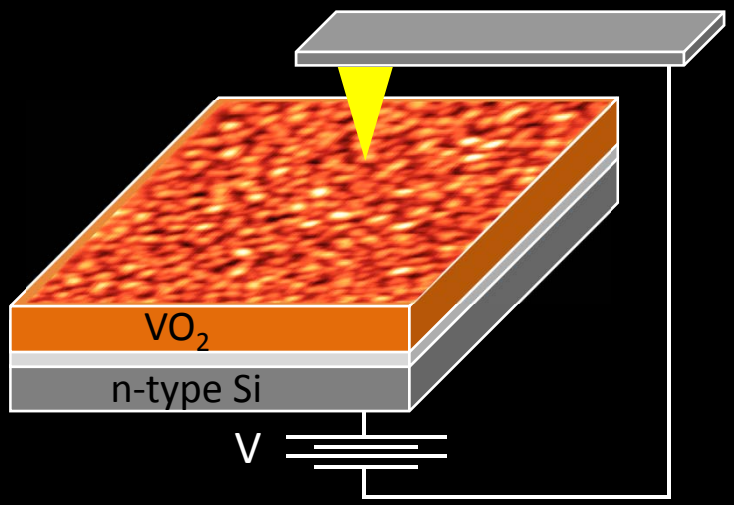
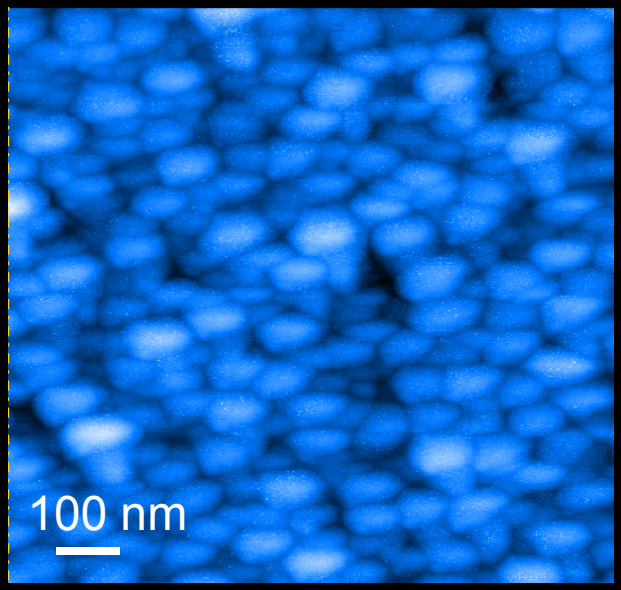
Nanoscale Thermal Mapping of VO_2

Jenny Hoffman





Contributors:

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Prof. Shriram Ramanathan
Harvard School of Engineering & Applied Sciences

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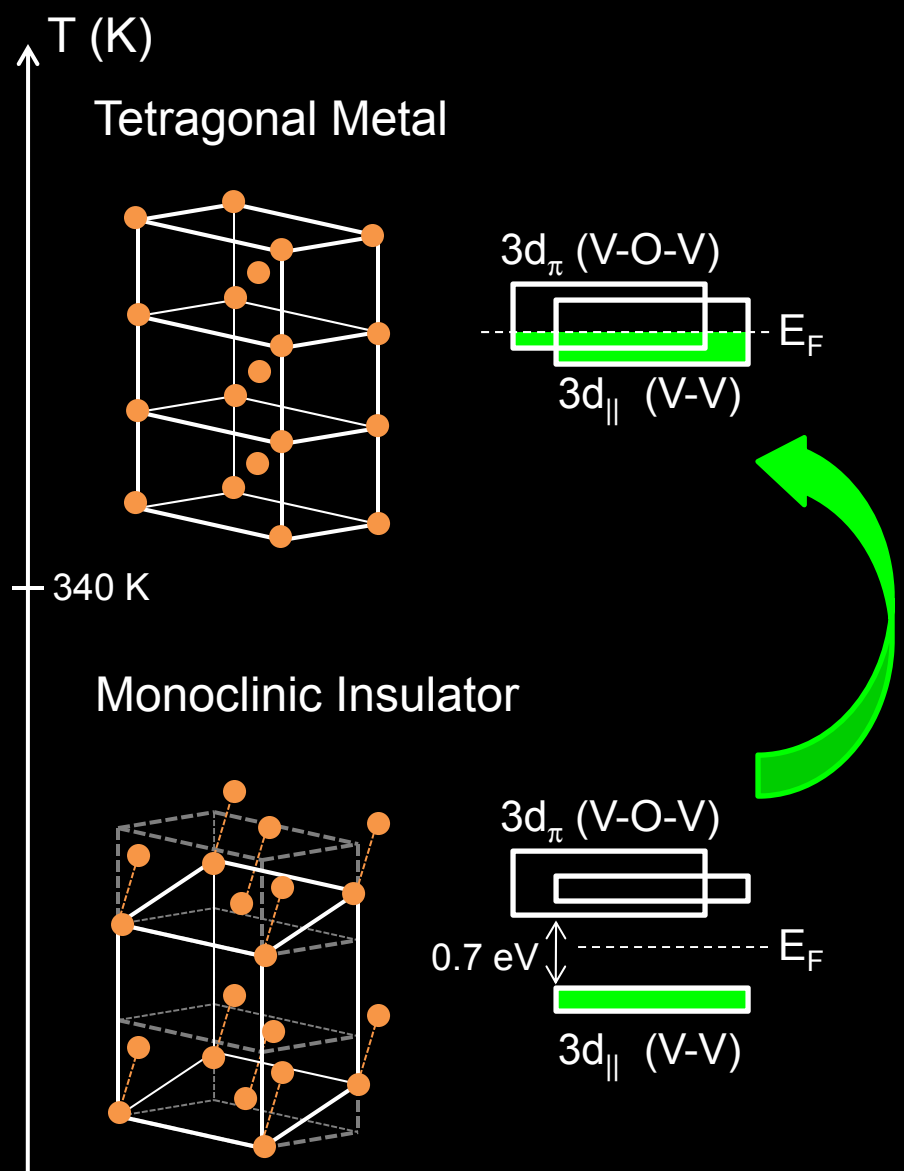
NSEC

VO_2 Insulator to Metal Transition



Goodenough, J.Solid State Chem 3, 490 (1971)

Insulator-Metal Transition

- temperature: ~340 K
- uniaxial stress: ~38 kbar
- optical excitation
- electric field???? ~10^7 V/m

Transition features

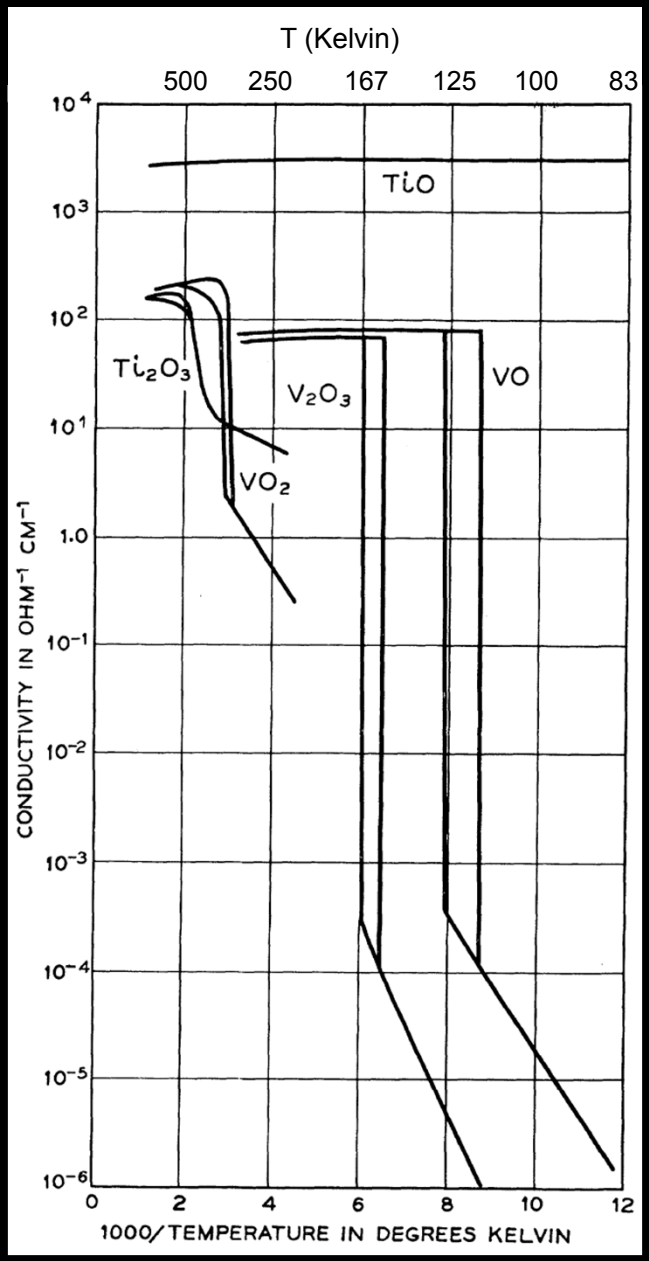
- tunability near room temperature
- 80 fs switching time
- large change in optical reflectance
- high resistivity ratio: up to 10^5

Applications

- sensors
- data storage
- memristors
- tunable metamaterials

Can the transition be triggered by E-field alone??

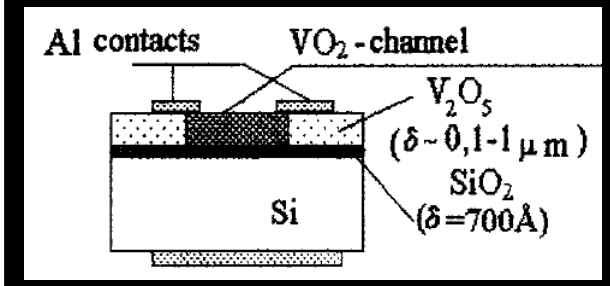
Thermal vs. Electronic Transition?

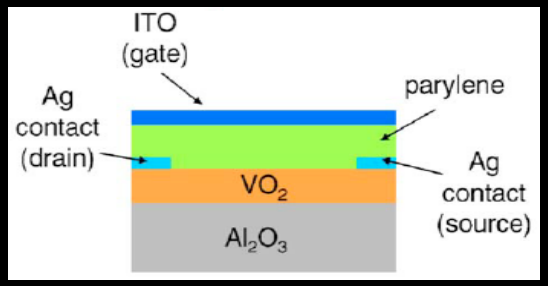


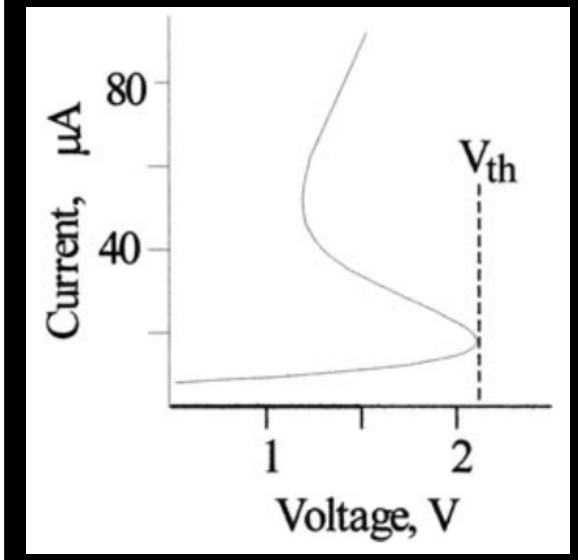
Morin, PRL 3, 34 (1959)

Considered a thermal transition…

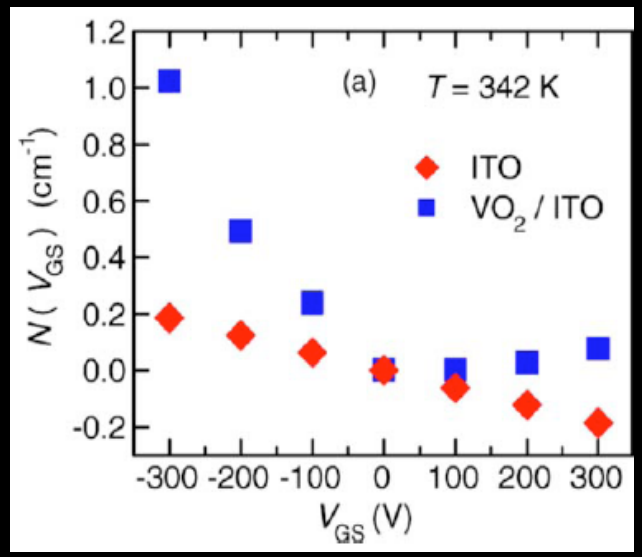
…until 40 years later: electronic triggering?







Stefanovich, JPCM 12, 8837 (2000)



Qazilbash, APL 92, 241906 (2008)

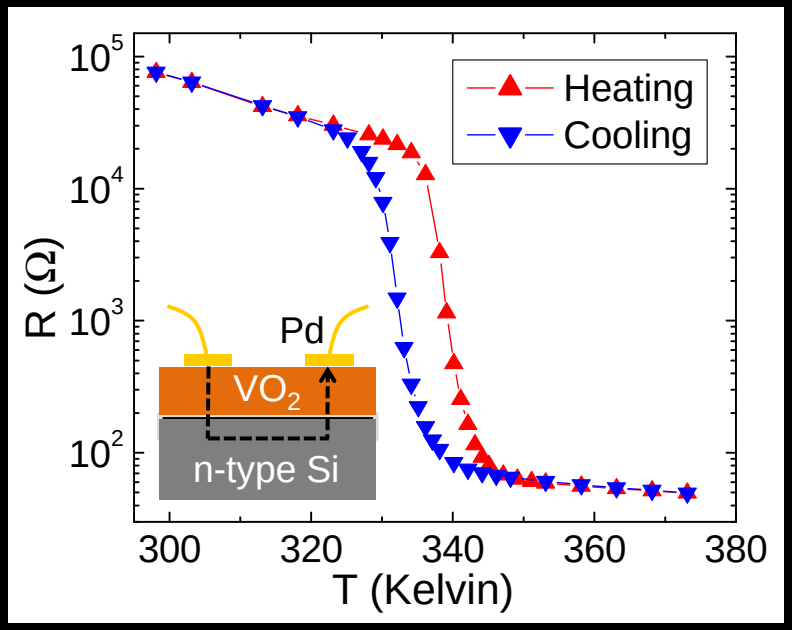
Caveats:

1. Joule heating?
2. electrical breakdown of gate?

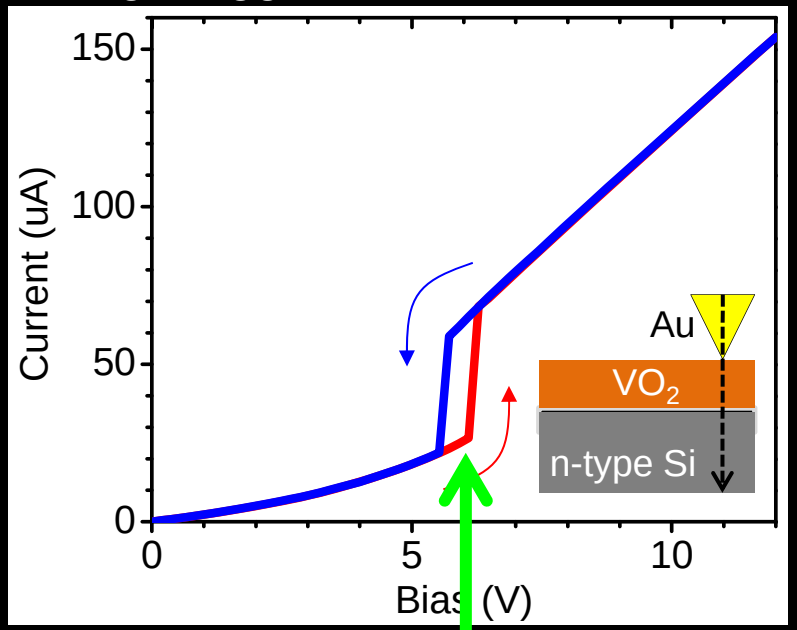
Motivations

1. VO_2: E-field vs. Joule heating

Bulk thermal transition



Voltage-triggered transition



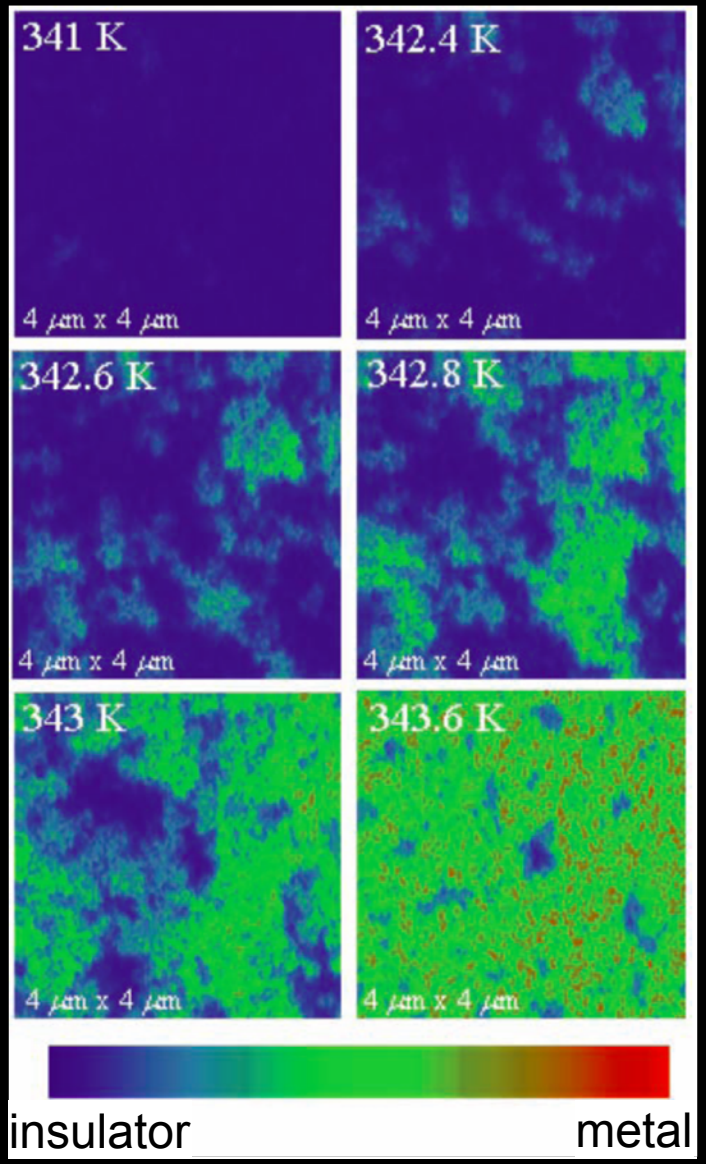
Kim, Ko, Frenzel, Ramanathan, Hoffman, APL 96, 213106 (2010)

Question boils down to:
what is the local temperature here?

2. General scanning technique for nanoscale T measurement

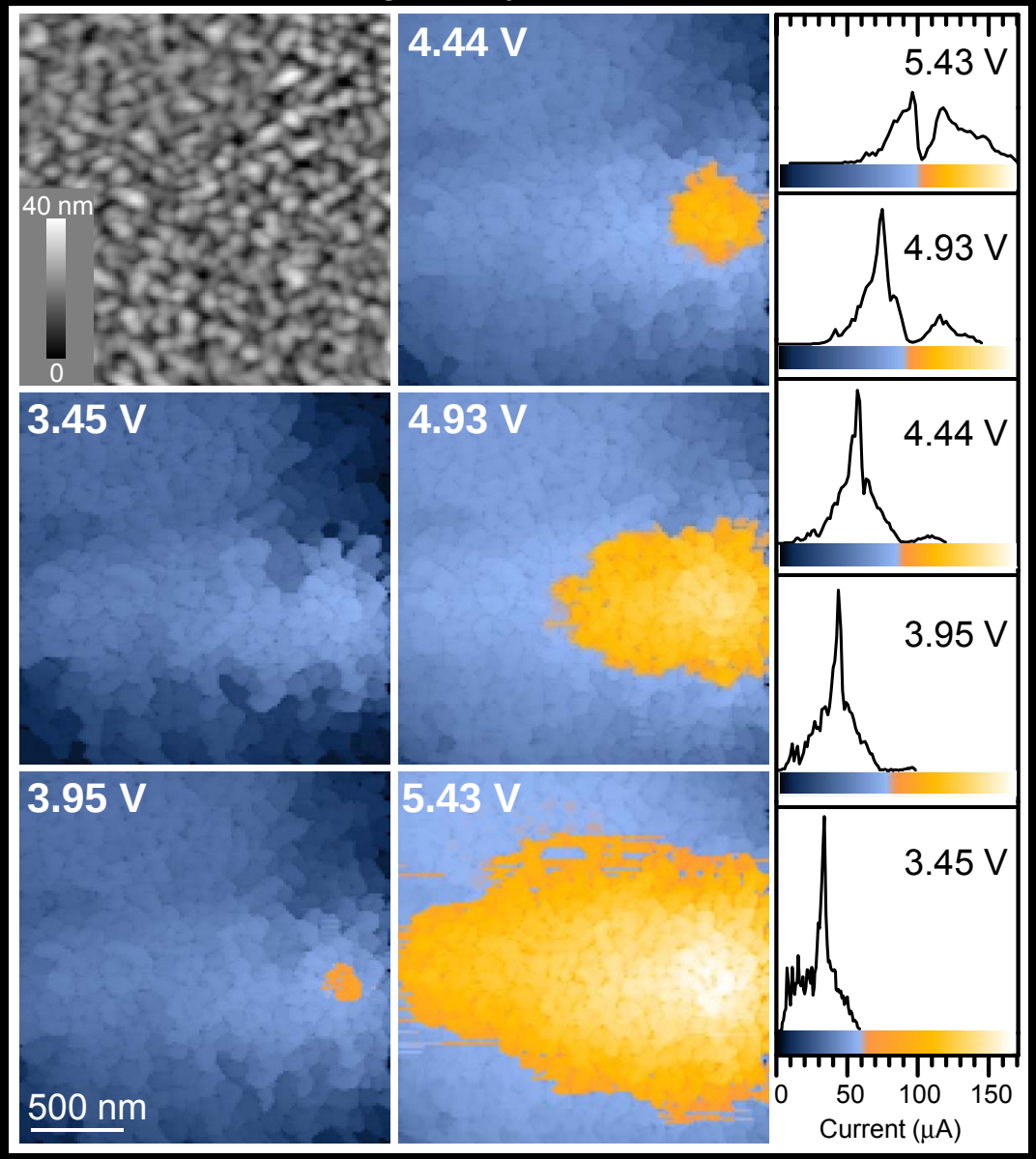
Inhomogeneity → need local probe

Thermal inhomogeneity:



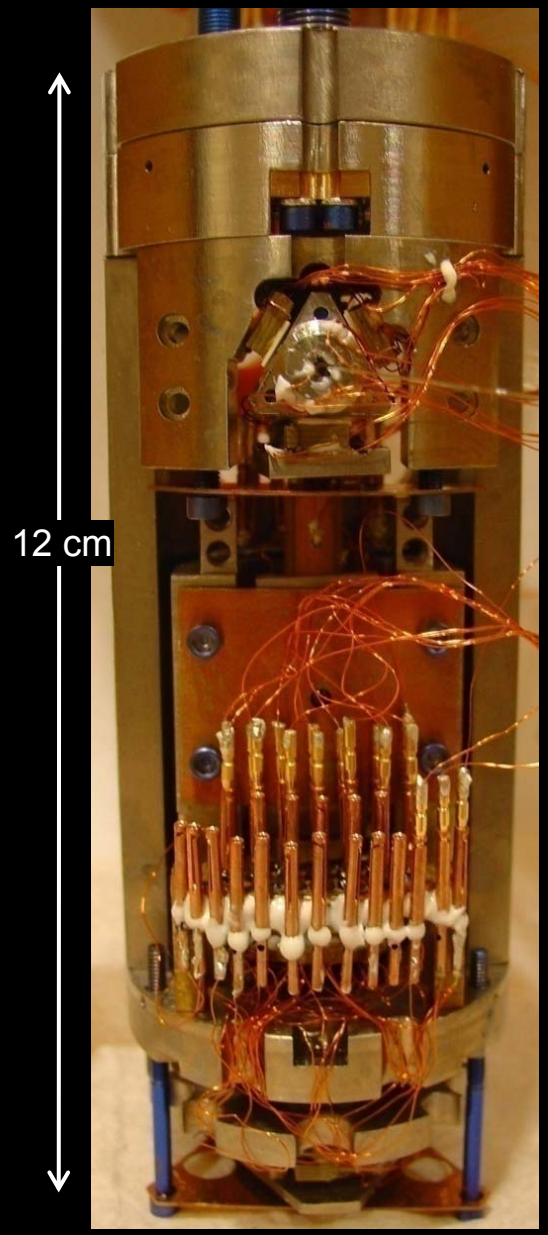
Qazilbash, Science 318, 1750 (2007)

Electrical inhomogeneity:

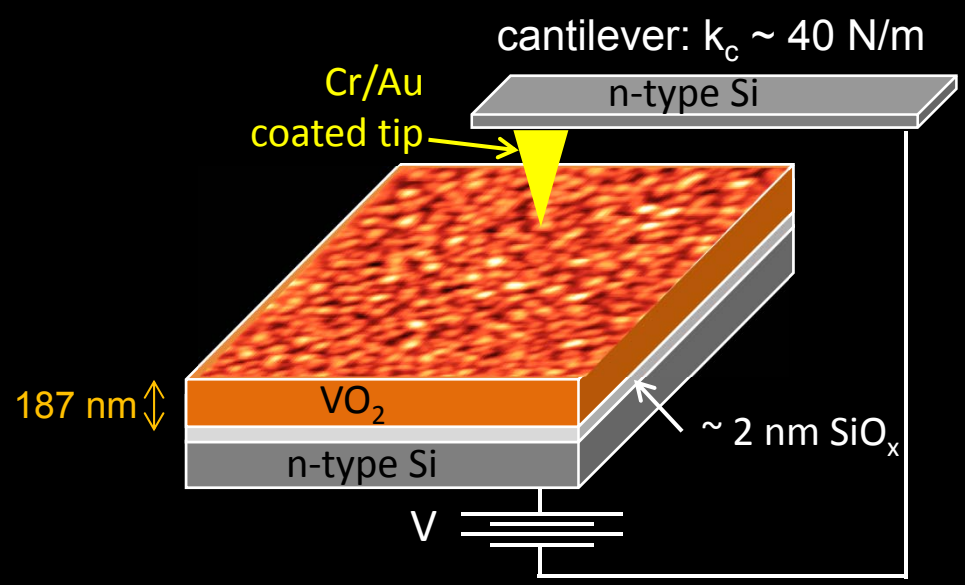


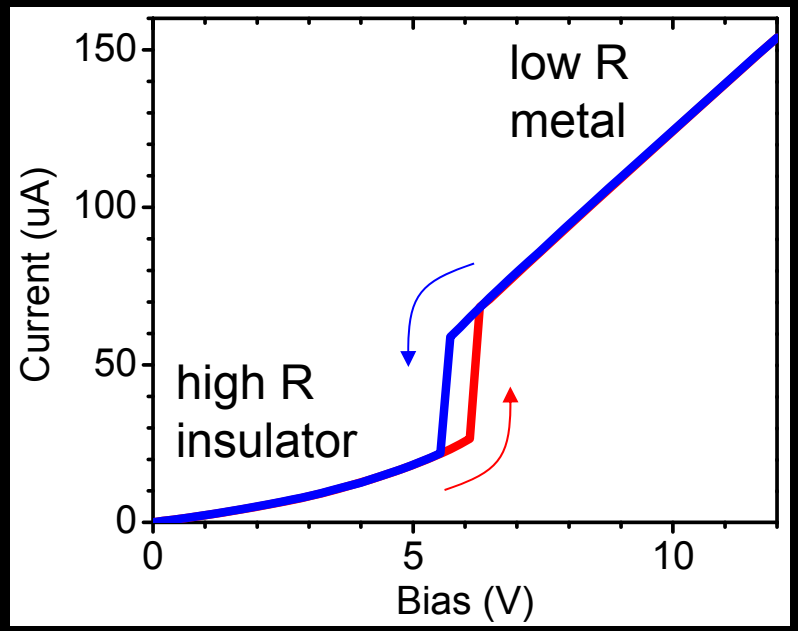
Kim, Ko, Frenzel, Ramanathan, Hoffman, APL 96, 213106 (2010)

Local probe: conducting force microscope



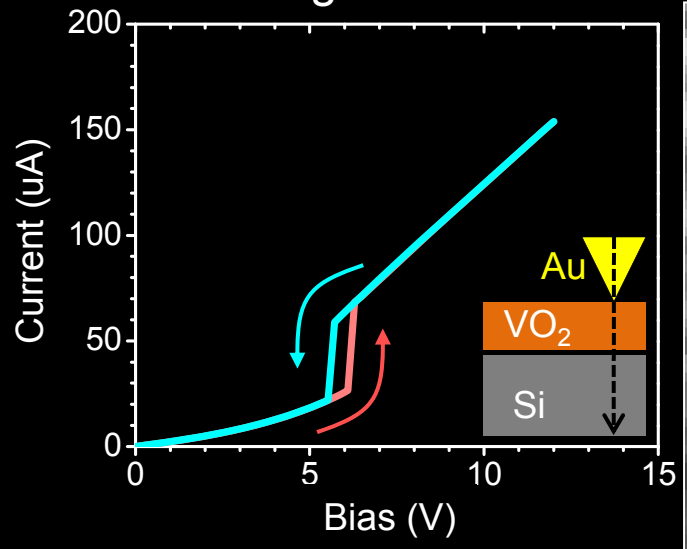
built by Dr. Jeehoon Kim



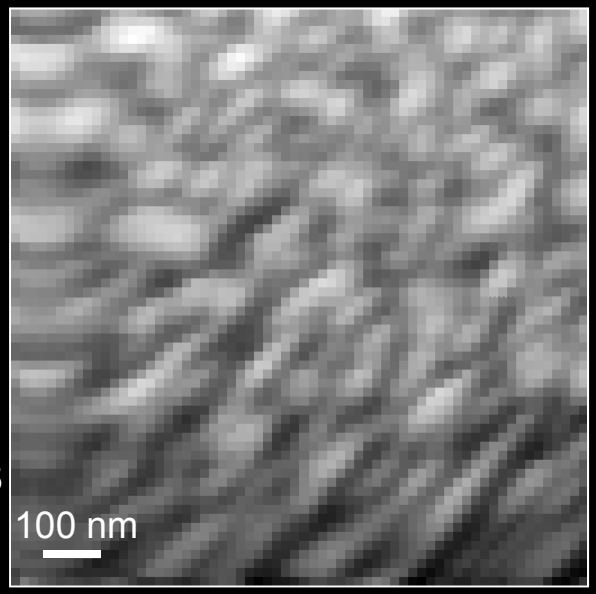


IV map

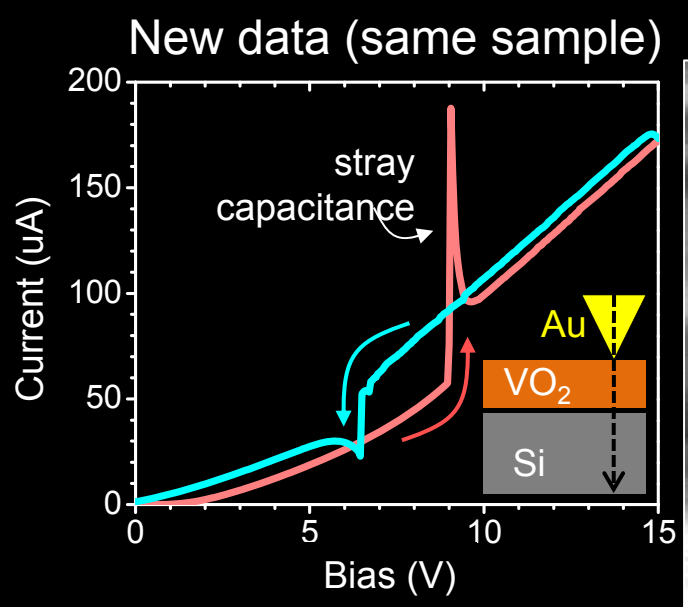
Original data

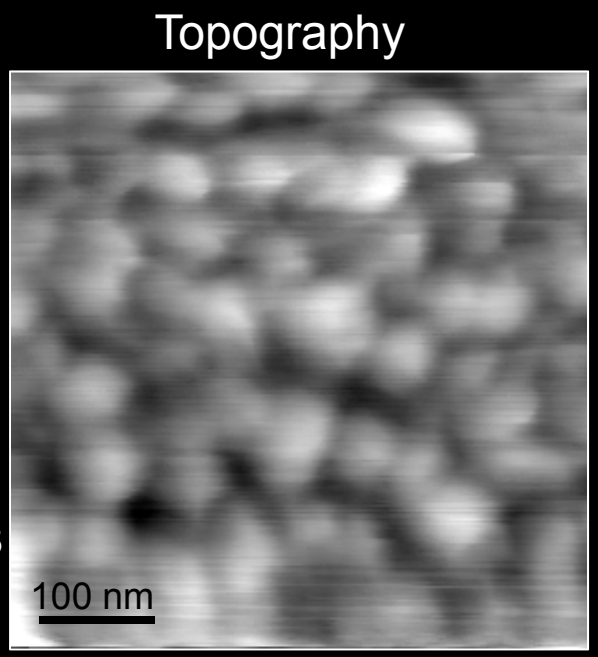


Topography

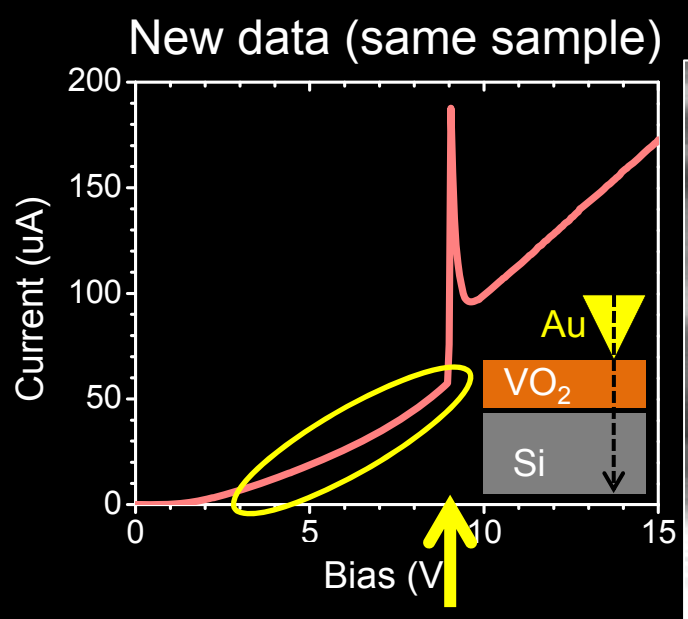


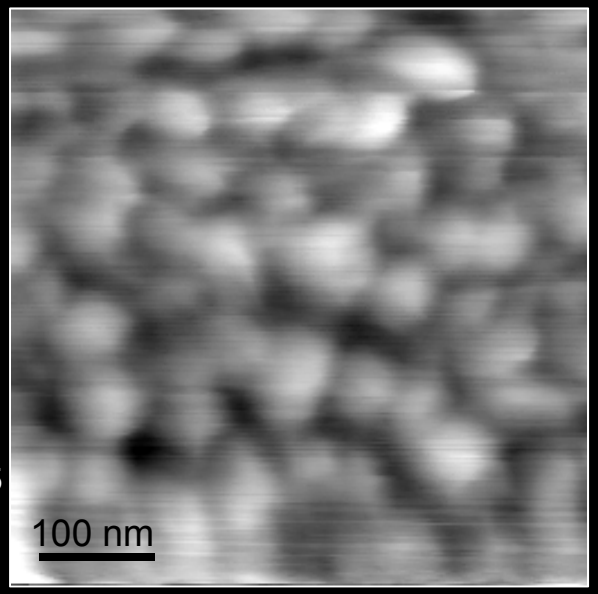
High-resolution IV map





High-resolution IV map



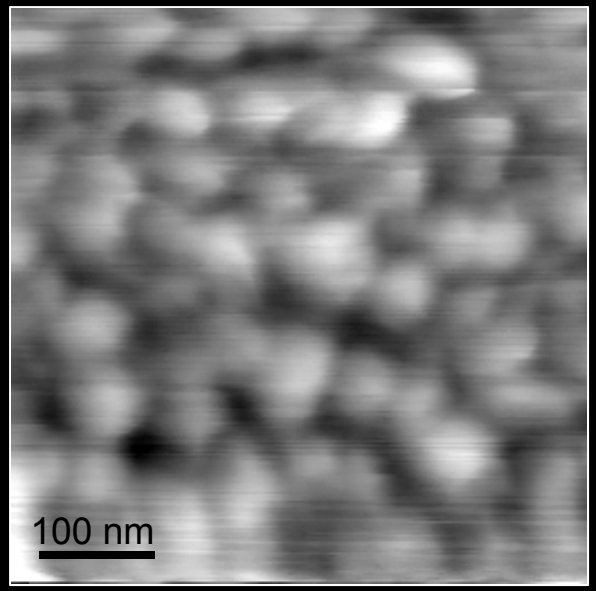


High-resolution IV map

V at transition

÷

Topography



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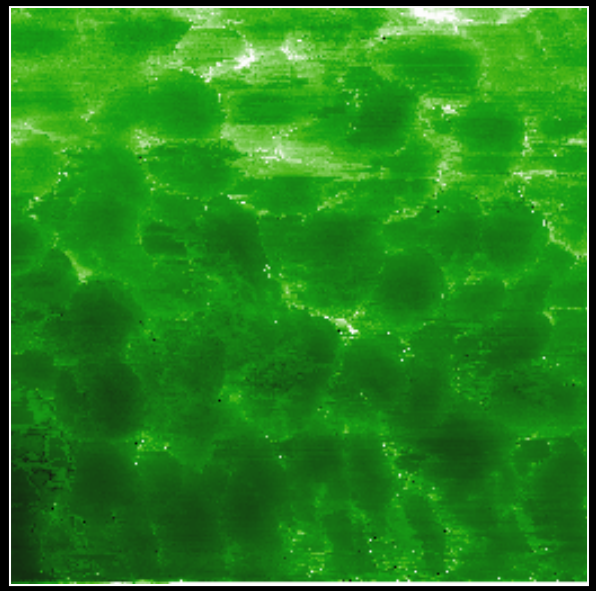
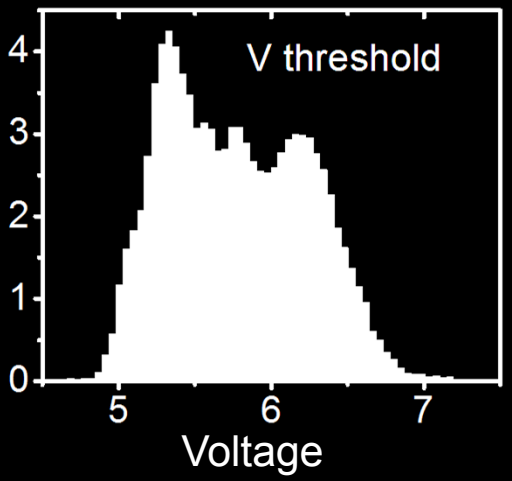
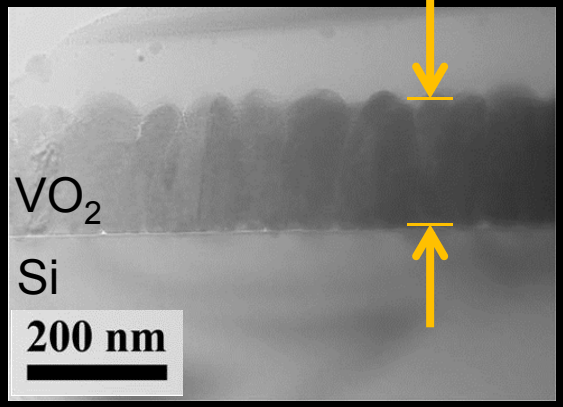
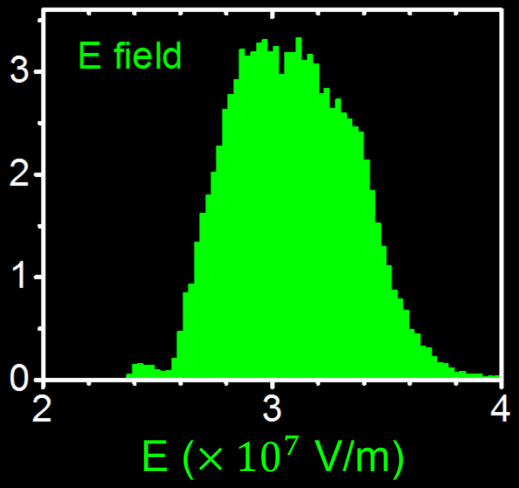
E-field





TEM: $\langle d \rangle = 187 \pm 13$ nm

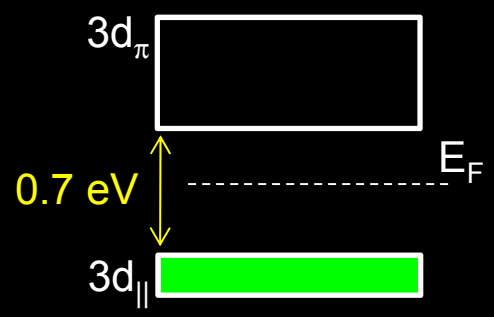




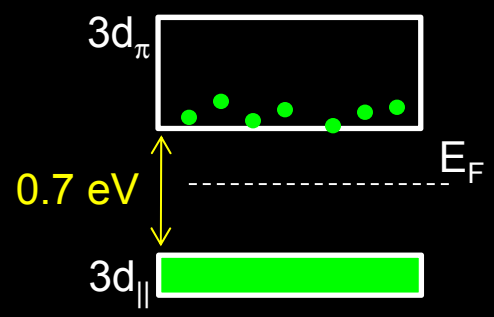
But how can we get T at transition?

Poole-Frenkel effect

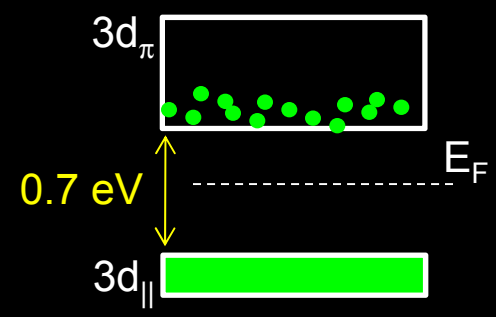
1. VO_2 at T=0, V=0:

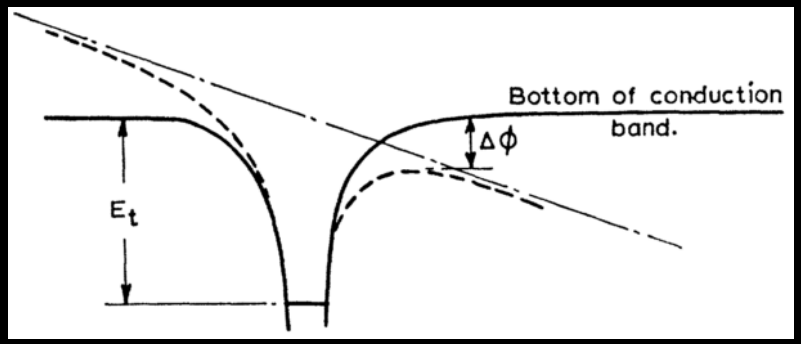


2. VO_2 at room T, V=0:



3. VO_2 at room T, V>0:





$$\sigma = \sigma_0 \exp\left[\frac{\sqrt{e^3 E/\pi\varepsilon_0\varepsilon}}{k_B T}\right]$$

$$\ln\left(\frac{I}{V}\right) = \underbrace{\frac{e^{3/2}}{\sqrt{4\pi\varepsilon_0}k_B}}_{\text{fundamental constants}} \frac{1}{\sqrt{d\varepsilon T}} V^{1/2} + C$$

temperature

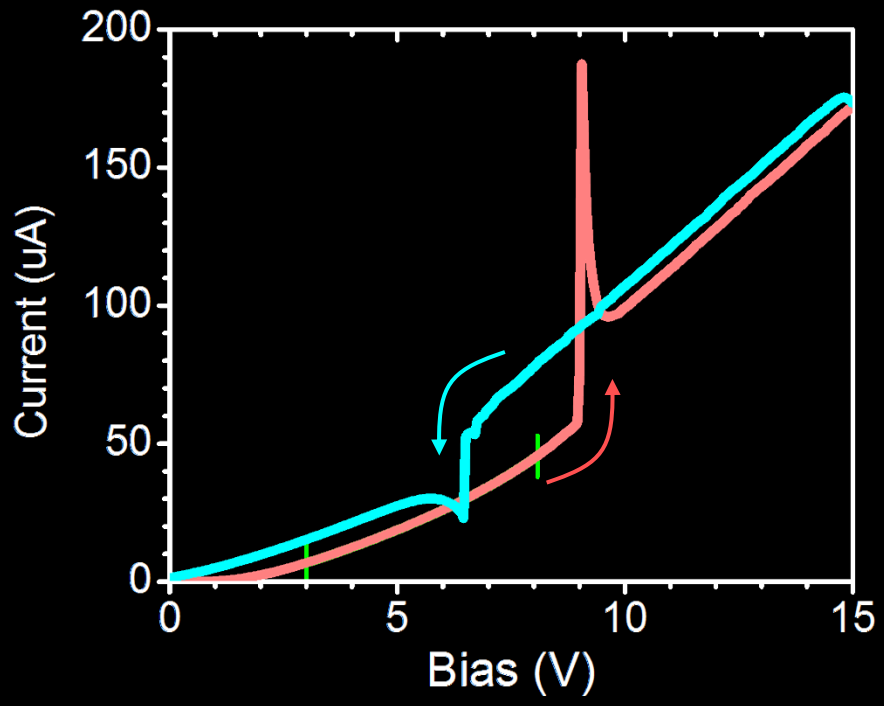
high freq. dielectric

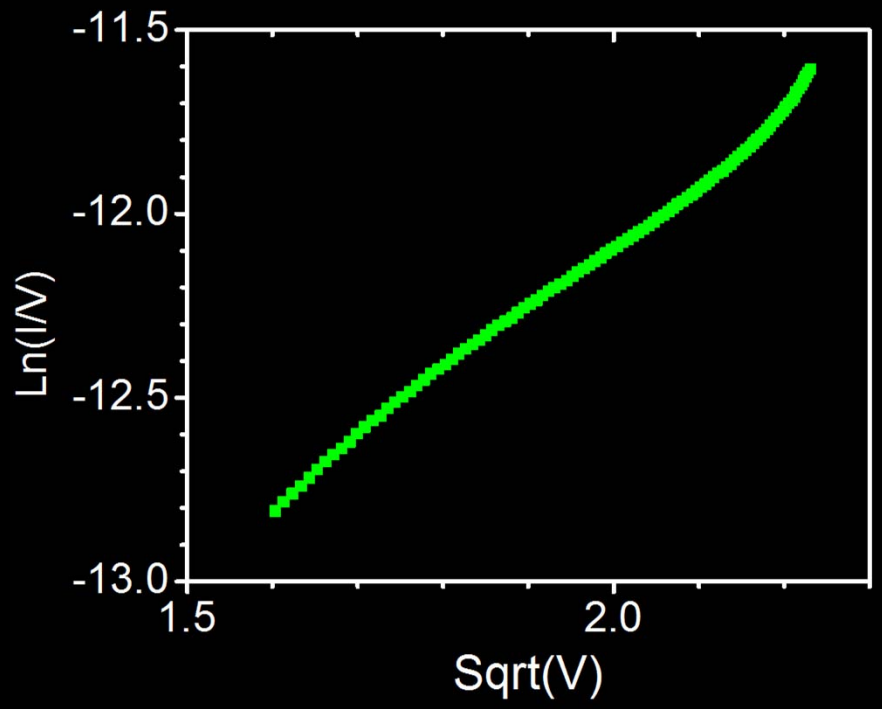
film thickness

Frenkel, Physical Review 54, 647 (1938)
Simmons, Physical Review 155, 657 (1967)

Poole-Frenkel slope

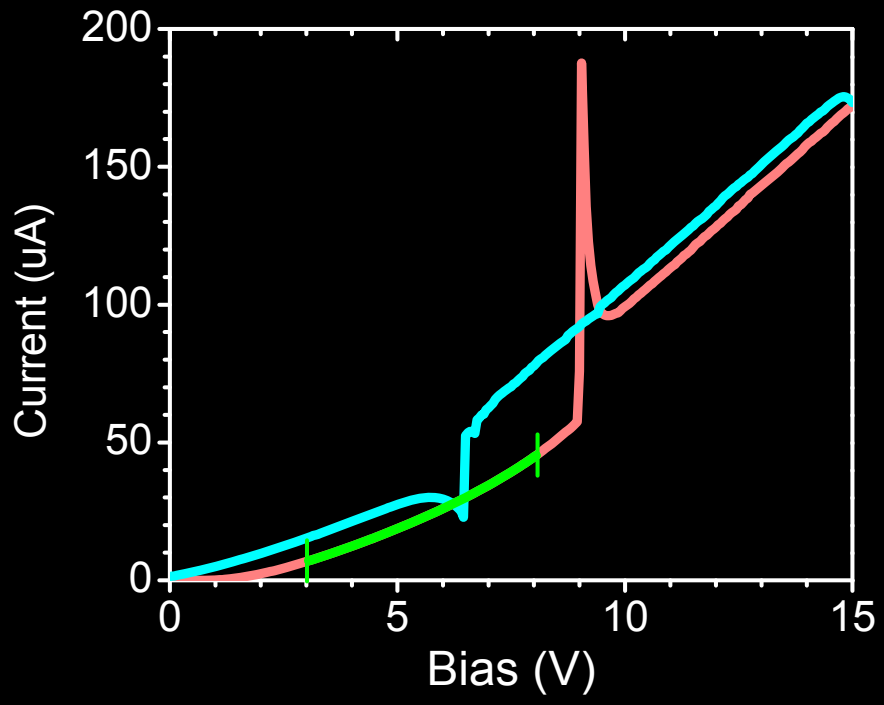
$$\ln\left(\frac{I}{V}\right) = \frac{e^{3/2}}{\sqrt{4\pi\varepsilon_0}k_B}\frac{1}{\sqrt{d\varepsilon T}}V^{1/2} + \mathrm{C}$$

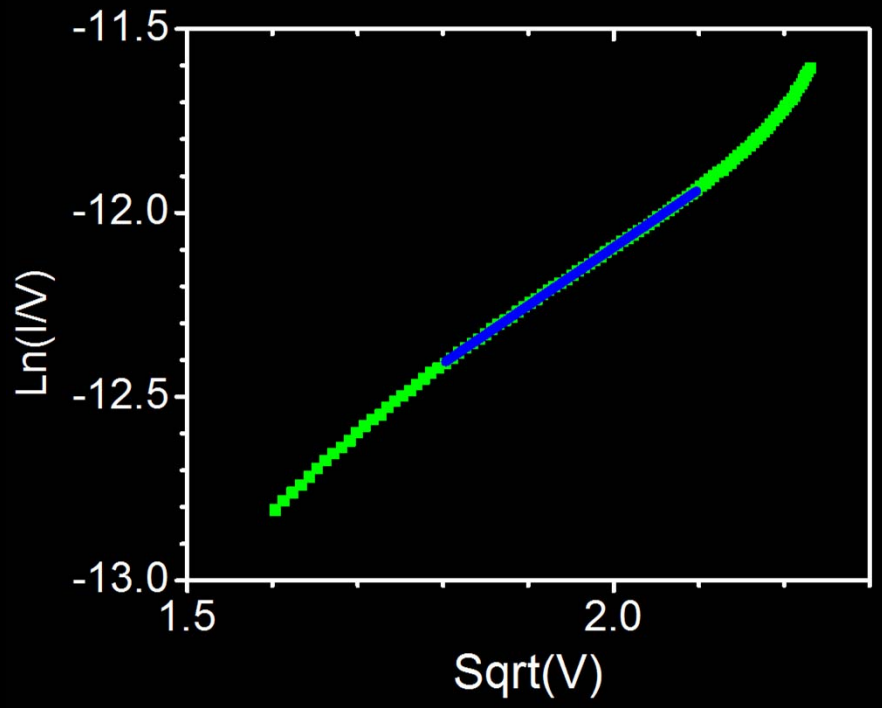




Poole-Frenkel slope

$$\ln\left(\frac{I}{V}\right) = \overbrace{\frac{e^{3/2}}{\sqrt{4\pi\varepsilon_0}k_B}\frac{1}{\sqrt{d\varepsilon T}}}^{\text{slope} \equiv P = 1.57} V^{1/2} + \mathrm{C}$$





Poole-Frenkel slope

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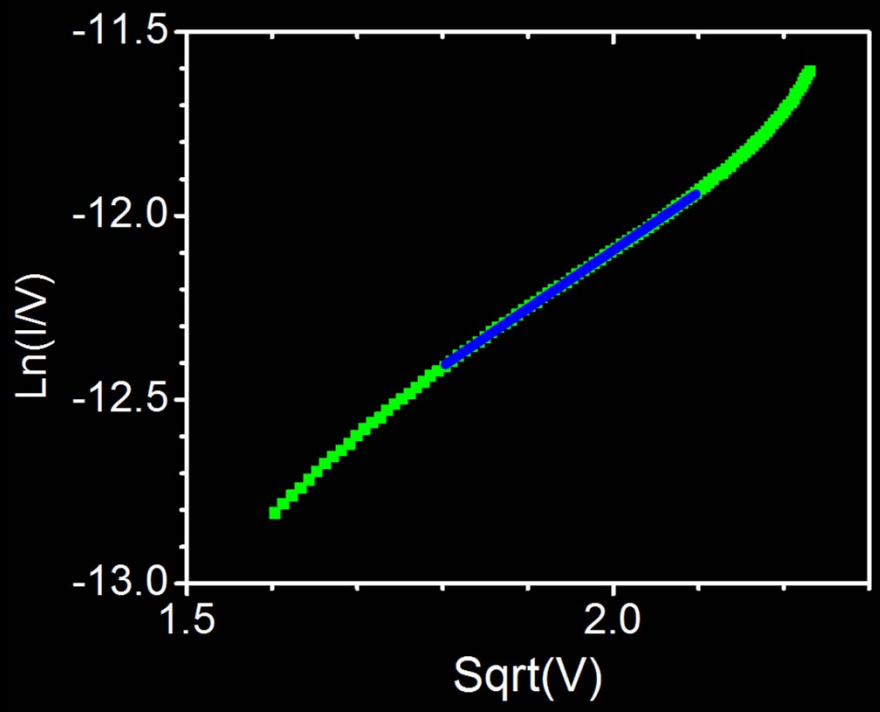
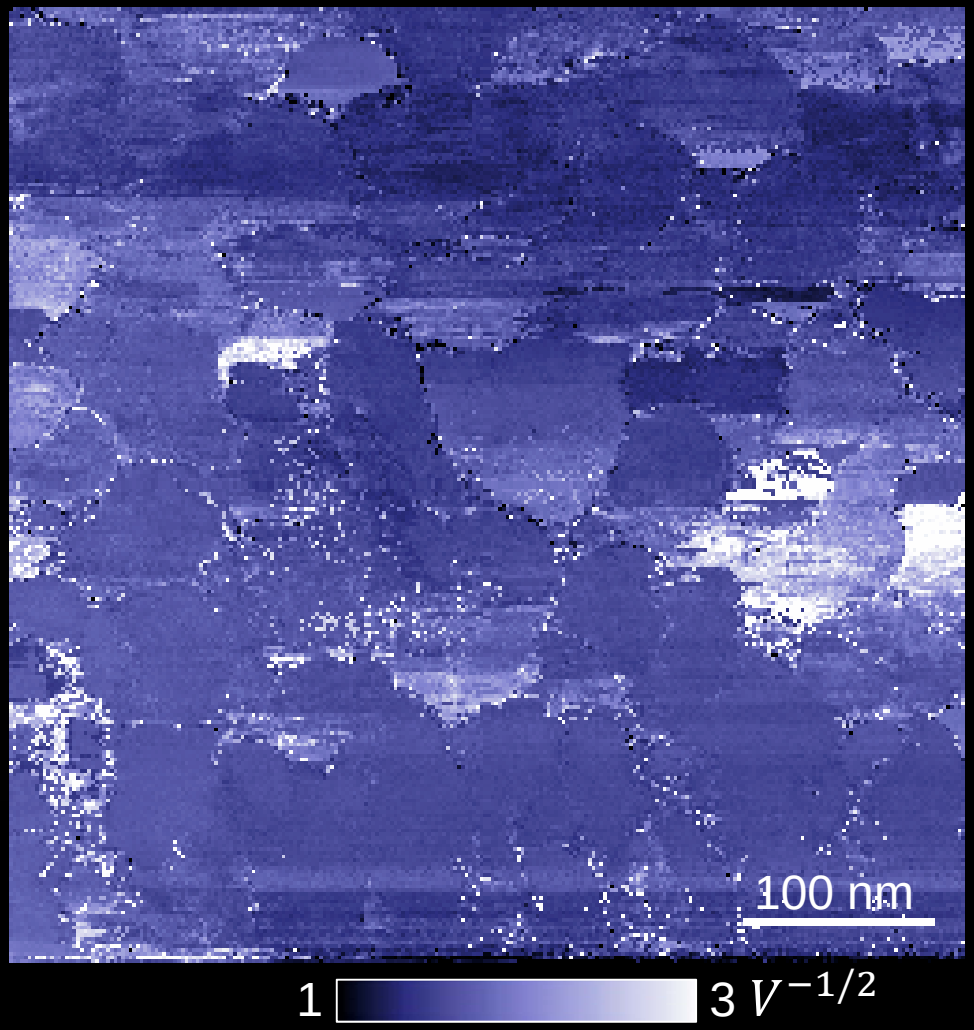


slope P



Solve for local temperature

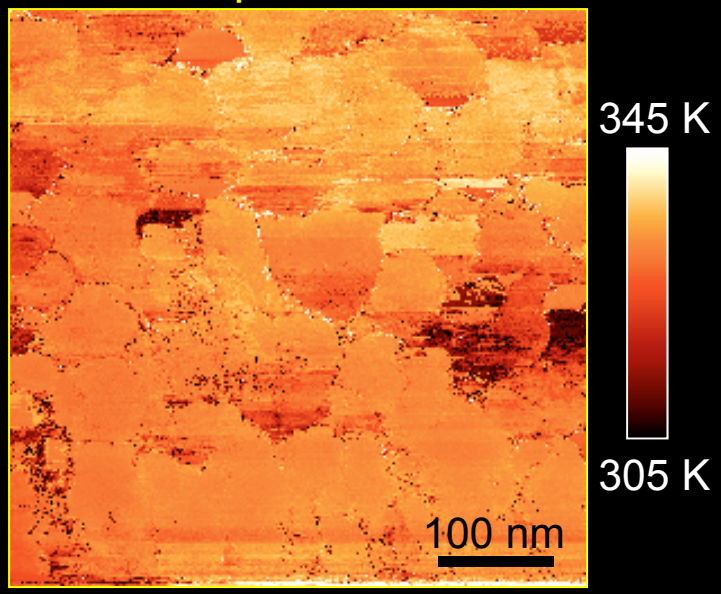
$$\ln\left(\frac{I}{V}\right) = \overbrace{\frac{e^{3/2}}{\underbrace{\sqrt{4\pi\varepsilon_0 k_B}}_{\text{fundamental constants}}}\frac{1}{\sqrt{d\varepsilon T}}}^{\text{slope} \equiv P = 1.57} V^{1/2} + \mathrm{C}$$

temperature

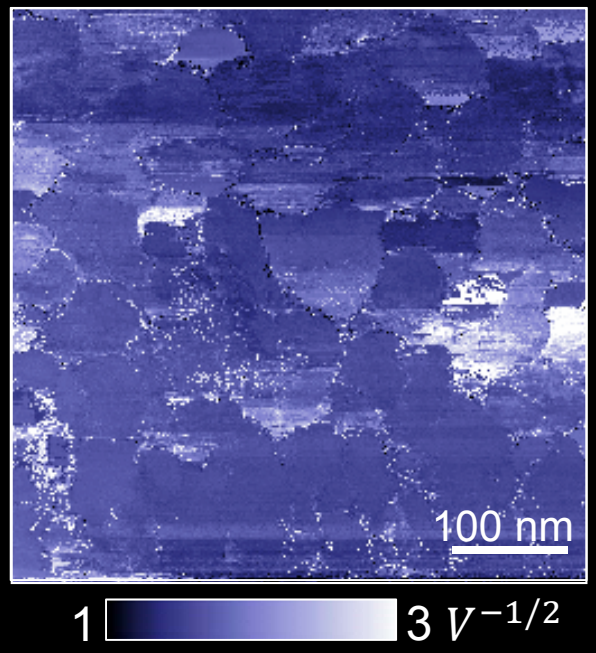
high freq. dielectric

film thickness

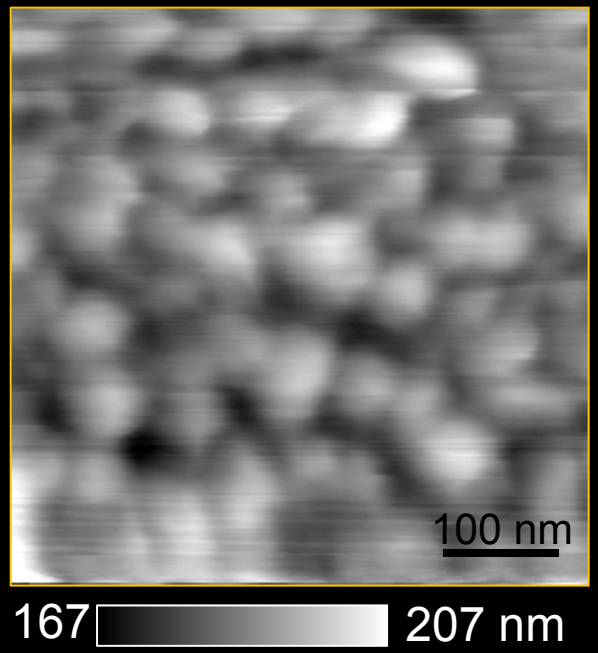
Temperature T



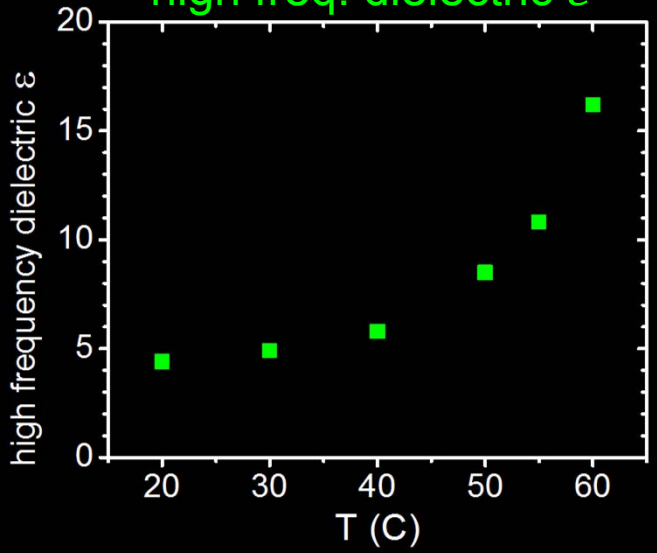
slope P



film thickness d

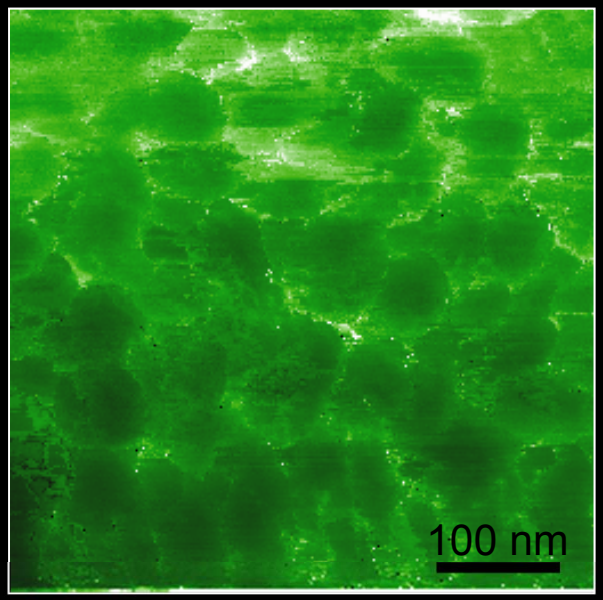


high freq. dielectric ε



Compare E-field vs. Temperature

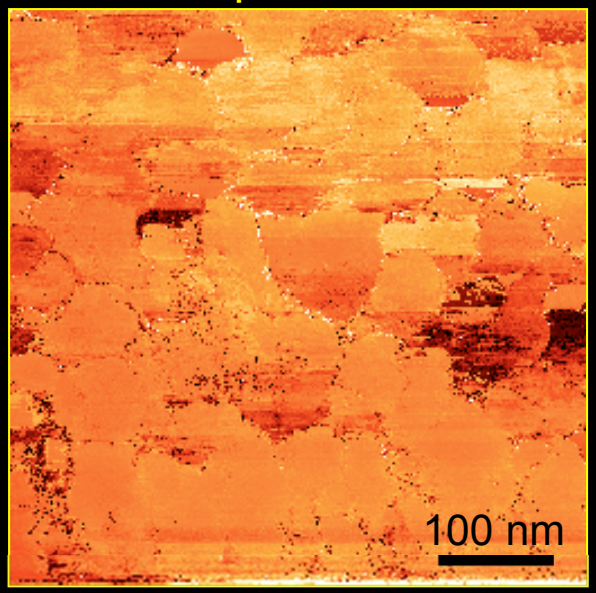
E-field



4×10^7 V/m

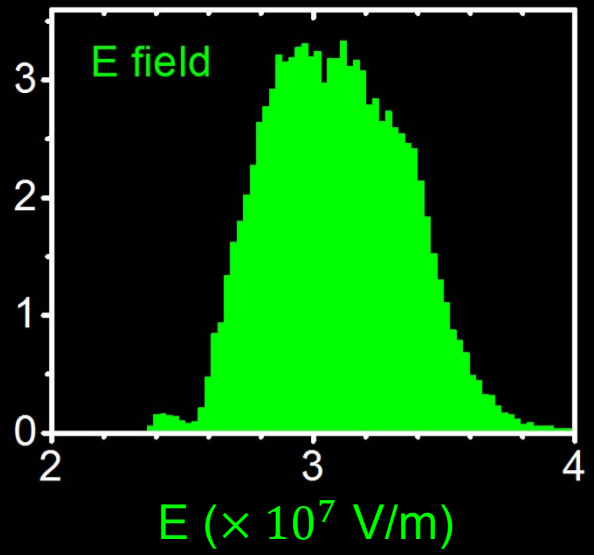
2×10^7 V/m

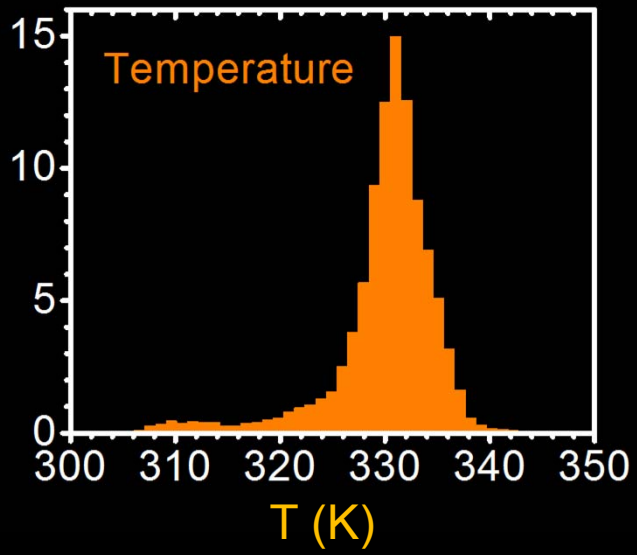
Temperature T



345 K

305 K



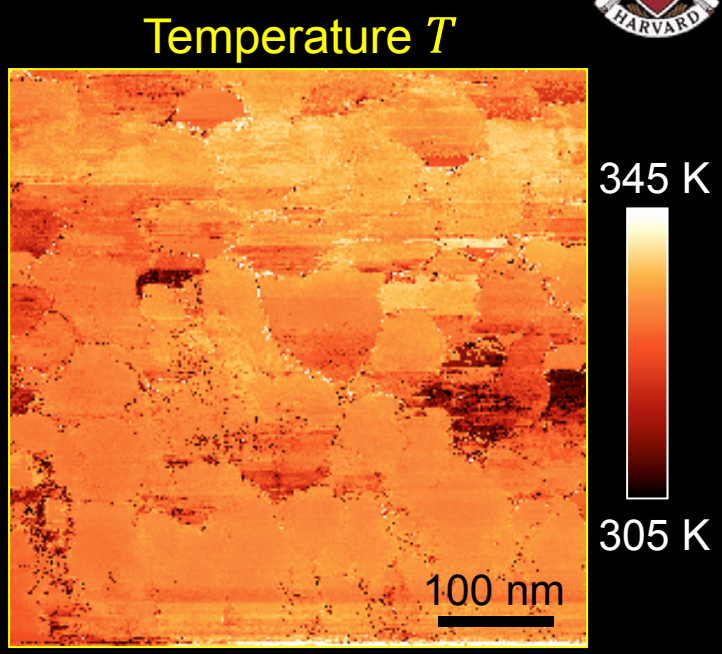


→ No special E-field

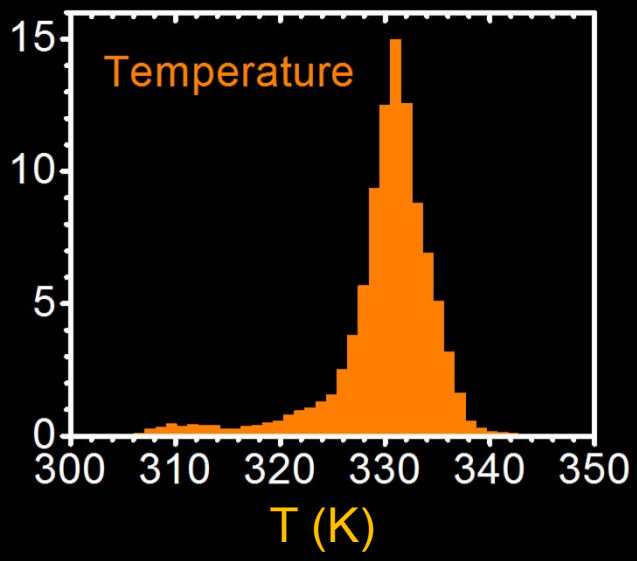
→ $T_{\text{avg}} = 332$ K (c.f. $T_c = 339$K)

Conclusions

1. Joule heating is primarily responsible for insulator-to-metal transition in VO_2 (2-terminal geometry on Si)



2. Poole-Frenkel mapping via conducting AFM provides a new general scanning technique for nanoscale T measurement on insulating films



$$\ln\left(\frac{I}{V}\right) = \frac{e^{3/2}}{\sqrt{4\pi\varepsilon_0}k_B}\frac{1}{\sqrt{d\varepsilon T}}V^{1/2} + C$$