# Preparation and Study of Cross-Sectioned GaN HEMT Devices

**NASA NEPP – June 2014**

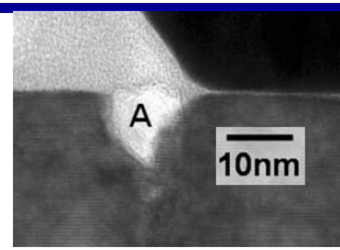
**Al Hilton**, E. Heller*, D. Dorsey*, J. Brown**, E. Moore**, J. Hoelscher**, S. Tetlak*, J. Beckman*, and the HiREV Team**

***Air Force Research Laboratory**
****Wyle Laboratories**

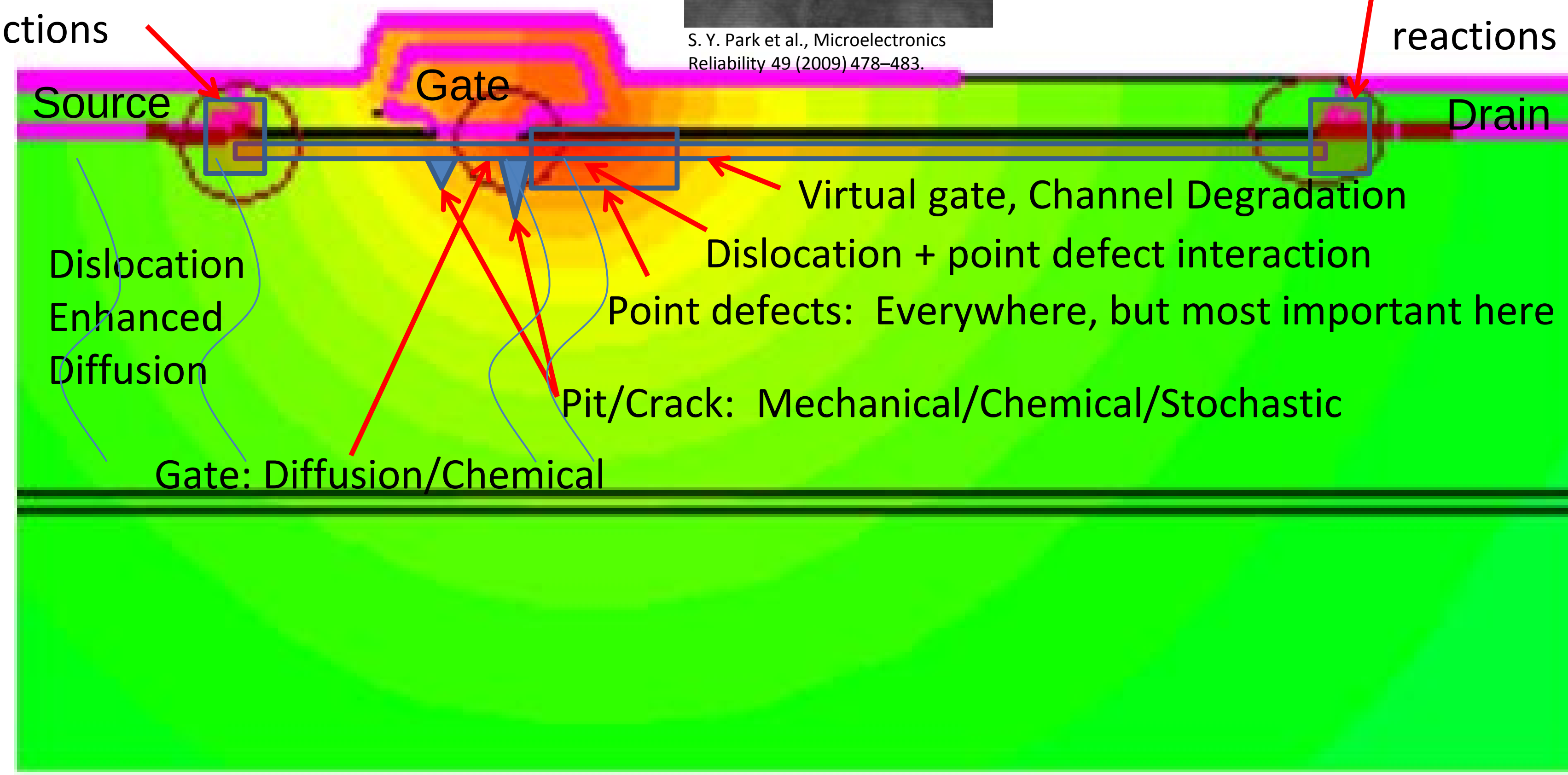
# Outline

- Motivation: Understanding Device Physics of Failure by Looking at Features Underneath the Gate
- How Cross-Sectional Samples are Prepared and How They Perform
- Brief Discussion of Scanning Probe Methods
- Results From Scanning Probe and Optical Studies

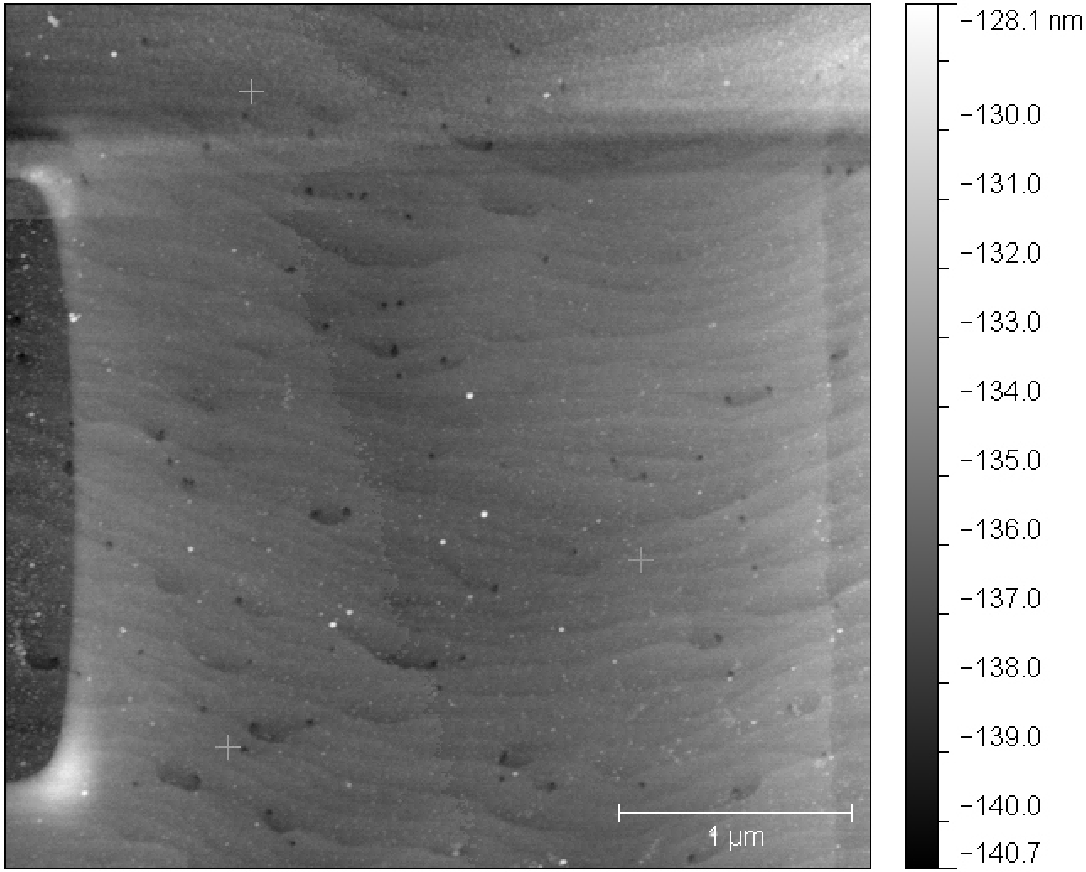
# What Happens Beneath the Gate?




S. Y. Park et al., Microelectronics Reliability 49 (2009) 478–483.

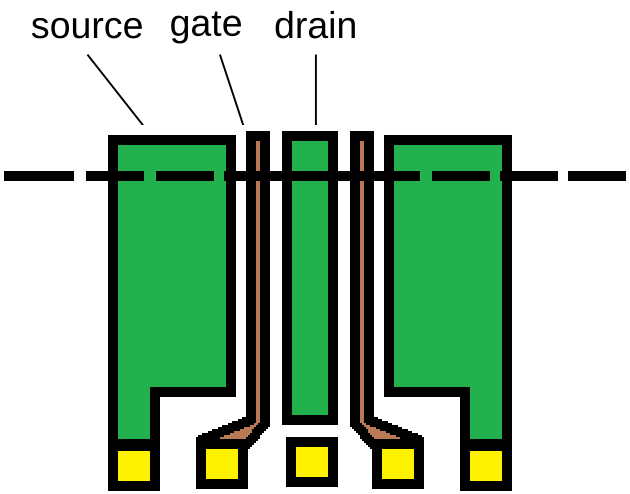


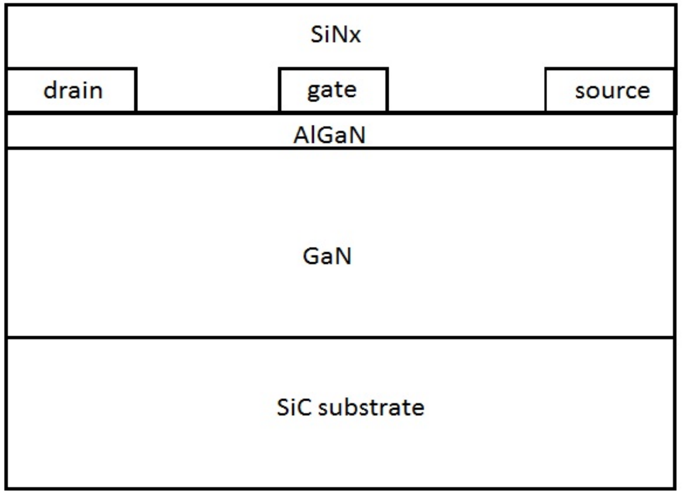
# What Happens Beneath the Gate?




Delayered AlGaN/GaN surface after chemical removal of device structures and passivating layers.

# Device Layout:




*(nominal drawings, not to scale)*

Custom devices from several foundries have been designed with gate pads on one side so as to be operable after sectioning. Devices are produced at a commercial foundry.

Devices with and without source-connected field plates are available for test.

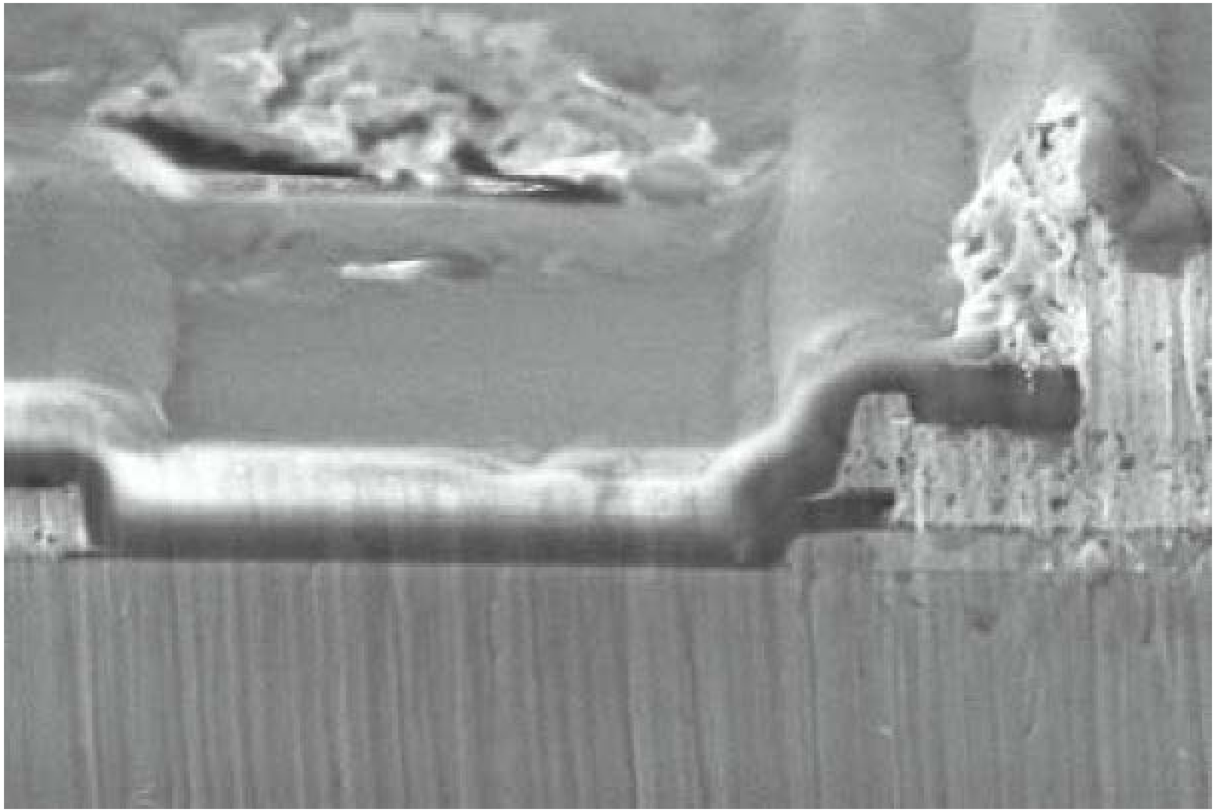
Gate is nominally ~1$\mu$m wide, channel is a few $\mu$m wide.

GaN thickness is a few $\mu$m.

# Cross-Sectioning:

- Devices are prepared with an initial mechanical polish followed by Ar ion milling.
- Resulting surfaces need to be as smooth as possible for scanning probe microscope experiments.
- Cross-sectioned devices need to perform similarly to intact devices.

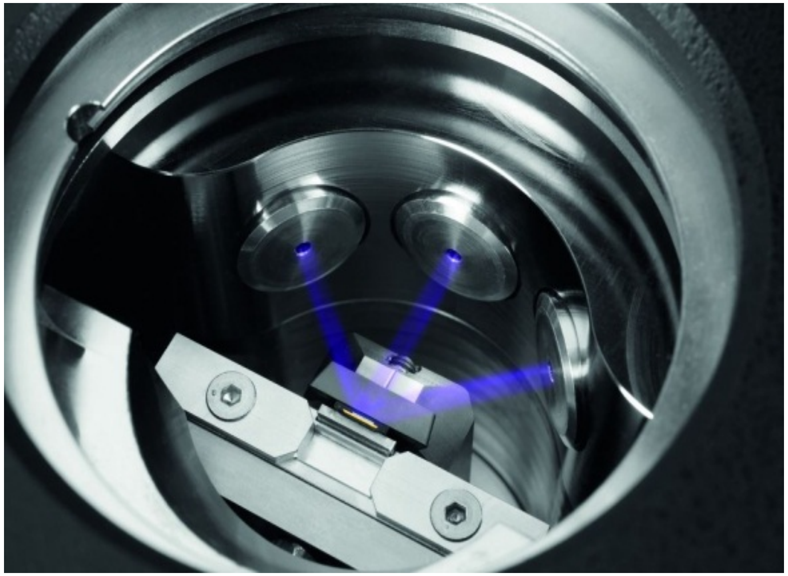
# Cross-Sectioning: Mechanical Polishing



Sample is polished with a series of SiC, diamond, and colloidal alumina polishing media.

Mechanical polishing with fine colloidal polishing media still leaves some polishing damage at the nanoscale.

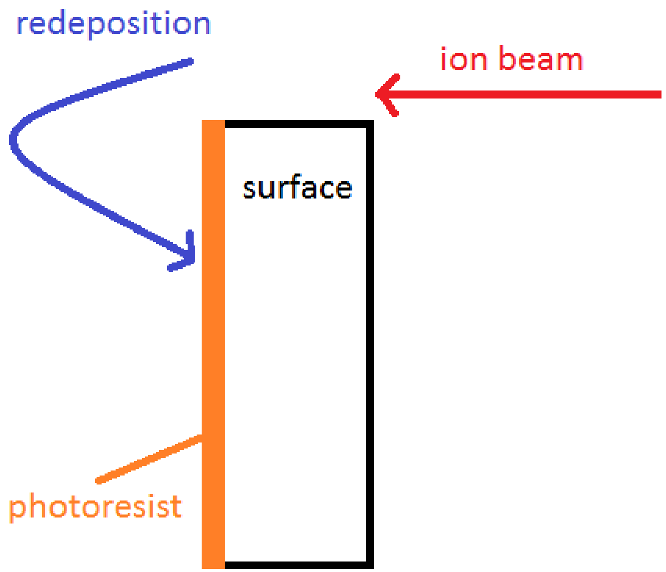
# Cross-Sectioning: Ion Milling



Leica TIC (Triple Ion Cutter) three-beam wide area milling tool.

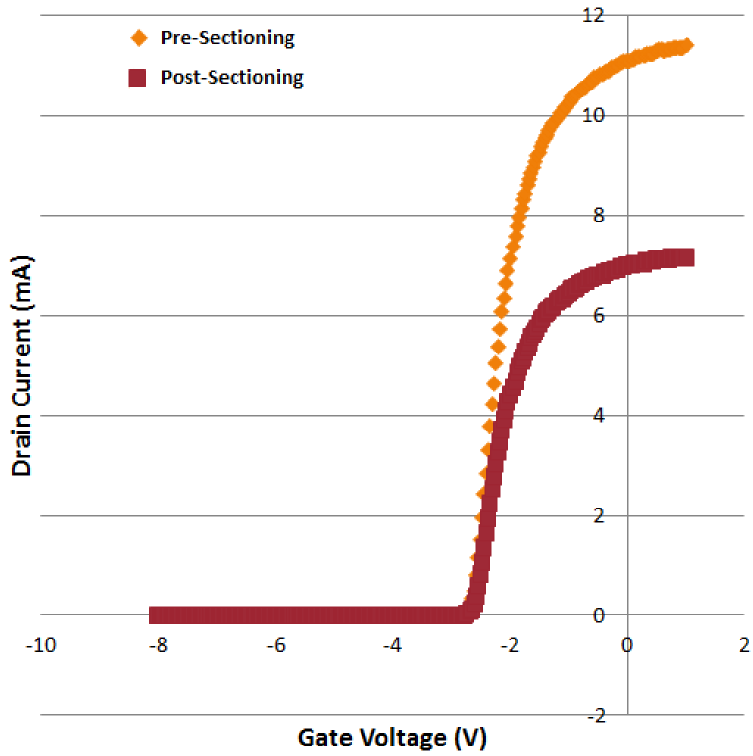
Sample is placed behind a mask and milled with 8keV Ar ion guns for several hours.

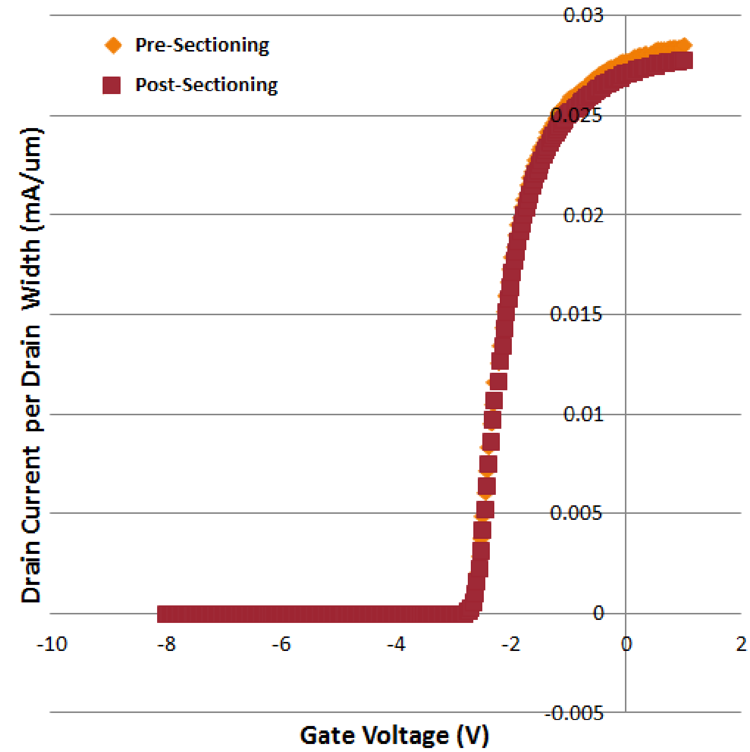
# Cross-Sectioning:




Ion milling tends to redeposit material on the active region of the device, which can be protected using an easily-removable photoresist layer.

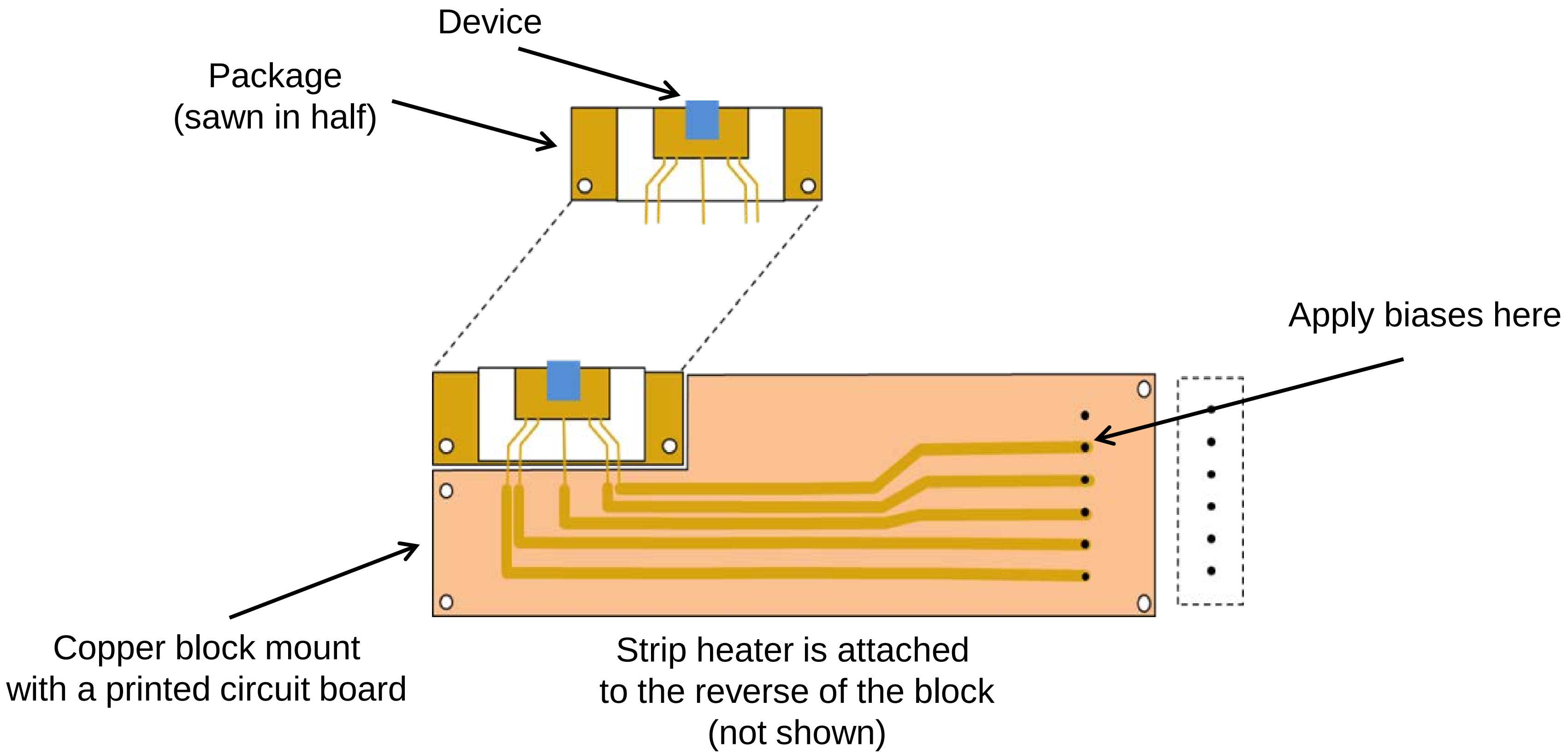
# Cross-Sectioning:



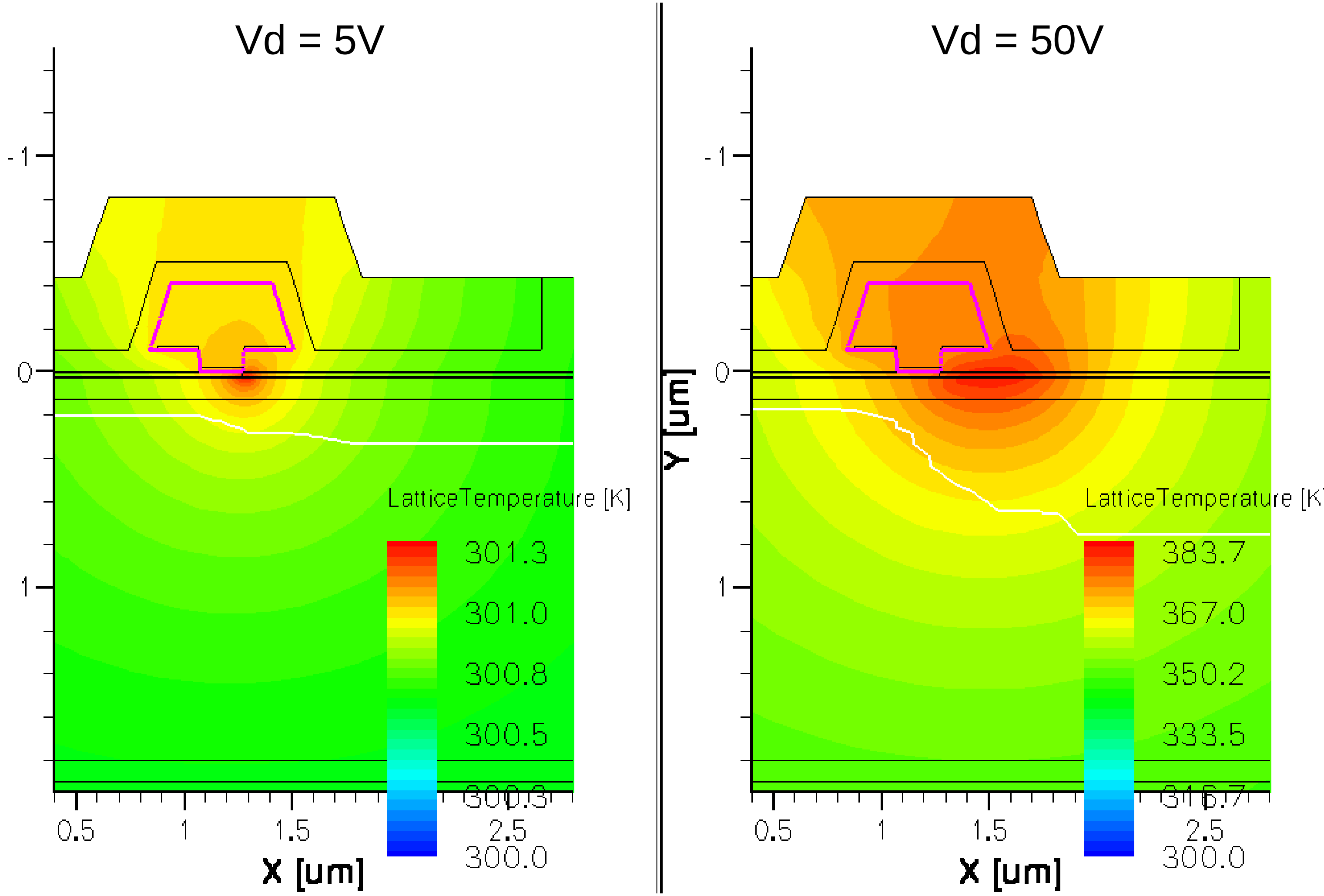

Cross-sectioned devices perform in a reasonably similar manner to intact devices

# Cross-Section Mount:



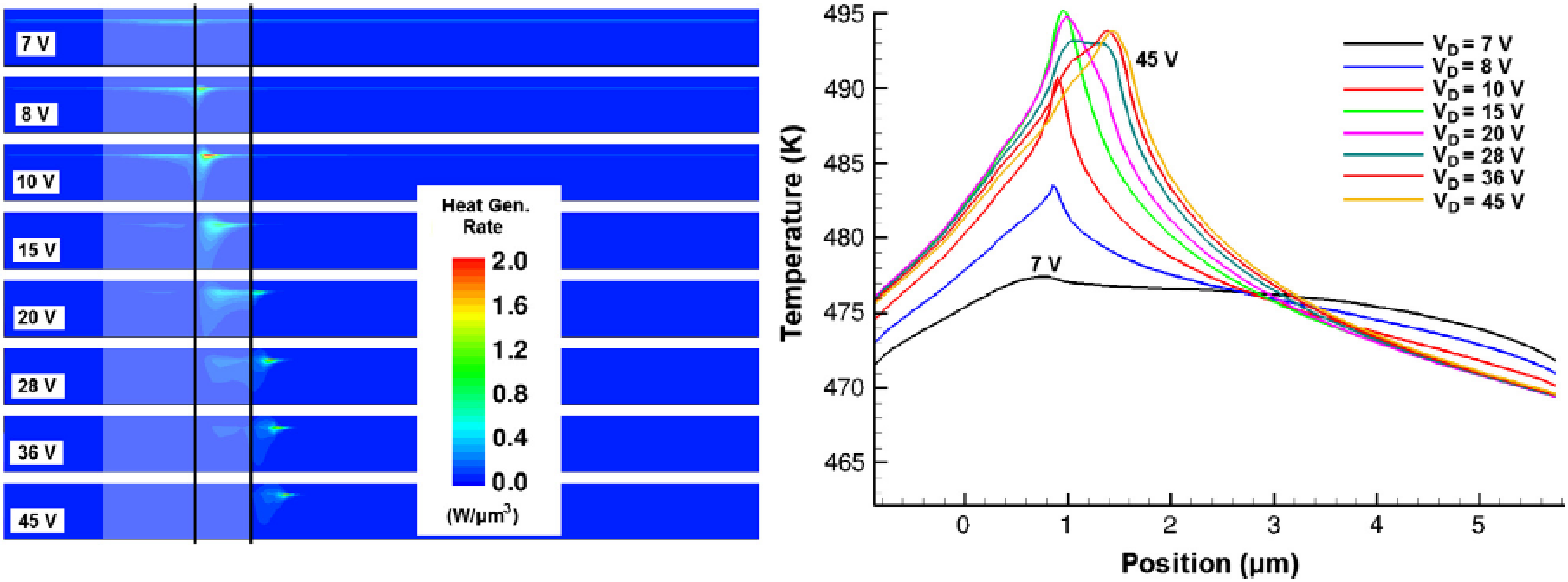

Will hold the device on edge for SPM or optical microscopy experiments, and allows for electrical operation and temperature control of the device.

# Photoemission Study: Predicted Hot-Spot Migration




DISTRIBUTION A. Approved for public release; distribution unlimited.

# Photoemission Study: Predicted Hot-Spot Migration

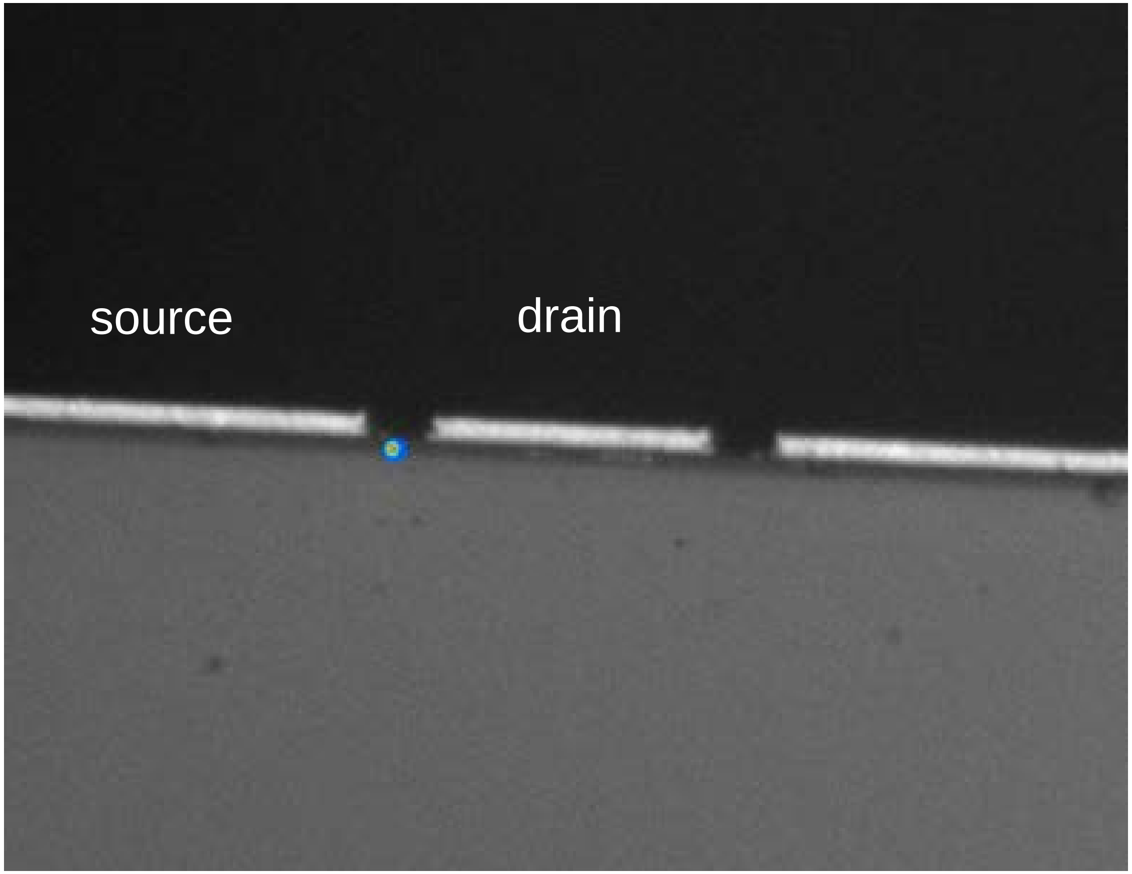



Modeled channel heat generation and temperature under equivalent 10W power conditions.

E. Heller, S. Choi, D. Dorsey, R. Ventury, S. Graham, *Microelectronics Reliability* **53** (2013) 872-877.

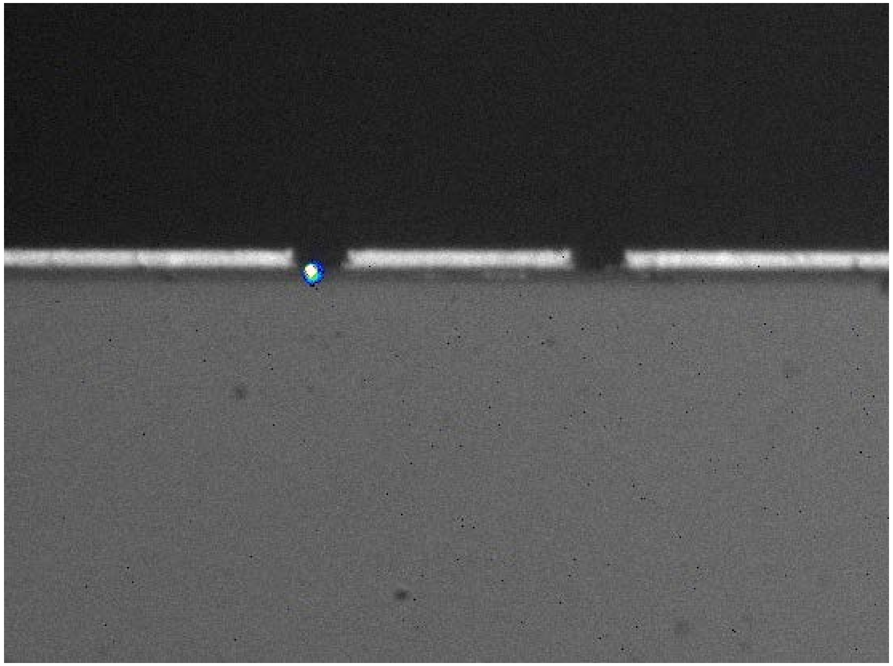
DISTRIBUTION A. Approved for public release; distribution unlimited.

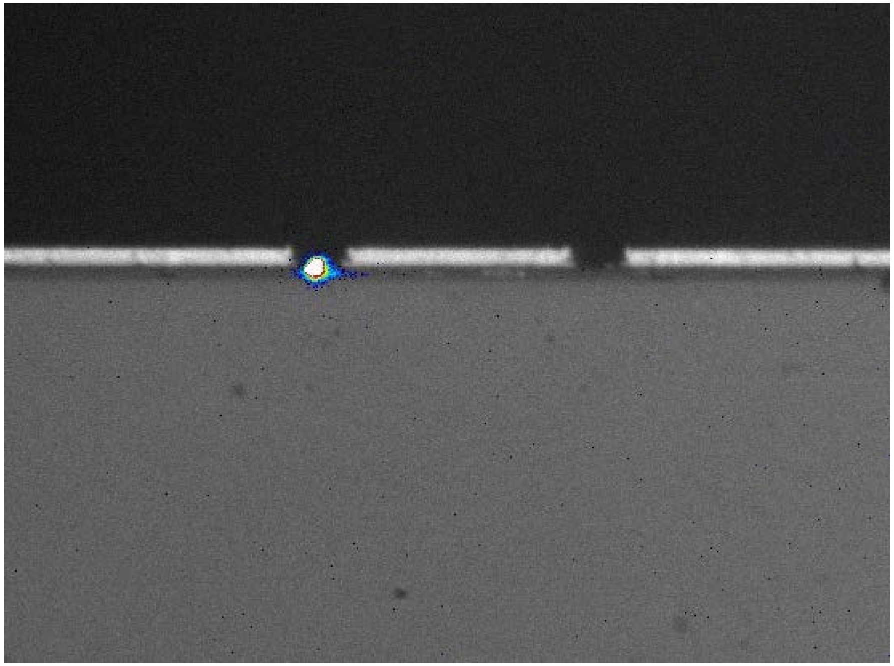
# Photoemission Study




Photoemission map at 0.5mW power, 10V drain

# Photoemission Study



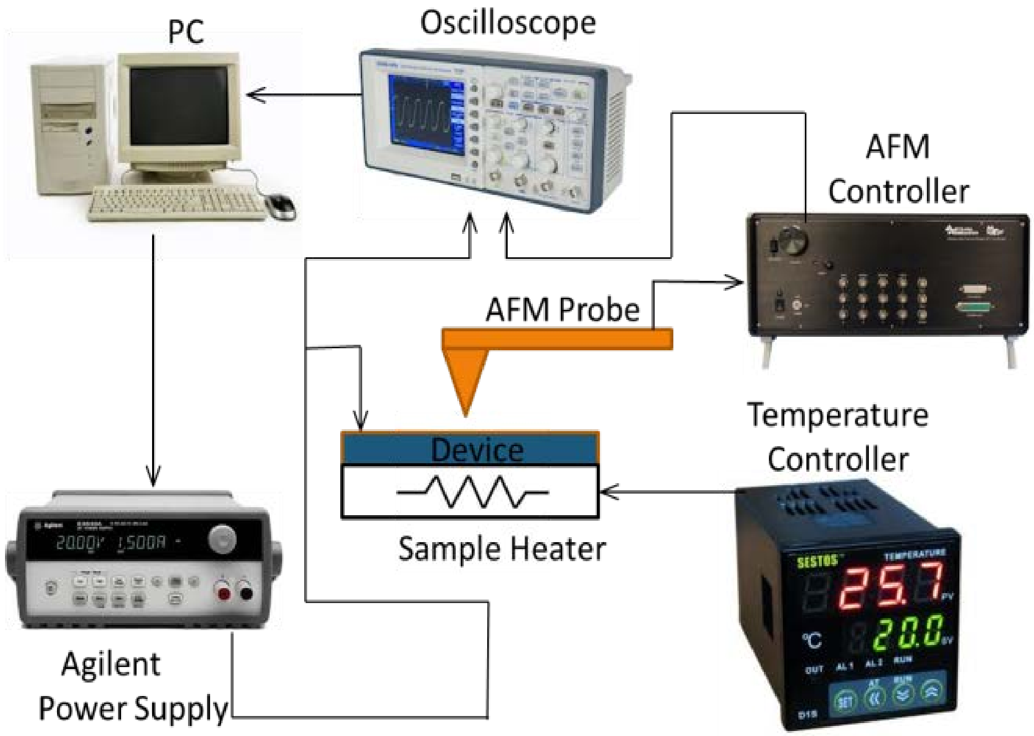


0.5mW power, 20V Vd, 25 μA Id

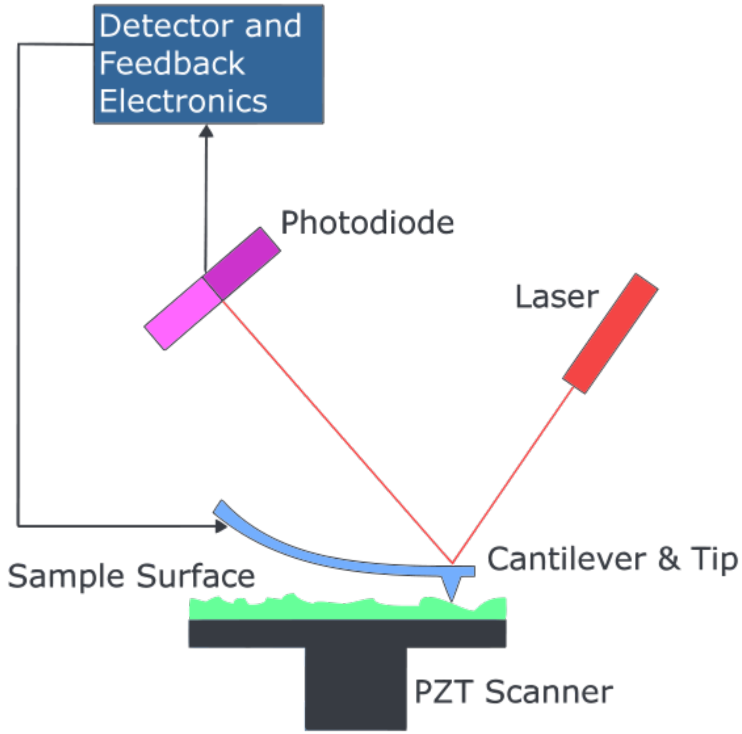
0.5mW power, 80V Vd, 6.25 μA Id

Shift and change in size in photoemission "hot spot" with increasing drain bias

# Scanning Probe Microscopy (SPM)



# Scanning Probe Microscopy (SPM)




In an atomic force microscopy (AFM) experiment, a sharp probe is scanned across a sample surface.

Probe deflection alters the path of the reflected laser beam, which is measured by a position-sensitive diode.

Topographic images with nanometer-scale resolution can be recorded.

*From: http://en.wikipedia.org/wiki/File:Atomic_force_microscope_block_diagram.svg*

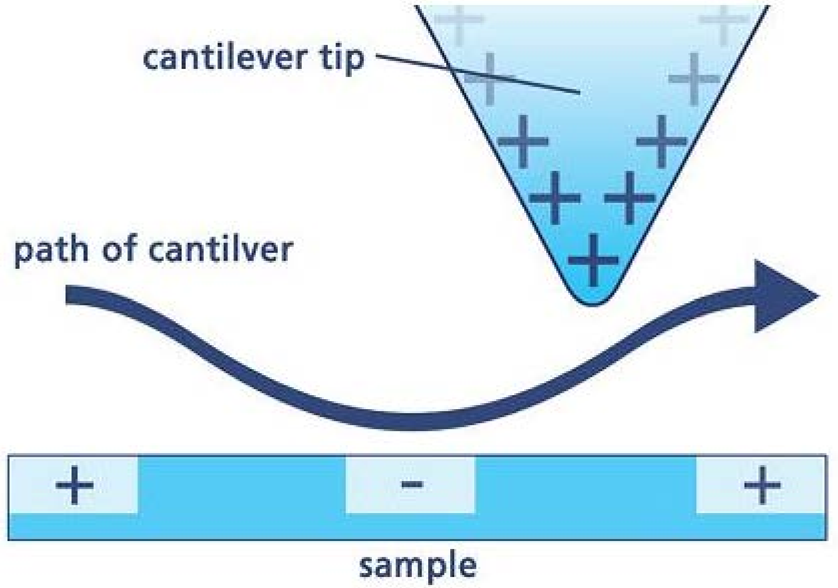
# Scanning Probe Microscopy (SPM)

With metal-coated probes, an electric potential can be applied during imaging, and local electric properties can be mapped along with topography.

A wealth of SPM techniques are available, including

- Current-Sensing AFM
- Electric Force Microscopy
- Kelvin Probe Microscopy
- Magnetic Force Microscopy
- Scanning Tunneling Microscopy
- Scanning Capacitance Microscopy
- Scanning Microwave Microscopy
- Scanning Thermal Microscopy

# Electrostatic Force Microscopy (EFM) and Kelvin Probe Force Microscopy (KPFM or KFM)




For a conducting tip having a DC potential separated a short distance from the surface, the electrostatic force on the tip is

$$F_{electrostatic} = \frac{1}{2}\frac{\partial C}{\partial z}\Delta V^2$$

Which is sensitive to local surface charge.

# Electrostatic Force Microscopy (EFM) and Kelvin Probe Force Microscopy (KPFM or KFM)

For a conducting tip having a DC potential *and* an AC potential positioned above a surface with surface potential $V_{CPD}$,

$$V = (V_{DC} - V_{CPD}) + V_{AC} \cdot \sin(\omega t)$$

As before, the electrostatic force on the tip is $F = \frac{1}{2}\frac{dC}{dz}V^2$, so….

$$F = \frac{dC}{dz}[\frac{1}{2}(V_{DC} - V_{CPD})^2 + \frac{1}{4}V_{AC}^2] + \frac{dC}{dz}[V_{DC} - V_{CPD}]V_{AC}\sin(\omega t) - \frac{1}{4}\frac{dC}{dz}V_{AC}^2\cos(2\omega t)$$

With a lock-in detector at ω and a little math this simplifies to,

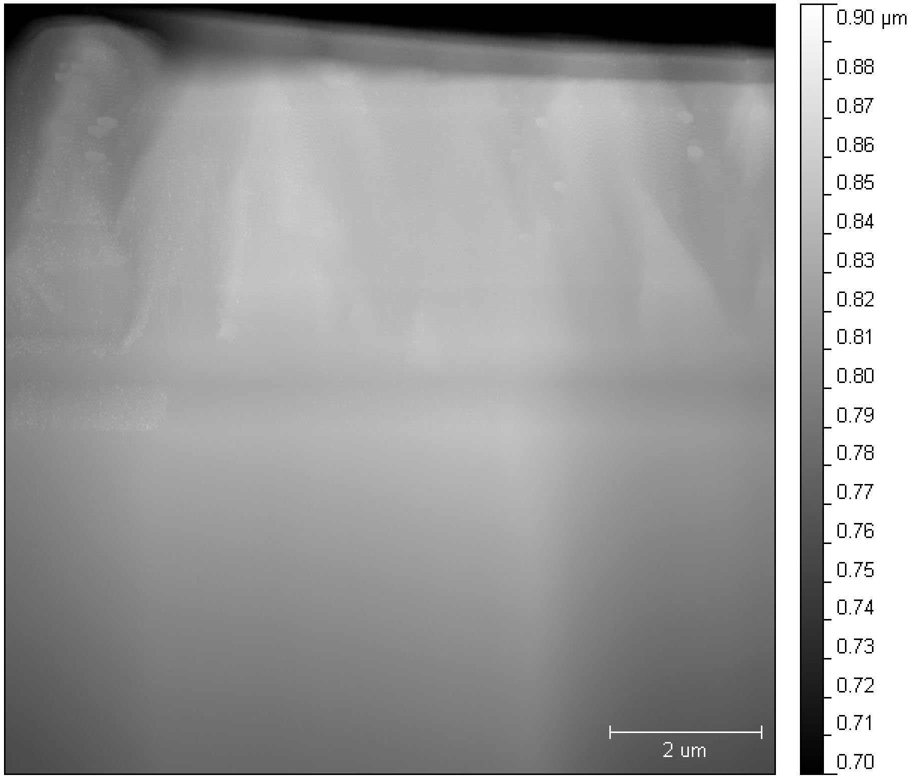
$$F_\omega = \frac{dC}{dz}[V_{DC} - V_{CPD}]V_{AC}\sin(\omega t)$$

In KPFM, a feedback mechanism adjusts $V_{DC}$ such that $F_\omega = 0$.

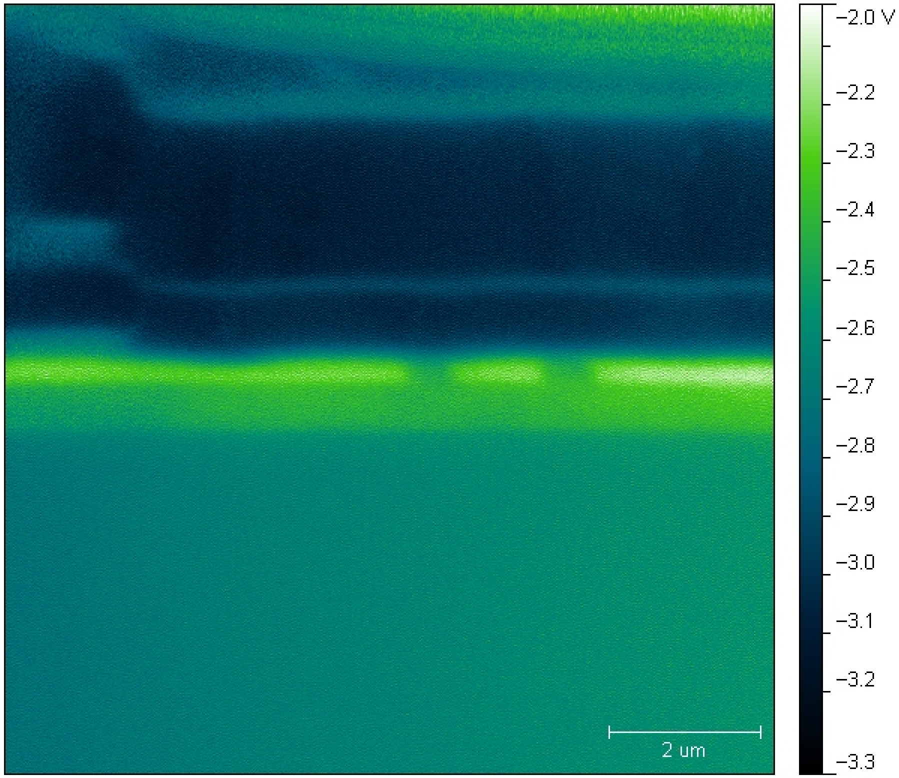
<u>When this happens, $V_{DC}$ = a measurement the local surface potential.</u>

# Scanning Probe Microscopy (SPM)

Surface Topography

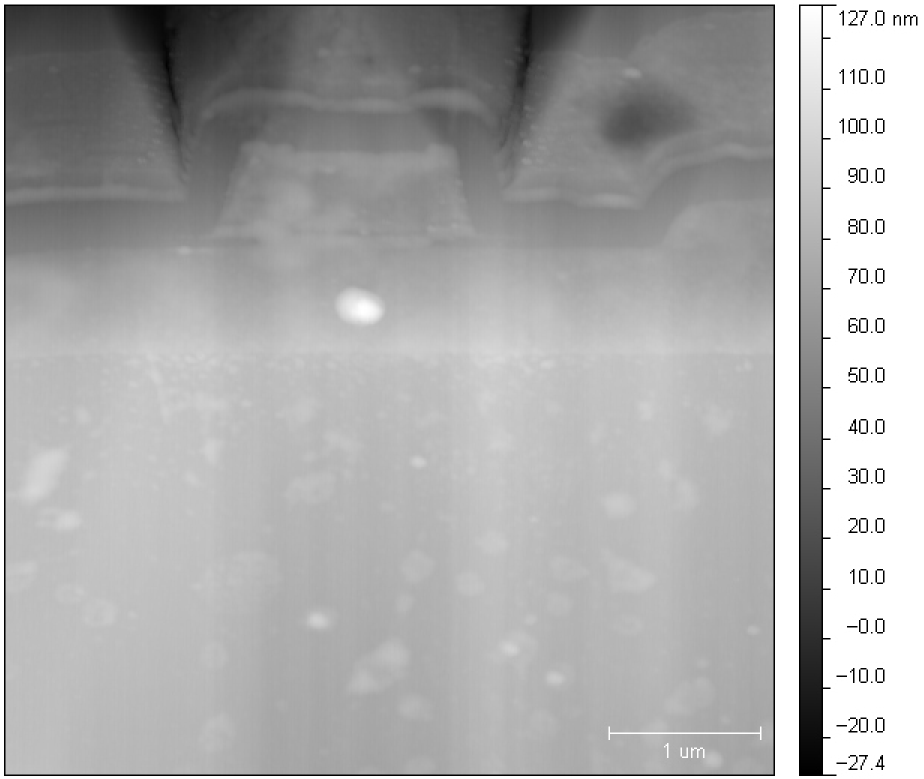



Kelvin Probe
Surface Potential Map (Unbiased)

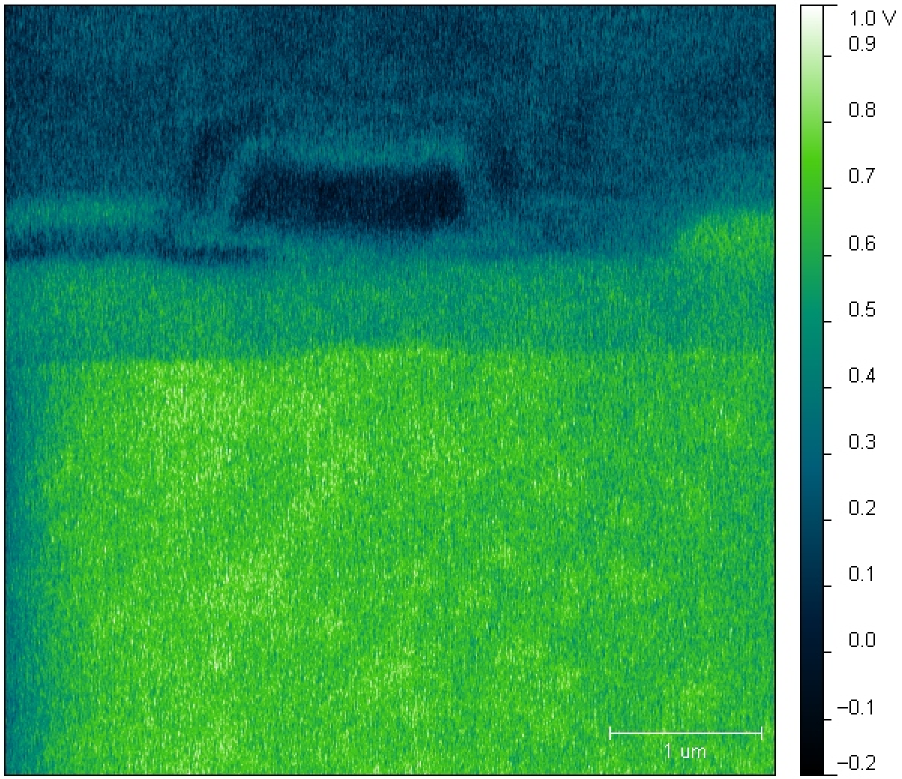


# Scanning Probe Microscopy (SPM)

Surface Topography

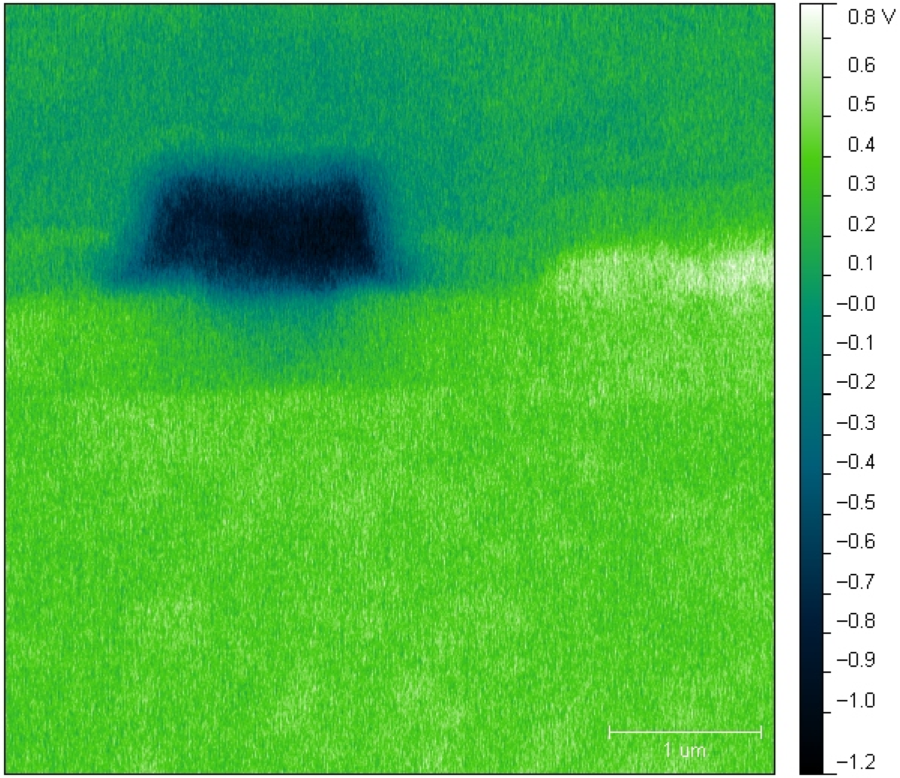



Surface Potential (unbiased)

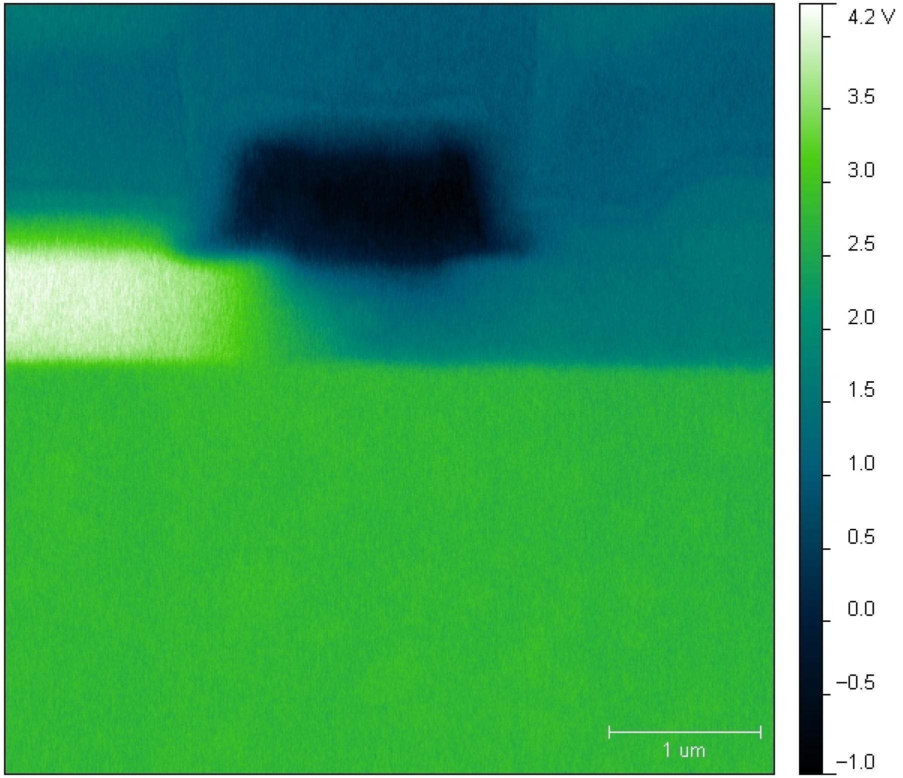


# Scanning Probe Microscopy (SPM)

Surface Potential
-2 Vg, 0 Vd

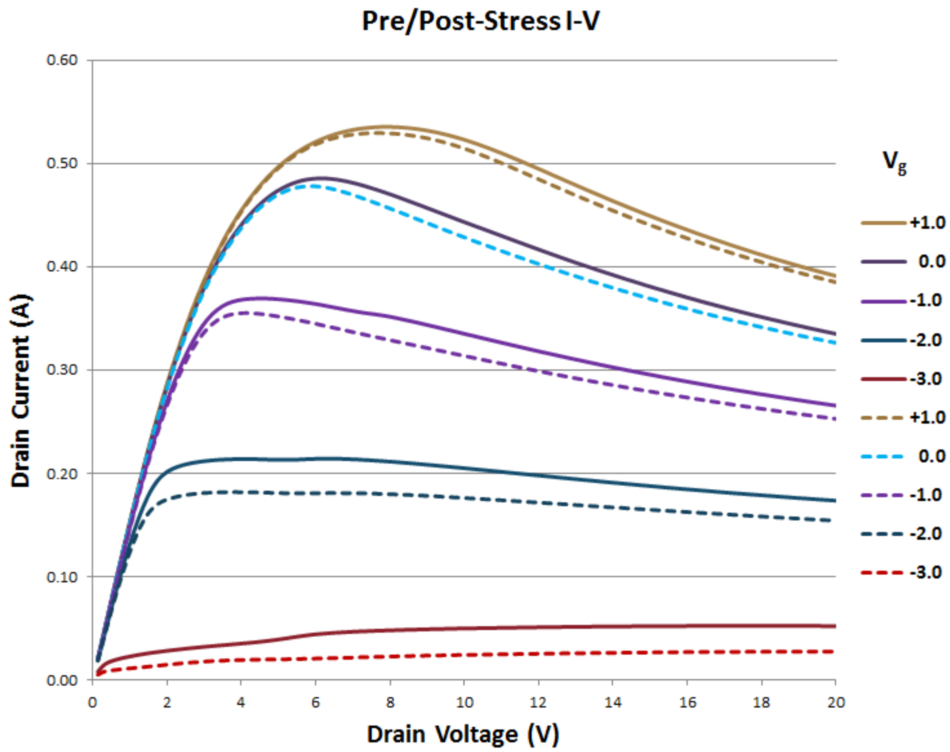



Surface Potential
-4 Vg, 5 Vd



# Transient Charge Traps

Trapped charges beneath the gate are believed to give rise to a "virtual gate," temporarily altering device behavior.

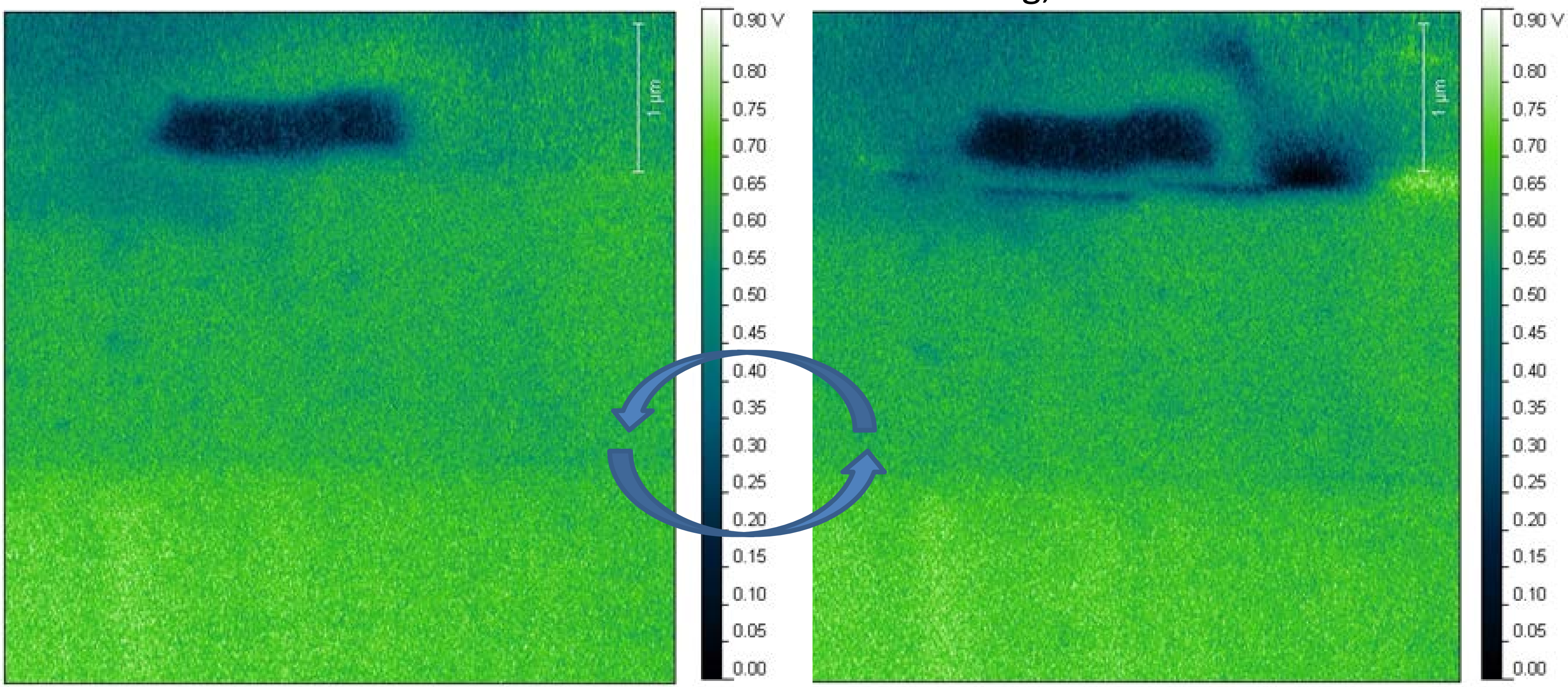



Reduced drain current after semi-on stress, which recovers after exposure to light.

# Time-Varying Surface Potential Maps

Unbiased Device Before Stress

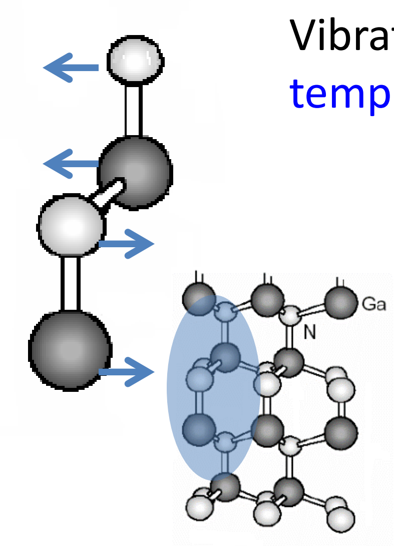
Unbiased Device After Pinchoff Stress
-8Vg, +20Vd for 2 min




Charge buildup dissipates over time, and device is restored to initial conditions after ~1 day

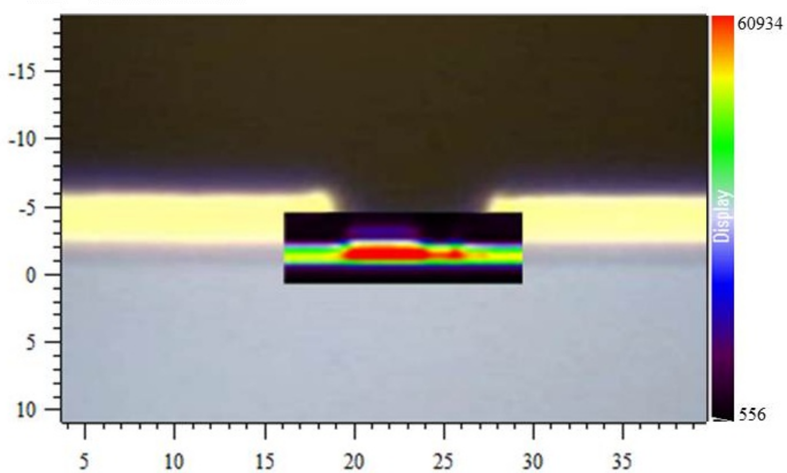
Similar results observed for hot-carrier stress conditions.

# Raman Spectroscopy

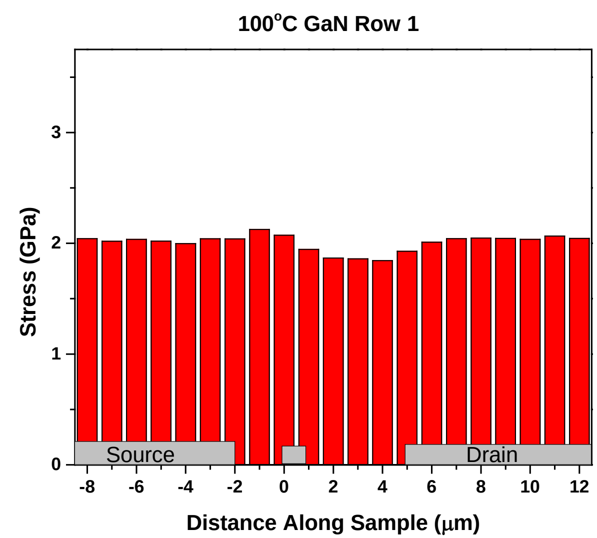



Vibrational spectroscopy to assess molecular movement, assess structure, temperature, uniformity, mechanical stress, thickness

- Inelastic scattering of a monochromatic excitation source
- Incident radiation interacts with phonons (lattice vibrations) resulting in an energy shift of the incident light.
- Incident photons excite vibrational modes in the sample, yielding scattered photons with diminished energy (Stokes scattering)
- Or, incident light interacts with phonons at a raised energy level, scattering photons at frequencies above the incident frequency (anti-Stokes scattering)




Raman intensity map of the GaN E2 peak




Strain map along the channel

DISTRIBUTION A. Approved for public release; distribution unlimited.

# Other Things We Plan on Investigating

- Quantify surface charge
- Measure the kinetics and distribution of charge traps
- Study devices that have been degraded through electrical/thermal stress
- Use cross-sectional measurements to validate modeling results

Funding partially provided by AFOSR, program officer Michael Kendra