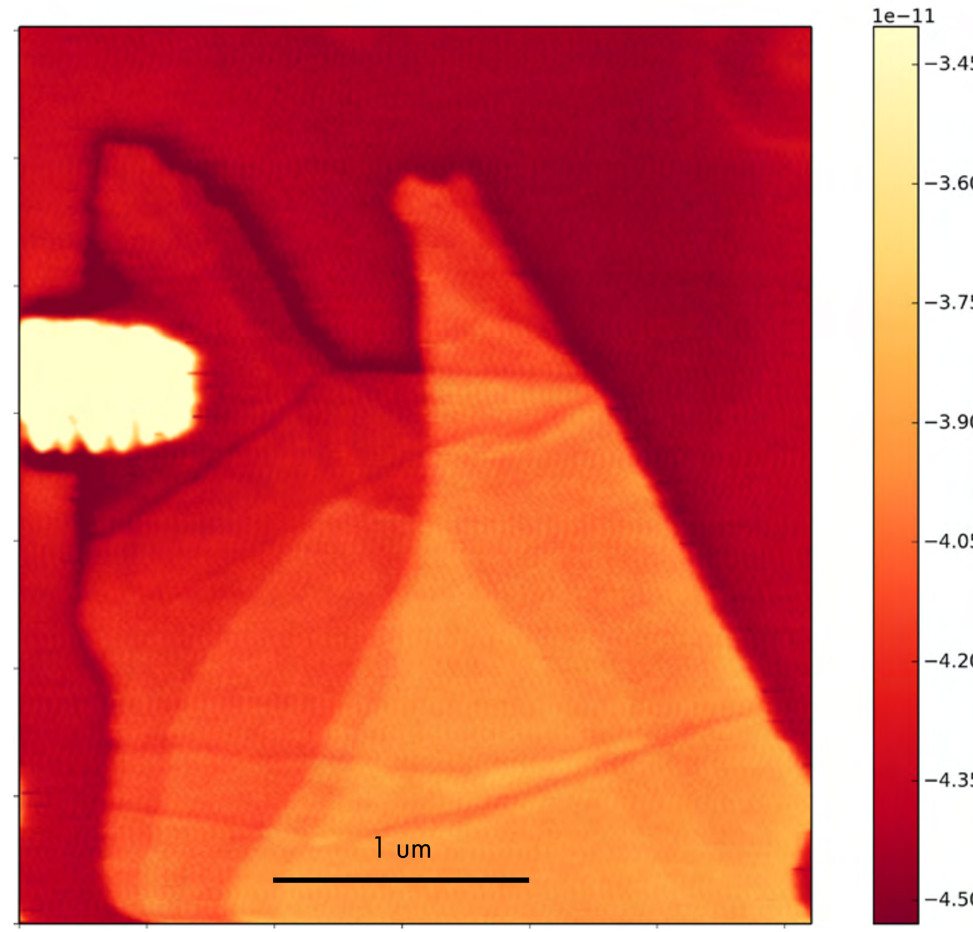
Separate layers and folding of the material is visible

MoS_2 secondary electron and EBIC image at 0 V bias.



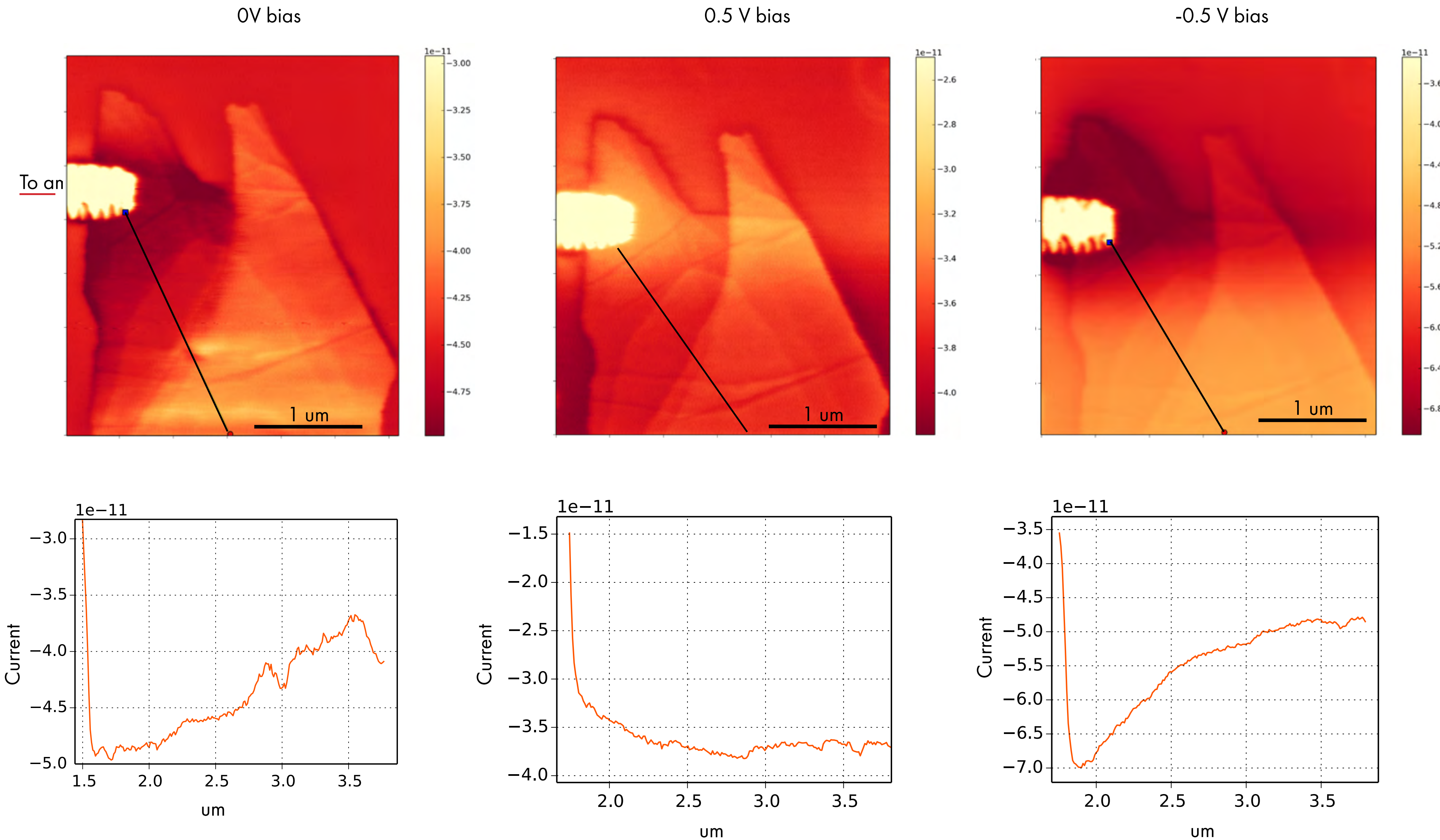


Secondary electron image

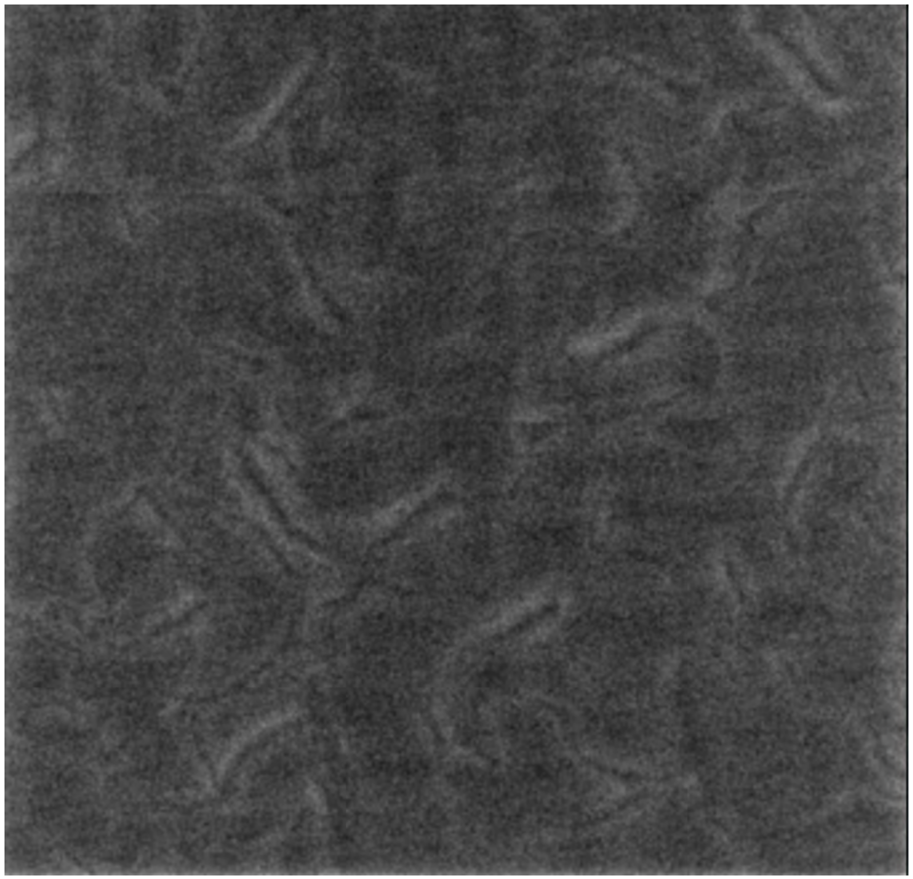


EBIC signal 0 V bias

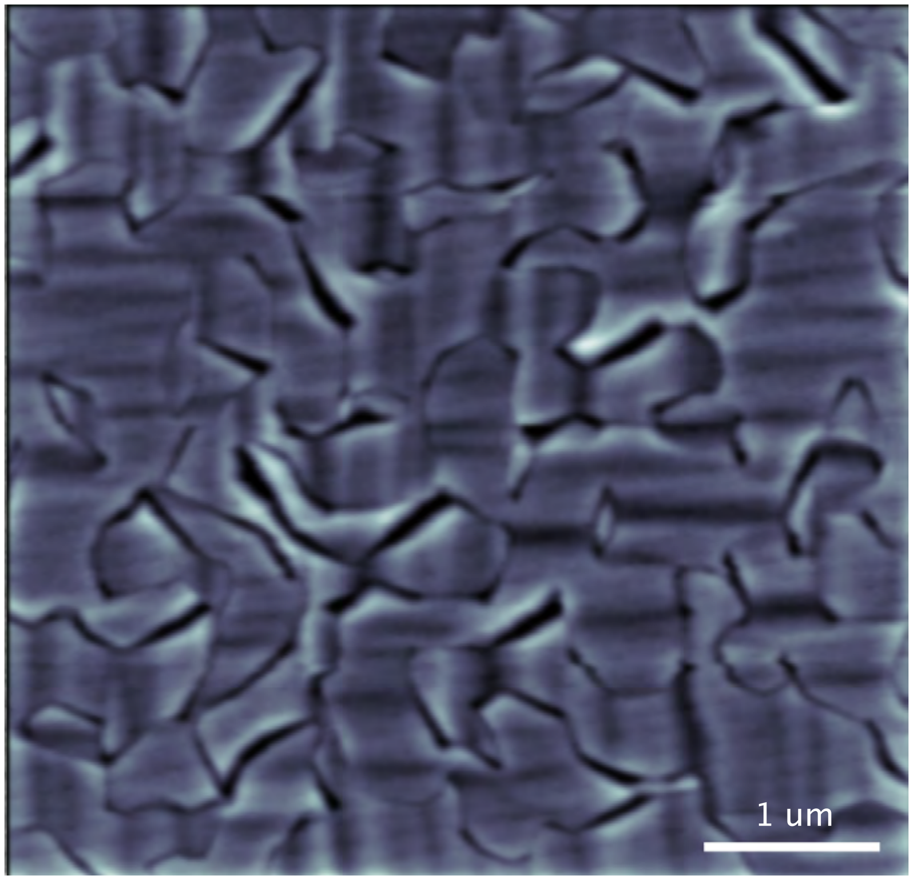
In a MSM device, applying a slight voltage bias changes the carrier type(electron and holes) collected at each contact.



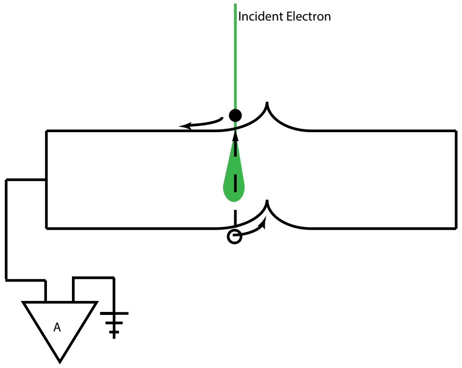
Electron beam absorbed current in a semiconductor show the effects of local fields due to defects.



Secondary Electron image of Antiphase domains of GaAs on Ge

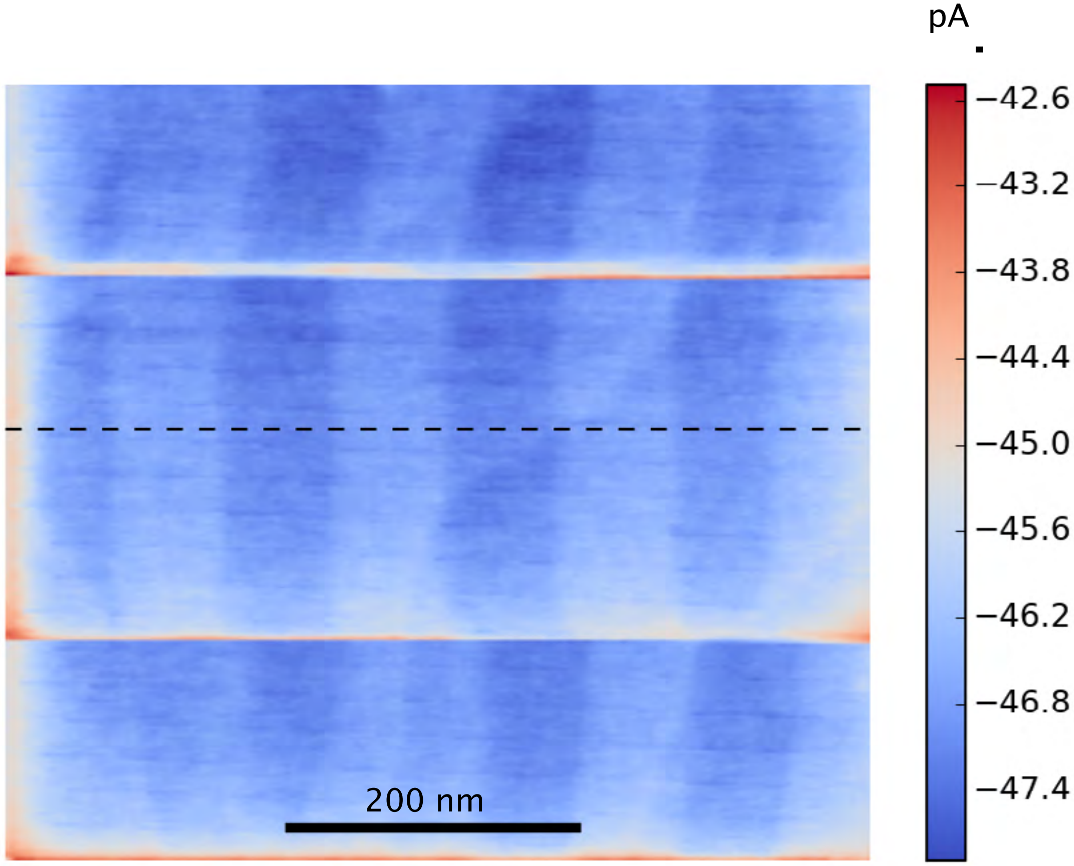


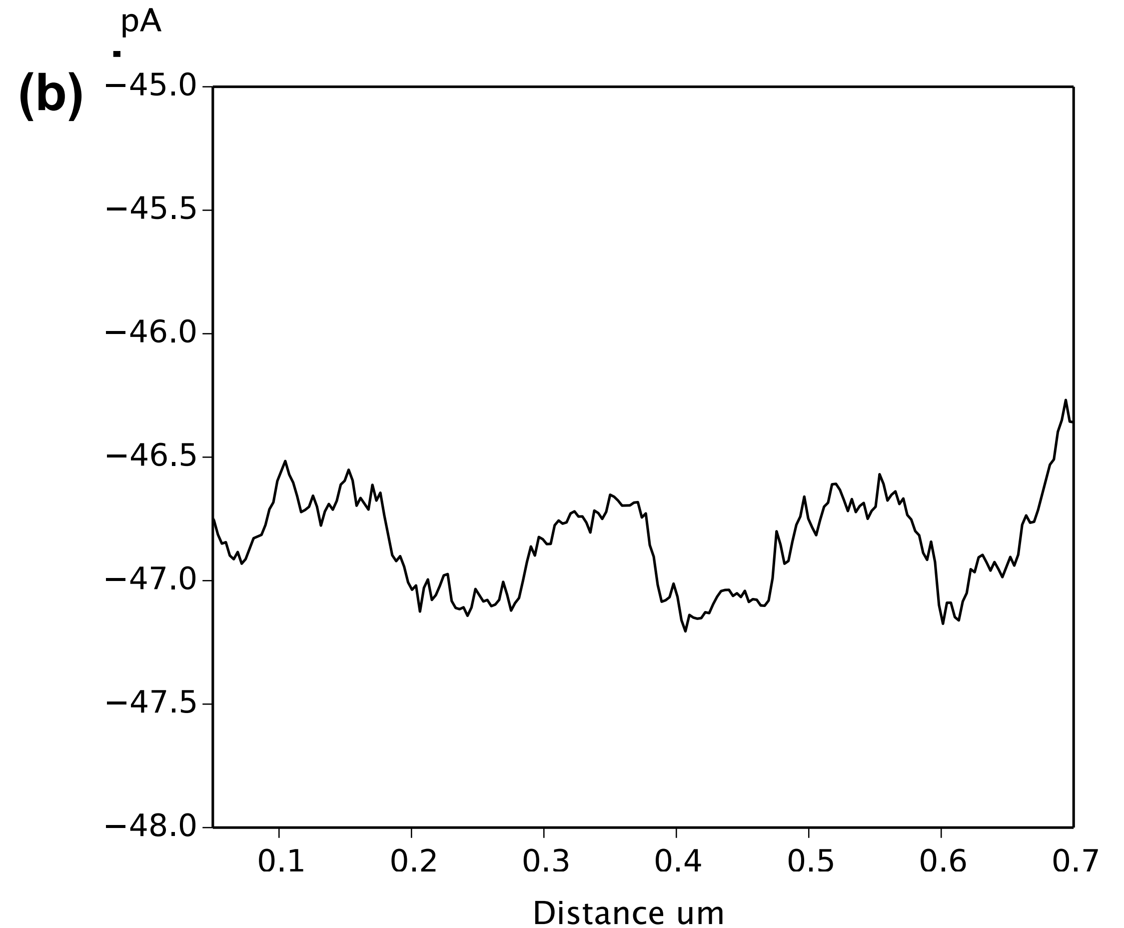
EBAC Antiphase domains of GaAs on Ge



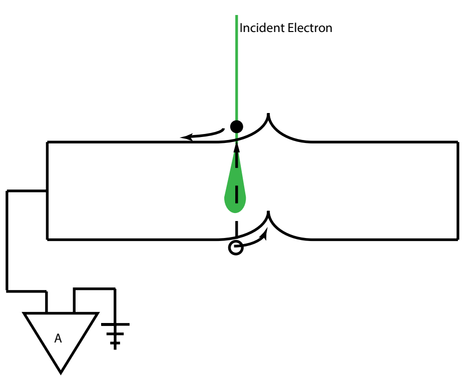
Remote EBIC or electron beam absorbed current an single contact is used and it is sensitive to local differences in E-field due to defects.

With electron beam absorbed current we imaged domains in bismuth ferrite, due to anisotropy of the crystal, with similar results to PFM and BF TEM.



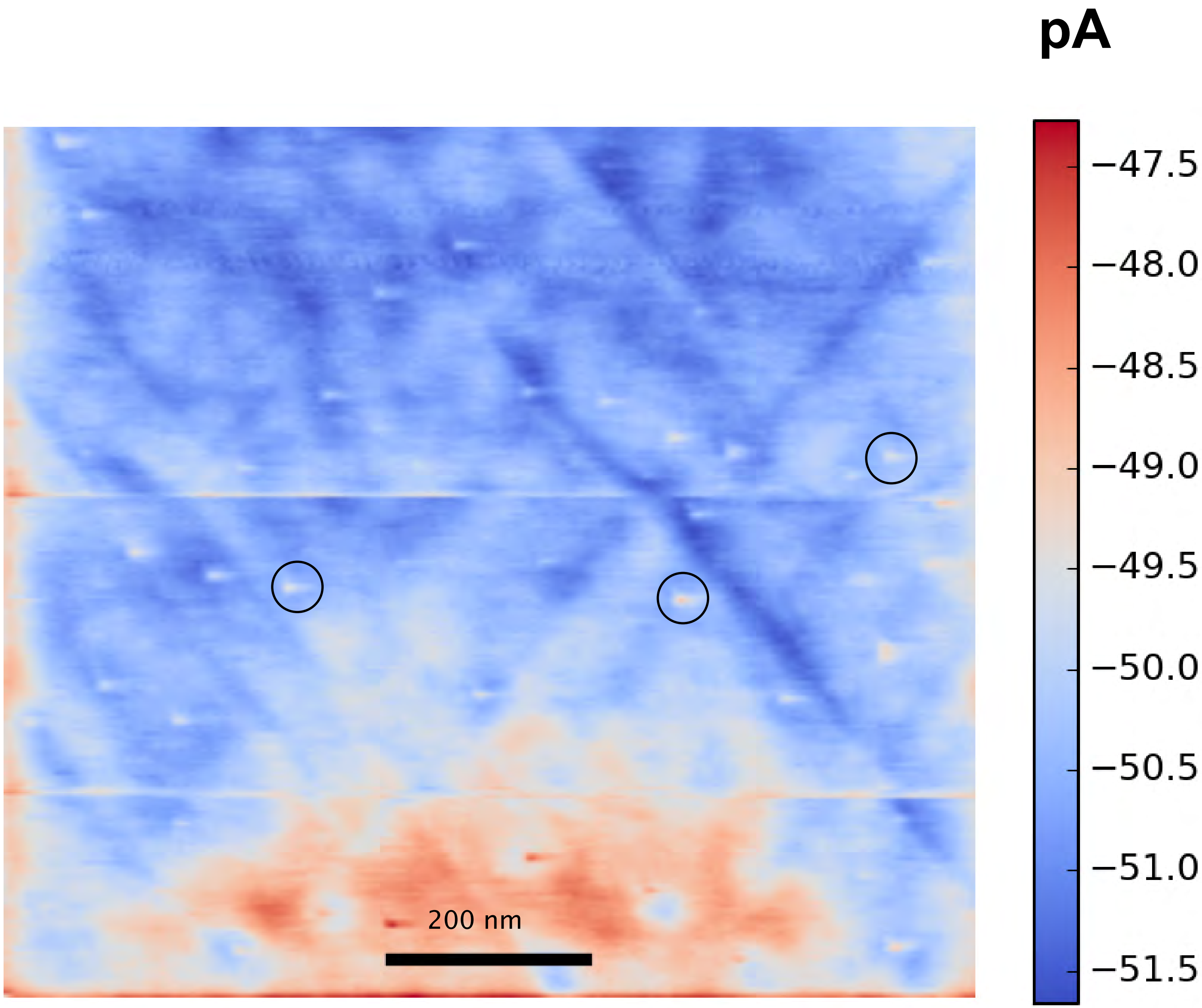


Step heights of STO substrate are visible

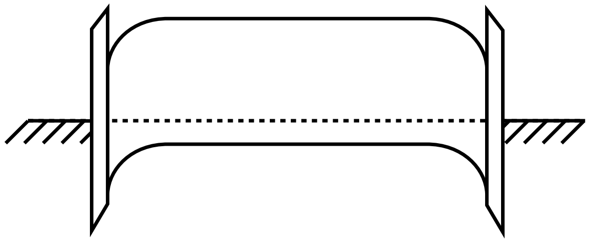


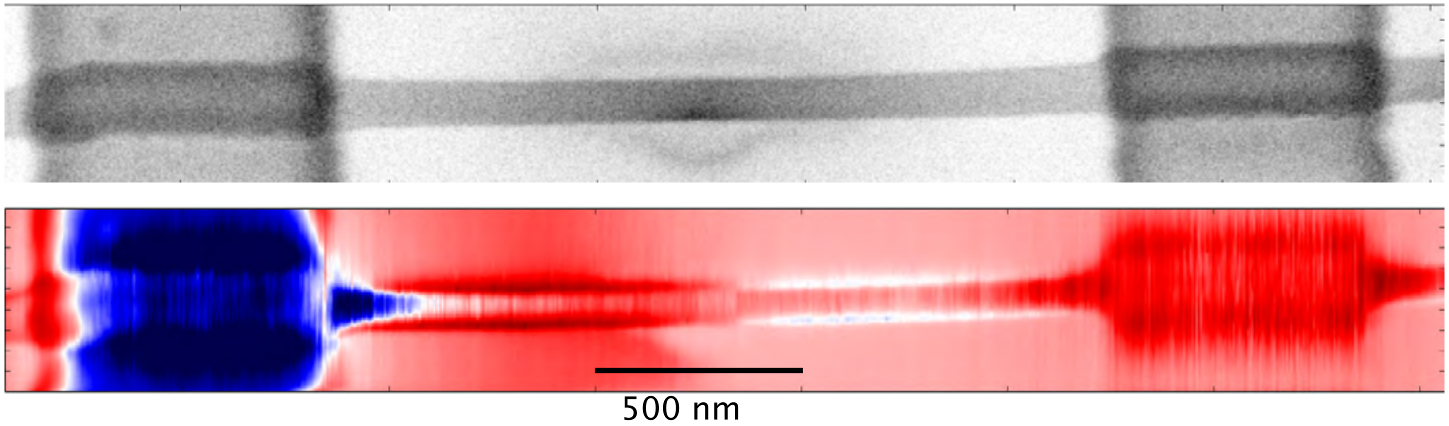
Remote EBIC or electron beam absorbed current an single contact is used and it is sensitive to local differences in E-field due to defects.

EBAC can image domain structures in PZT as well.



Bandbending in Ge nanowires with MSM contacts



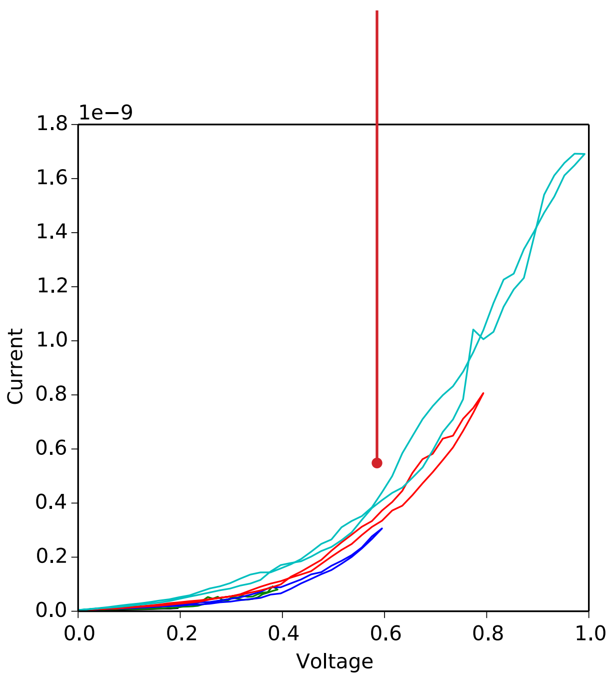


To separate the effects of high fields and local injected current we devised experiments where the EBIC scan would only be conducted at 0 V bias.

Voltage sweeps of increasing magnitude are conducted after EBIC scan.

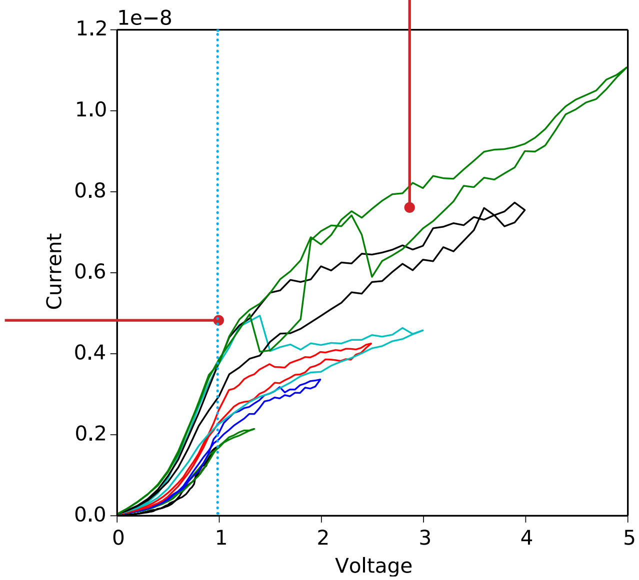
Transport data of Ge nanowire reveals two distinct modes of operation, one characteristic of a diode below 1 V and then ohmic above 1 V.

Sequential transport measurements are taken between EBIC scans. Below 1 volt these are all the response of a diode. These all have a exponential increase in current.

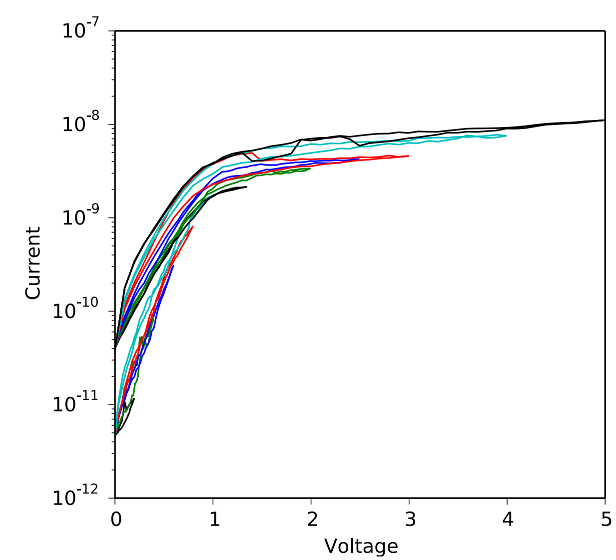


Hysteresis becomes more pronounced at higher voltages.

Above 1 volt the current response appears ohmic and increases with each scan.



Both sets of measurements plotted on a logarithmic scale.



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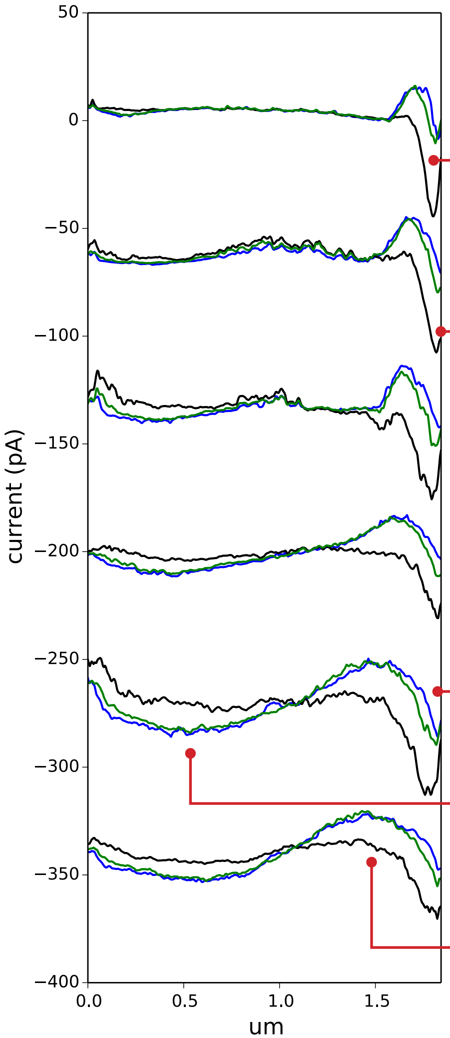
Looking at the EBIC images we can see the origins two different modes of operation evolve.

Extracted profiles from each scan at the center (black) and sides (blue and green).



Scan after voltage sweep:

0.0 V

0.2 V

0.4 V

0.6 V

0.8 V

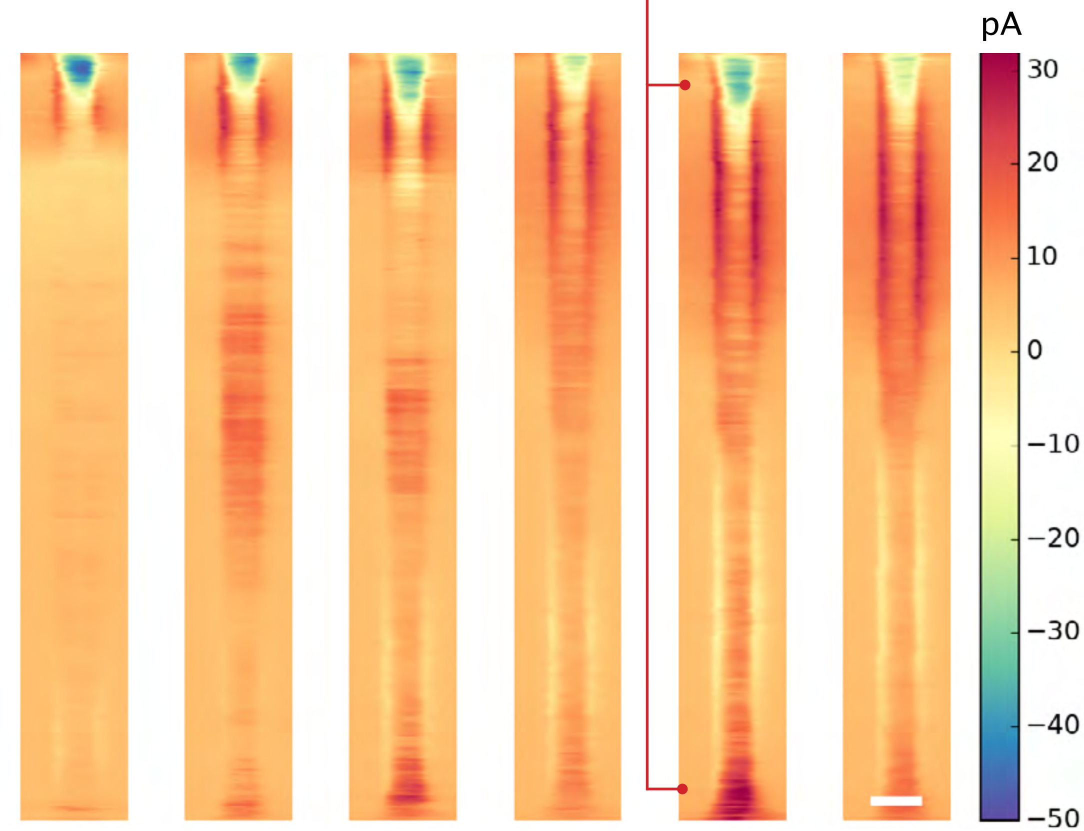
1.0 V

Center profile of Schottky MSM device with barriers present at the interface.

Ohmic behavior at the sides of the nanowire begin to emerge

Center of profile extends the diffusion length of Schottky contact.

The center of the wire had the response we expect of a Schottky contacted device with a sharp drop off at the junction interface.

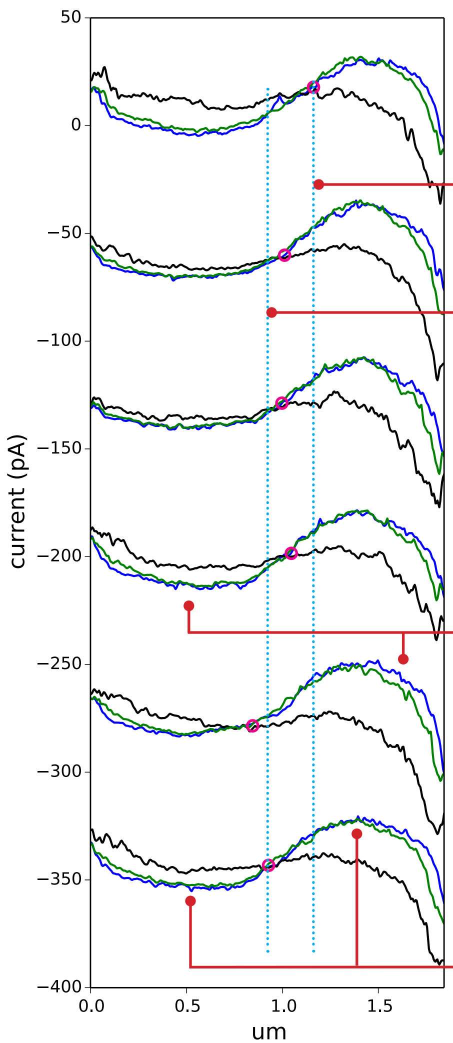


Imaged at 0V after bias applied

0.0 V 0.2 V 0.4 V 0.6 V 0.8 V 1.0 V

On the sides of the wire we see a current response that is the opposite sign that extends farther to the center of the wire with increase in voltage. Once it goes the entire length of the wire is when we start to see an ohmic response.

The two modes of response continue to evolve after voltage sweeps exceeding 1 V, as more charges follow through the nanowire and extend the regions where band bending is present.



Scan after voltage sweep:

1.4 V

The point where the signals cross and are equal shifts from the collection contact to the center of the device after higher voltage sweep

2.0 V

2.5 V

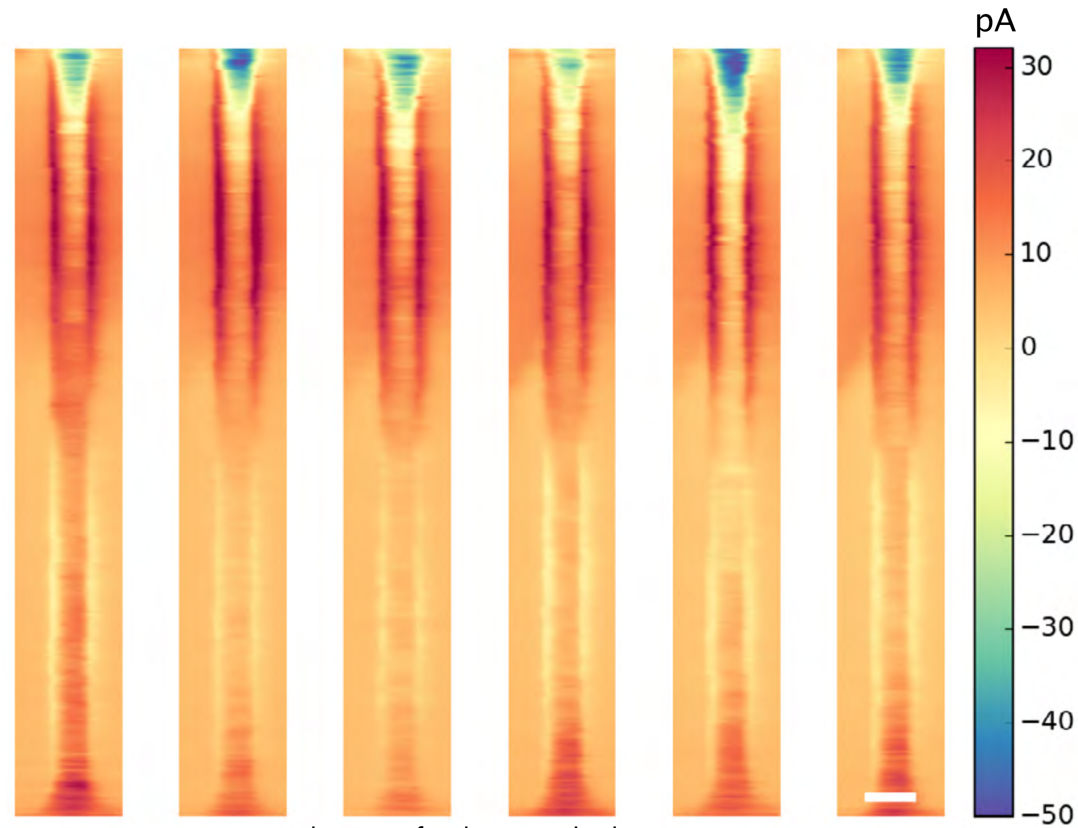
3.0 V

This cross over point shifts as the difference between signals broadens.

4.0 V

5.0 V

Eventually the difference on either side of the center evens out, and the cross over point settles at the center of the device.



Imaged at 0V after bias applied

1.4 V 2.0 V 2.5 V 3.0 V 4.0 V 5.0 V

All scans are done at 0V bias to see the effects of higher voltage sweeps on the properties on the nanowire.

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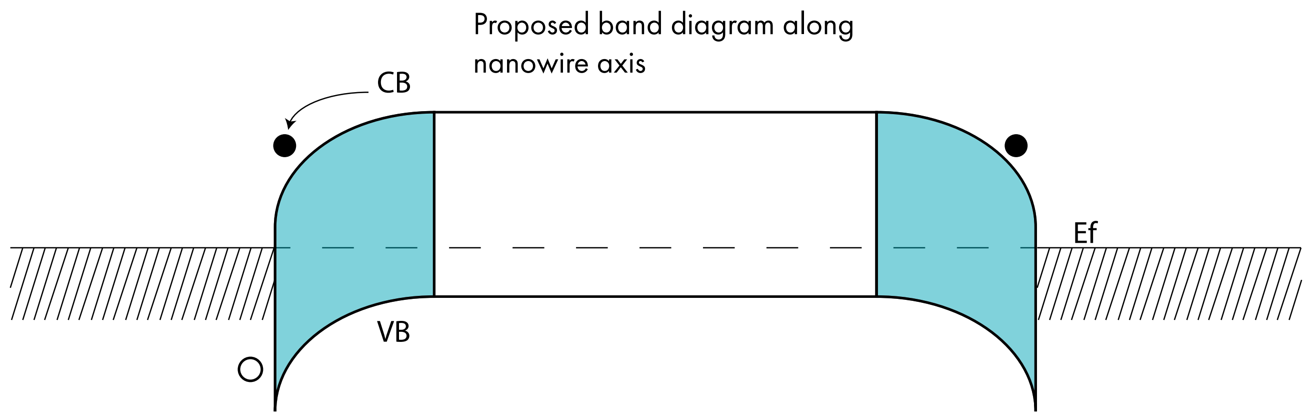
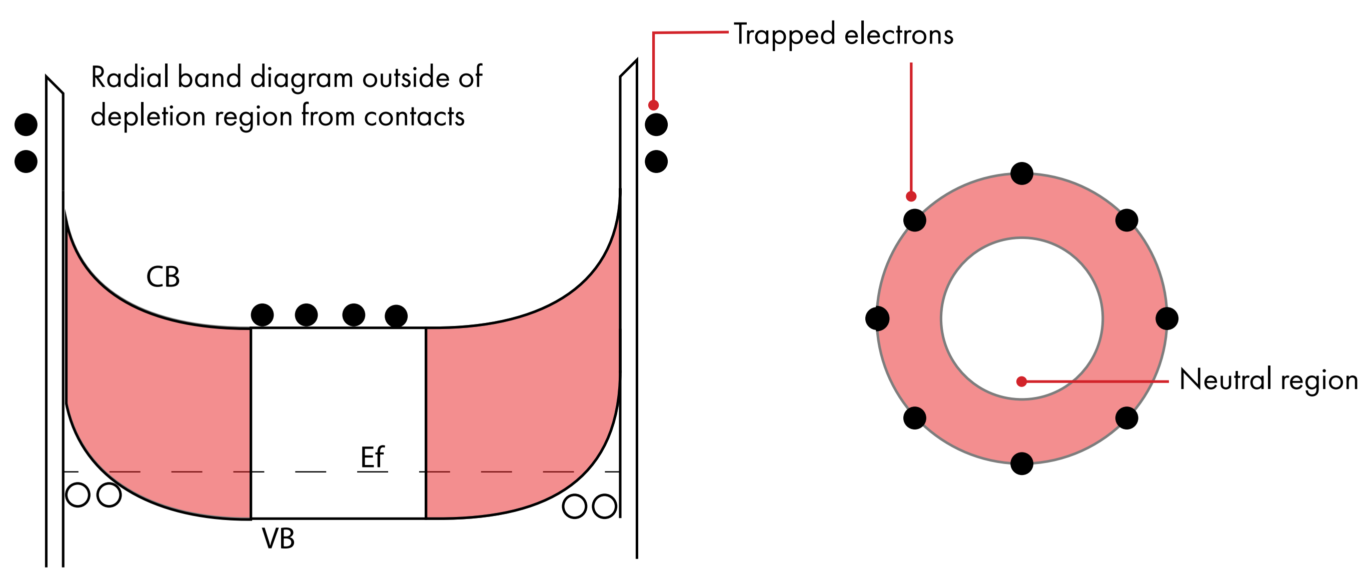
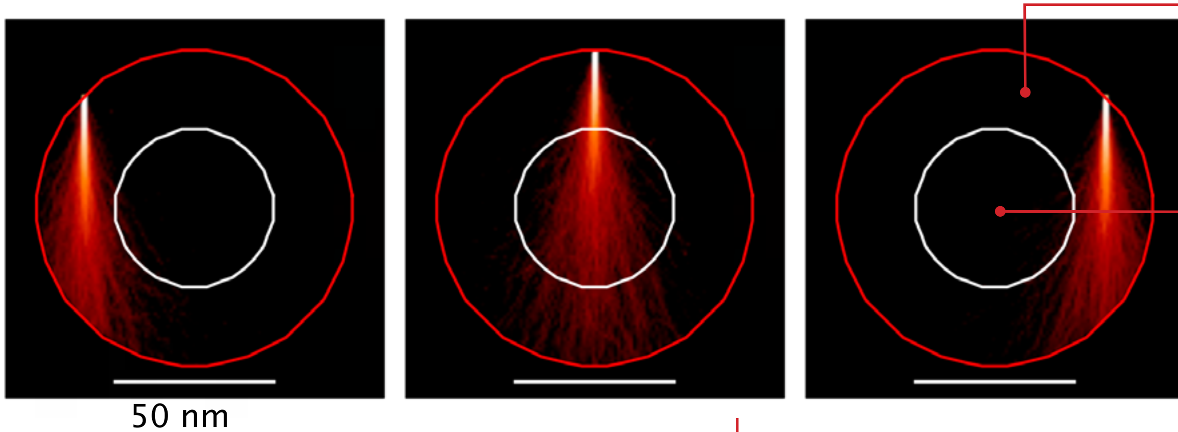
At either end of the nanowire there are depletion regions form the metal semiconductor region. Outside of the depletion region we have bandbending due to trapped electrons leading to an accumulation of holes.





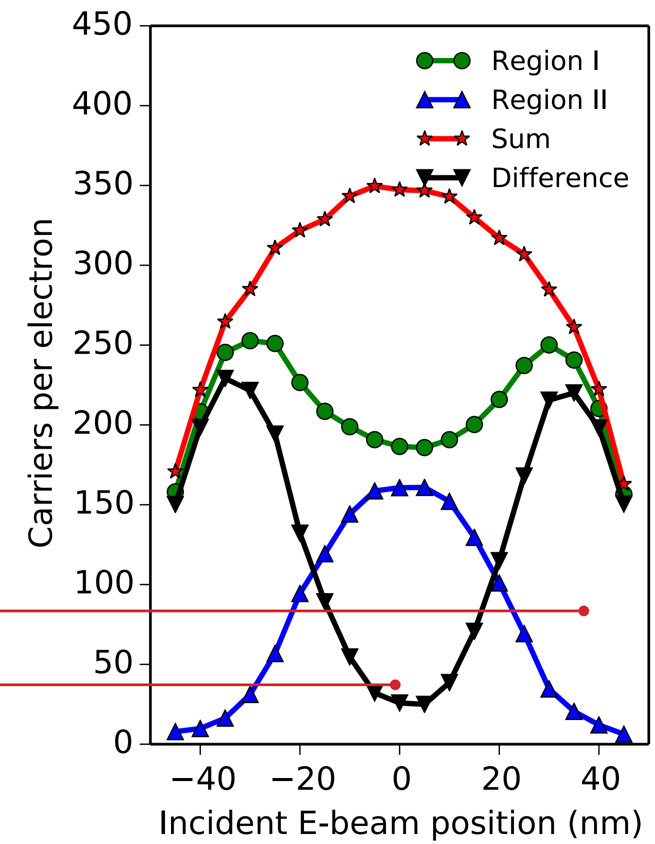
Due to bandbending at the surface and there are two distinct regions in the nanowire.

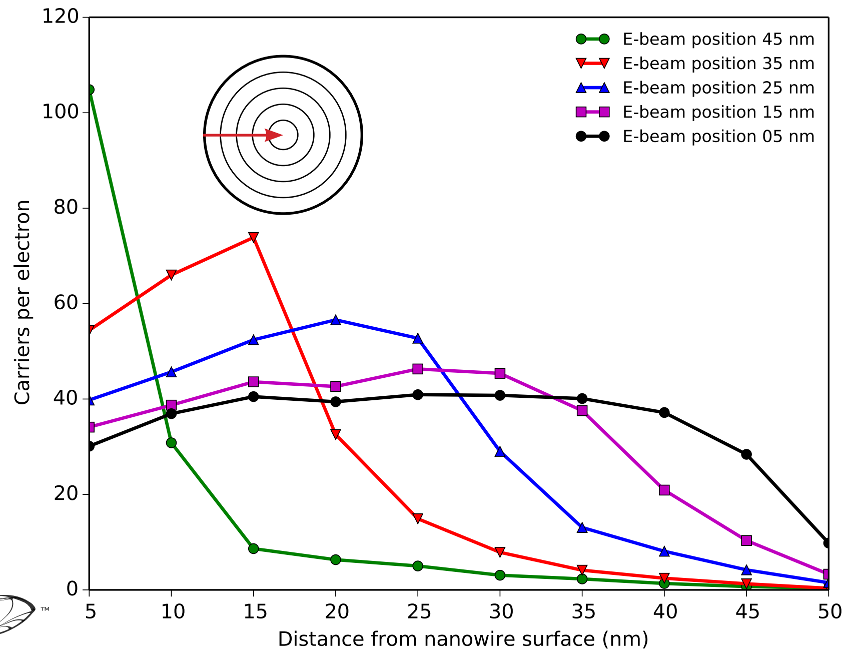
Interaction volume of electron beam with Ge nanowire cross-section.



Region I with bandbending at the surface

Region II





As the E-beam scans across the nanowire we calculate the total number of electron hole pairs generated at each position. The total signal can ether be a sum or difference.

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Extracting profiles across the nanowire we see a transition of the response from a sum of signals to a difference of signal.

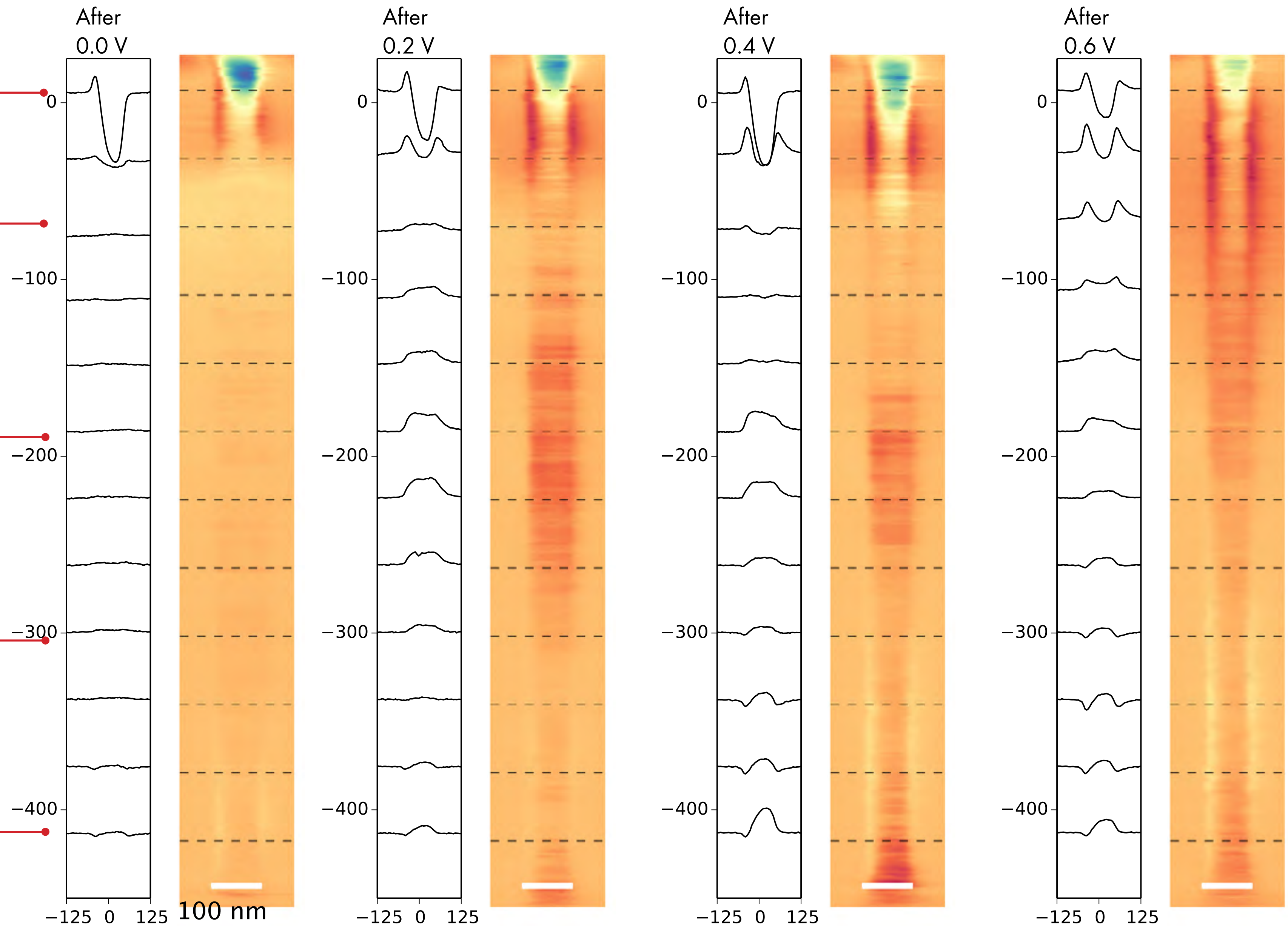
Depletion region, metal semiconductor junction.

Transition from sum to difference signal.

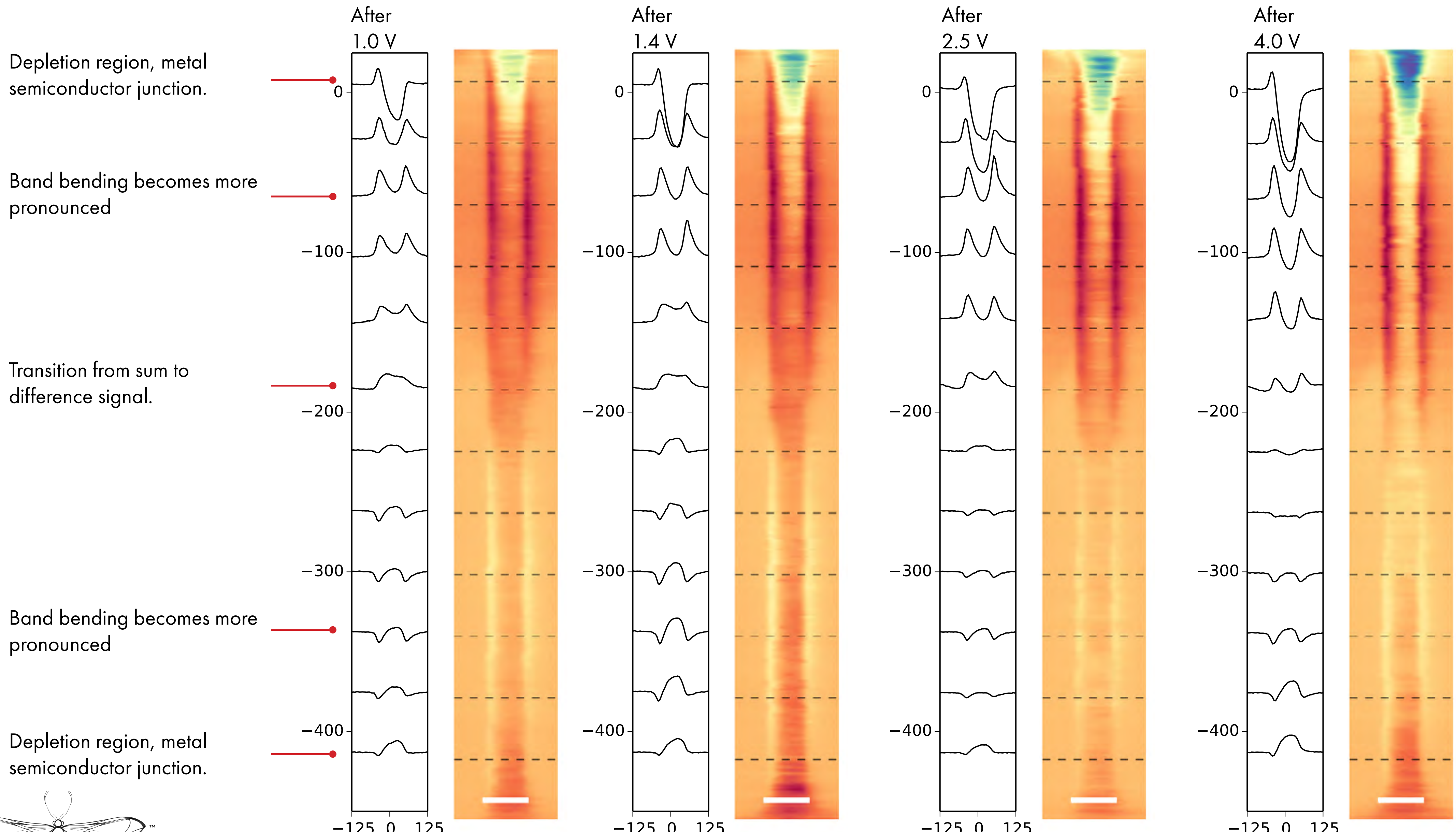
Transition from zero to sum signal.

Transition from sum to difference signal.

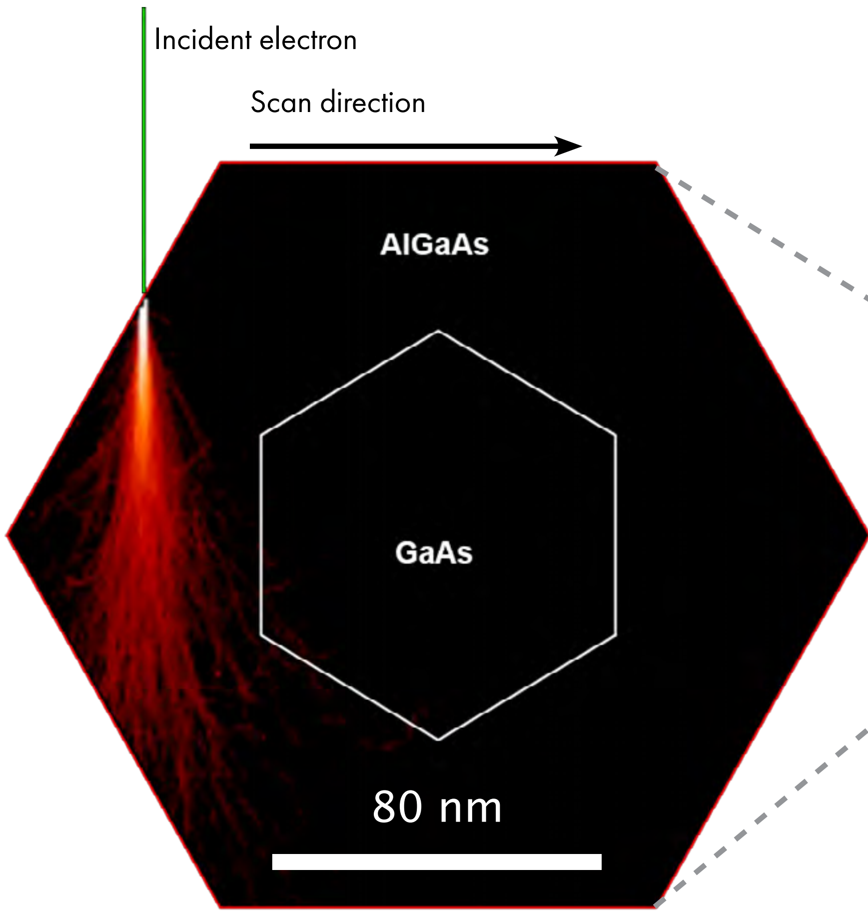
Depletion region, metal semiconductor junction.



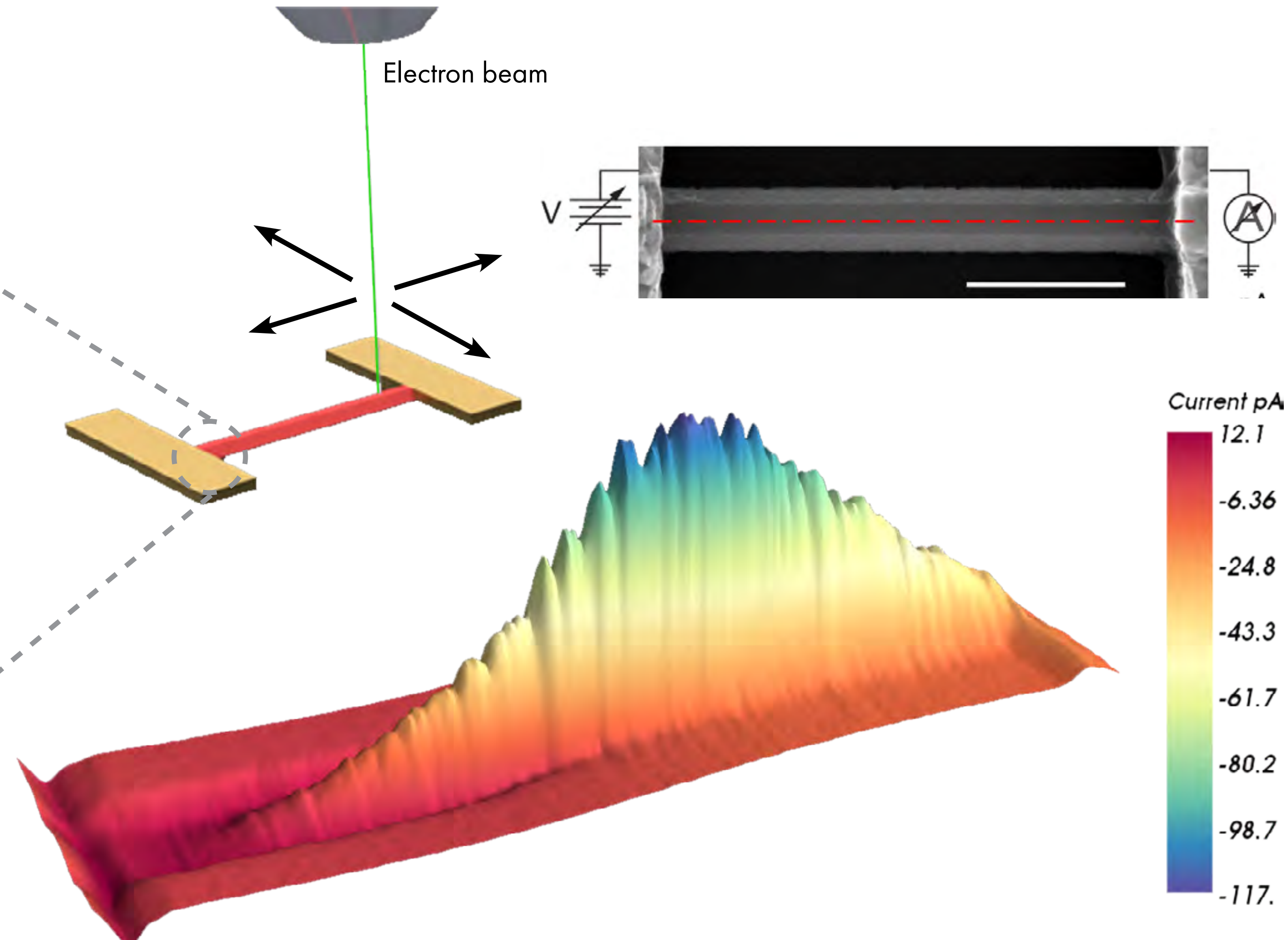
The signals from the regions with bandbending become more pronounced until they are present along the entire nanowire outside of the metal depletion region.



Probing carrier dynamics in GaAs/AlGaAs core/shell nanowires.



Energy Dissipated in Monte Carlo simulation of 500 electrons at 10kV

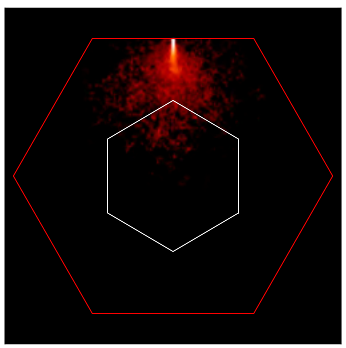


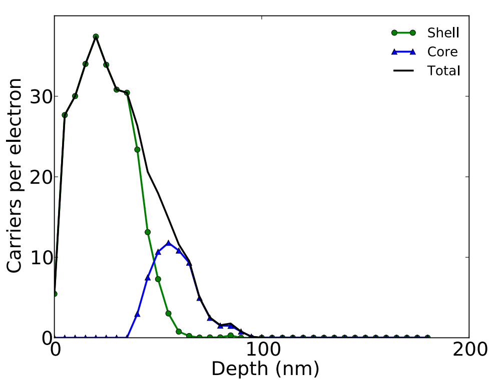
Response of core/shell nanowire at 0v bias shows different diffusion lengths for GaAs core and AlGaAs shell.

"Subsurface Imaging of Coupled Carrier Transport in GaAs/AlGaAs Core–Shell Nanowires" Nano Lett., 2015, 15 (1), pp 75–79 DOI: 10.1021/nl502995q

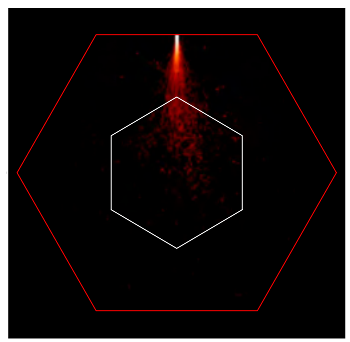
To characterize the GaAs and AlGaAs components we had to understand the interaction volume and the number of carriers generated in each.

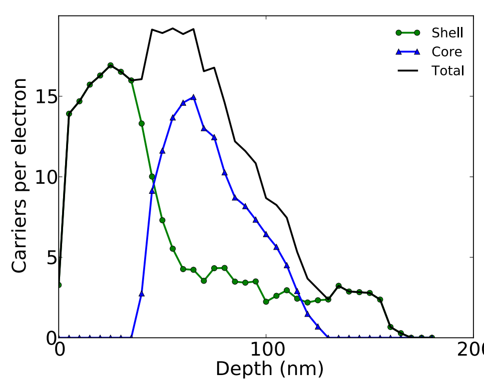
3 kV beam predominately interacts with shell



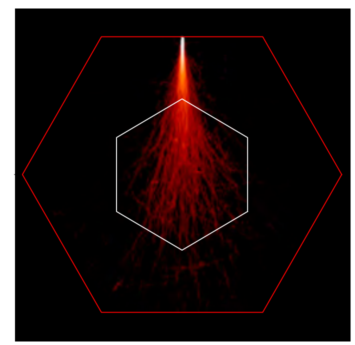


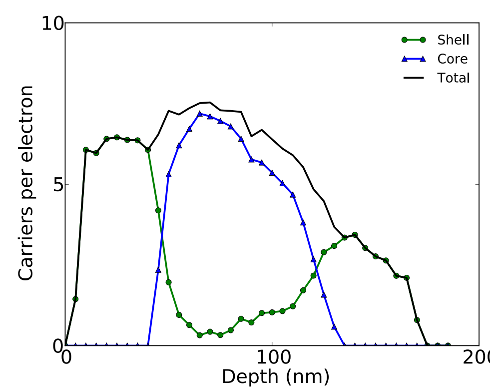
5 kV



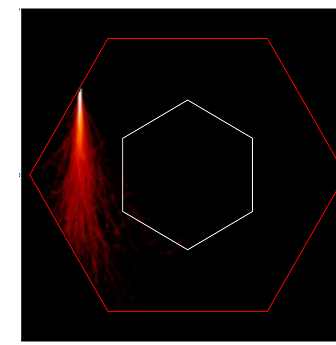


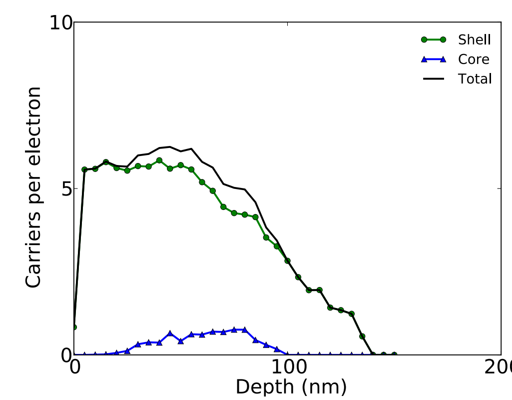
10 kv beam interacts with both core and shell in the center.



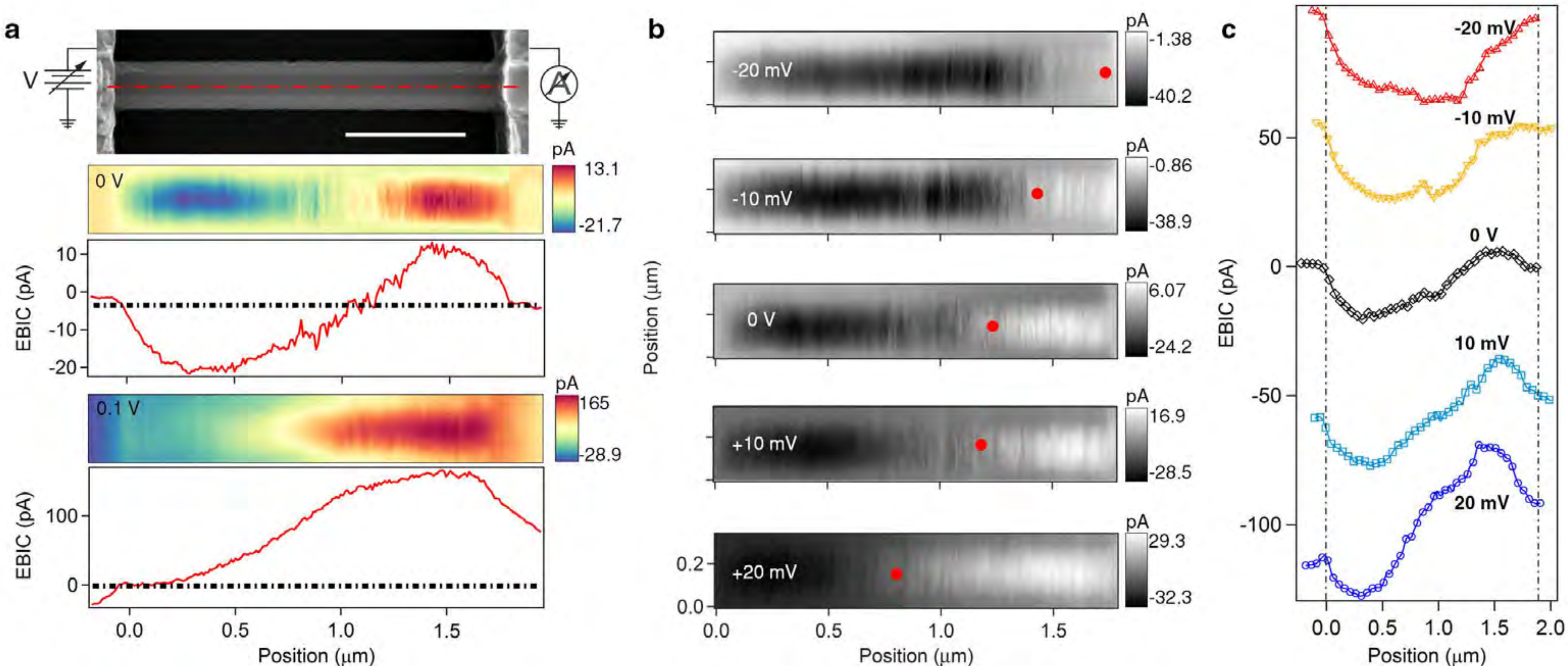


10 kv beam at the side only interacts with shell





At zero and +,-20mV bias low and beam energy we see an characteristic response of an ohmic nanowire.

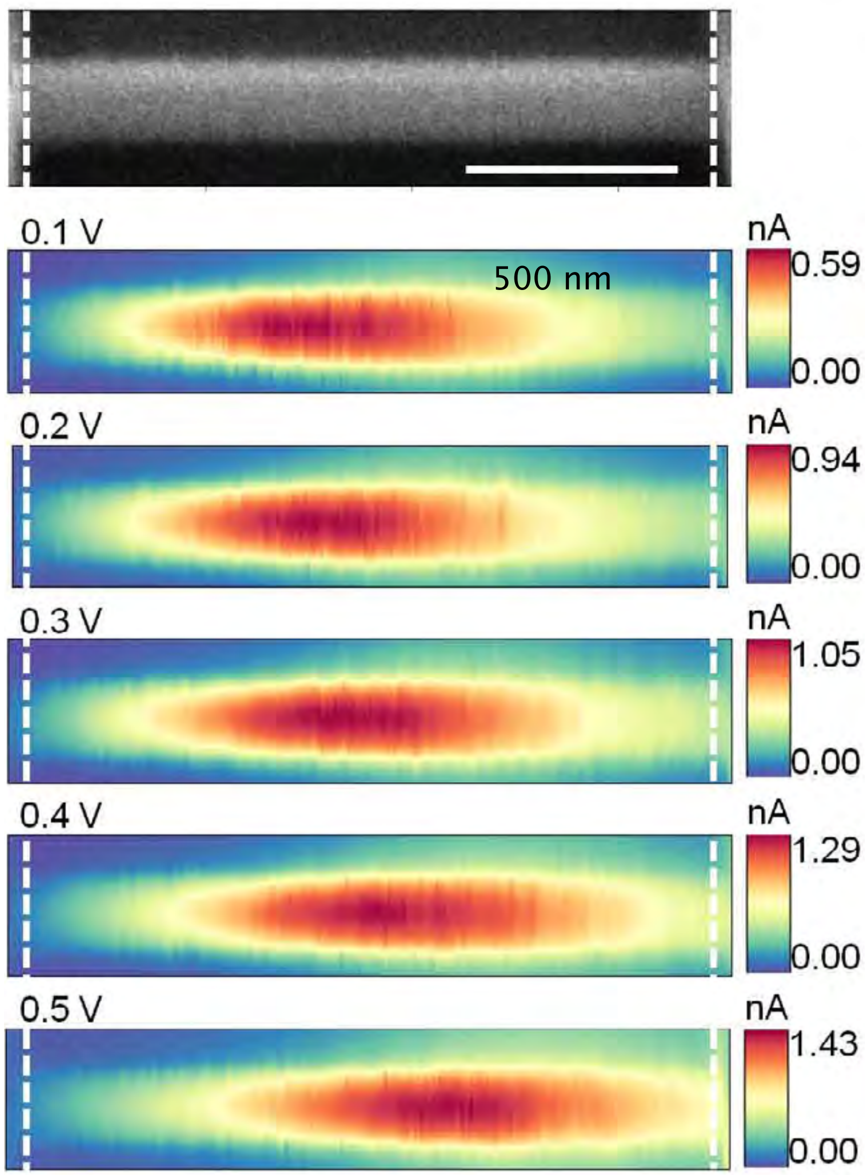


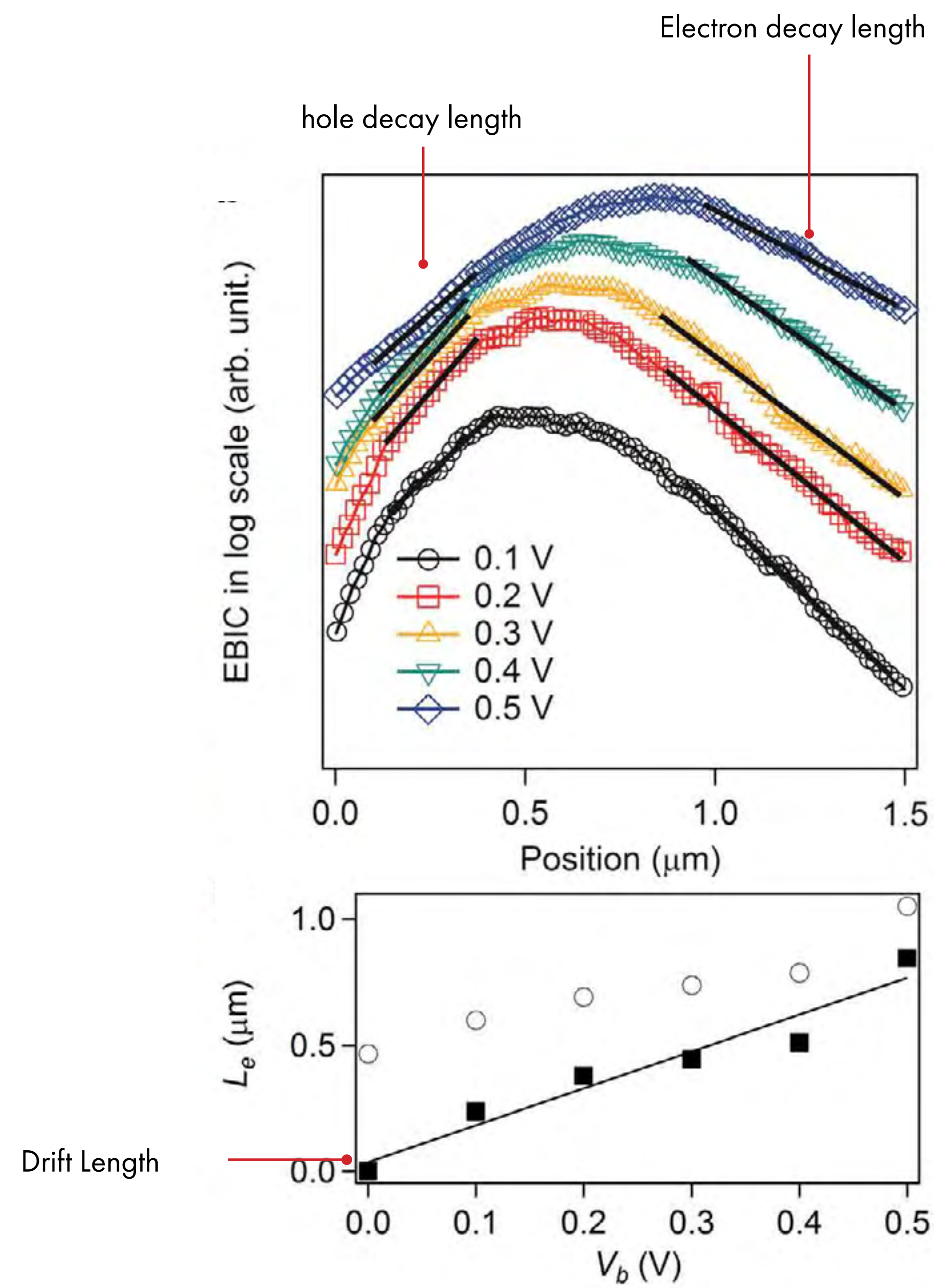
0.1 V is enough to overcome local potential difference

Shifting of zero current position

Antisymetric profile is due to potential from faster electron diffusion than holes leaving positive charge behind.

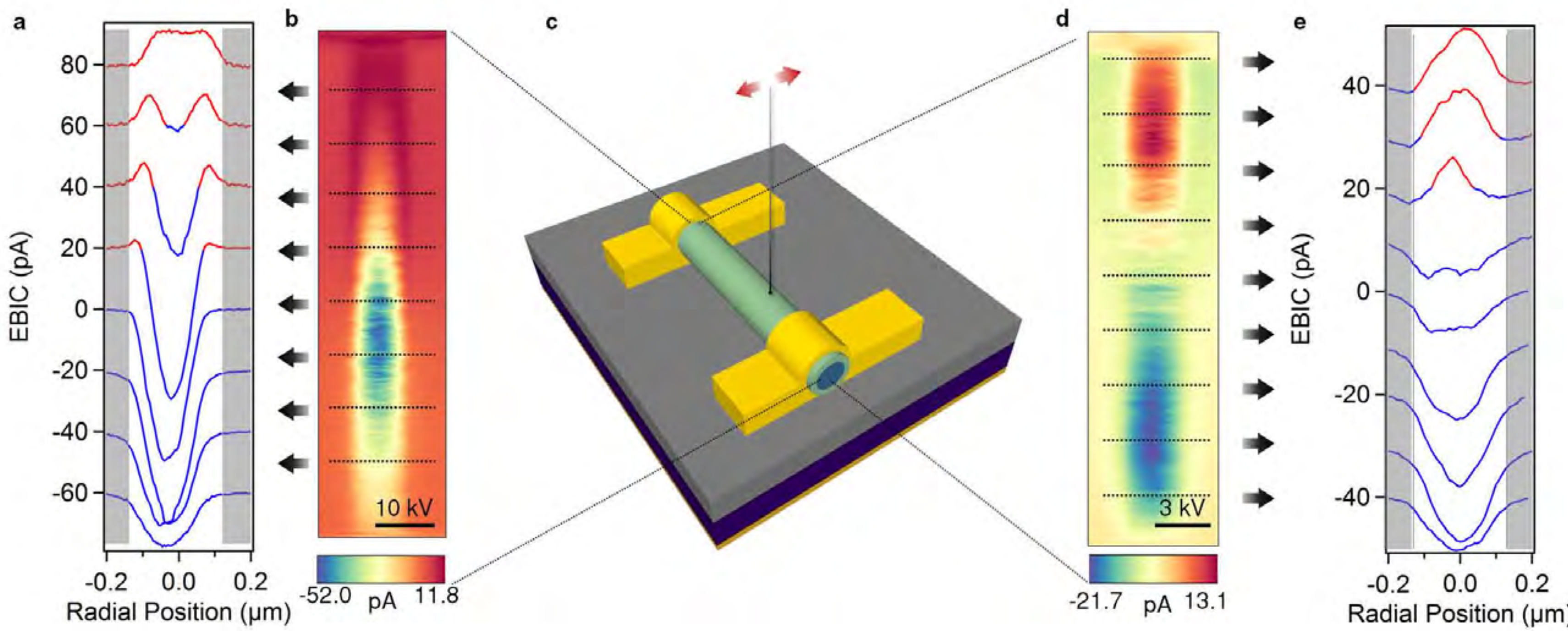
At higher applied bias in the shell we can separate the drift and diffusion components from the characteristic length.

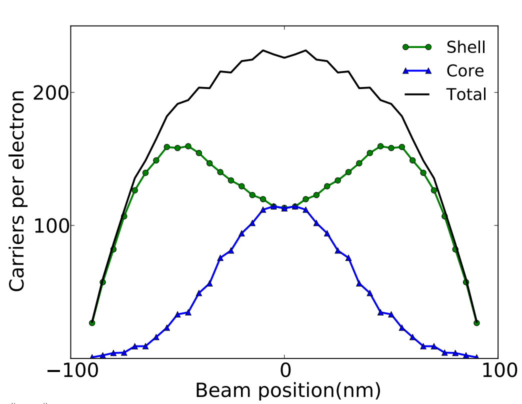


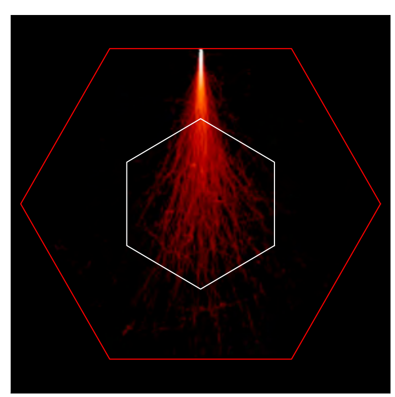


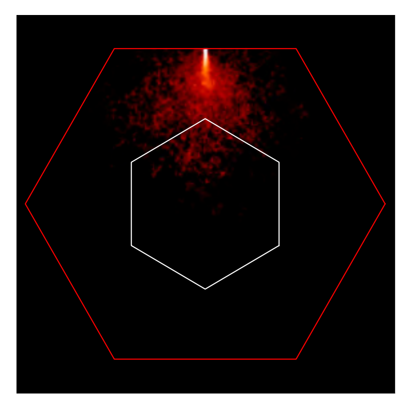
Radial profiles show separate EBIC response from AlGaAs shell material and GaAs core material.

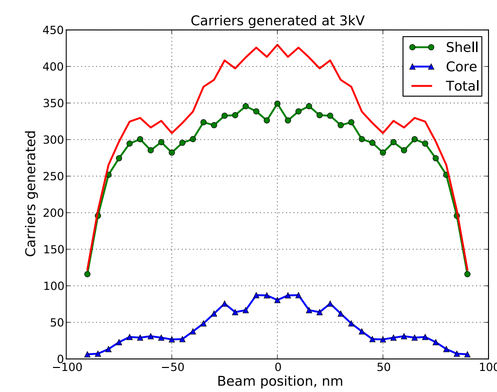
Change in sign from sides to center shows clear evidence that shell and core are separate conducting channels.











Conclusions

EBIC is an effective technique for measuring a broad range of devices and materials.

- Bulk devices
- Nanostructures
- 2D Materials
- Thin Films

Applying biasing conditions and conducting experiments in-situ reveals the underlying behavior of how devices function.

- Filling of surface trap states
- Extracting drift/diffusion lengths from radial structures

EBAC can be used to look at defects and variations in the crystal structure.

- BFO
- PZT
- III/V Materials

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