"Thin film projects in collaboration with Jlab: SRF, FEL and Photocathode projects. The specific case of VO2 and the FEL collaboration"

R. A. Lukaszew
Distinguished VMEC Professor
Physics Department
College of William and Mary

Collaborators and funding

- SRF
  - C. Reece
  - L. Phillips
  - A-M. Valente-Feliciano
- FEL
  - G. Williams
  - M. Klopf
  - S. Madaras
- Photocathodes
  - M. Poelker
  - M. Sutzman
- Other collaborators:
  - I. Novikova (W&M)
  - R. Wincheski (NASA-Larc)
  - E. Madaras (NASA-Larc)
- Funding
  - DOE, DTRA, NSF, VMEC, NRI

Thin Film Projects

1. SRF: Thin film alternatives to improve field gradients in SRF cavities. (DOE, DTRA).

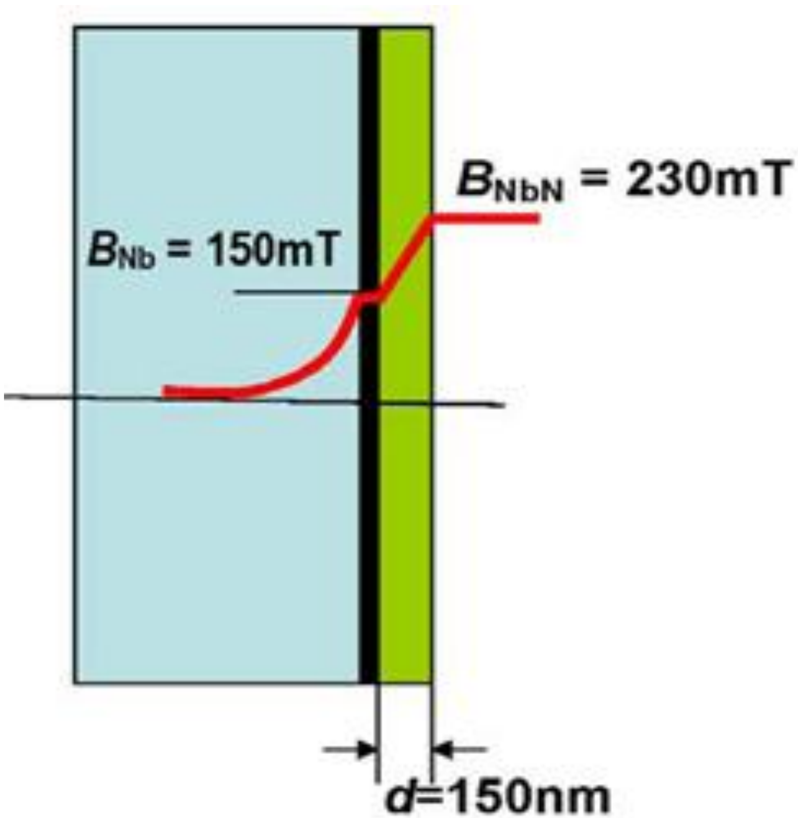
2. Photocathodes: novel materials for next generation acceleration sources (DOE).

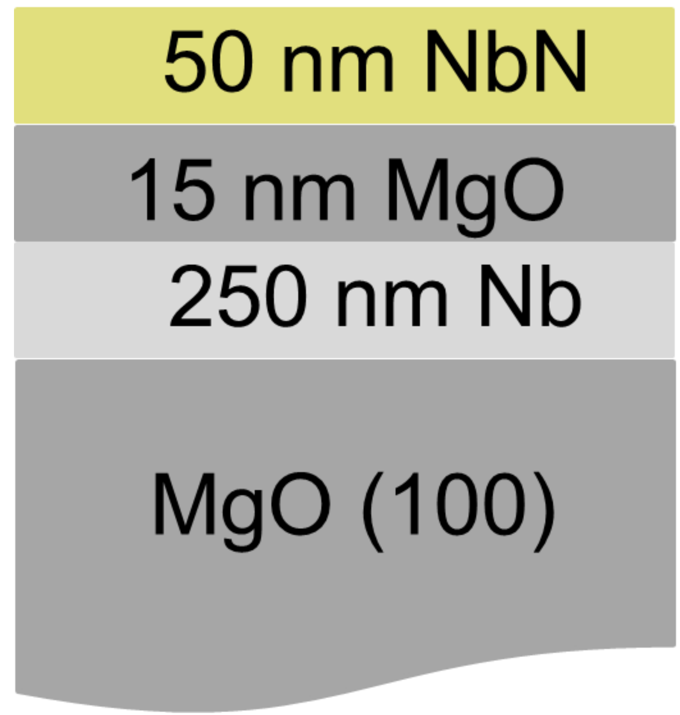
3. FEL: Fundamental studies on highly correlated thin film materials (NSF).

SRF

- Since 2010 we have been collaborating with the SRF group at Jlab in order to explore thin film venues to achieve higher field gradients than the maximum attainable limit using bulk Nb.
- We have achieved success demonstrating the feasibility of achieving shielding beyond bulk Nb using a multilayer approach proposed by A. Gurevich.
- Several peer reviewed publications have resulted from this effort as well as international and local conference presentations. Two graduate students – Doug Beringer and Will Roach- have received awards for their research efforts and are about to obtain their PhD degrees based on their work related to this project.
- We continue working toward optimization of the multilayer approach with alternative SC materials.

"Gurevich" model

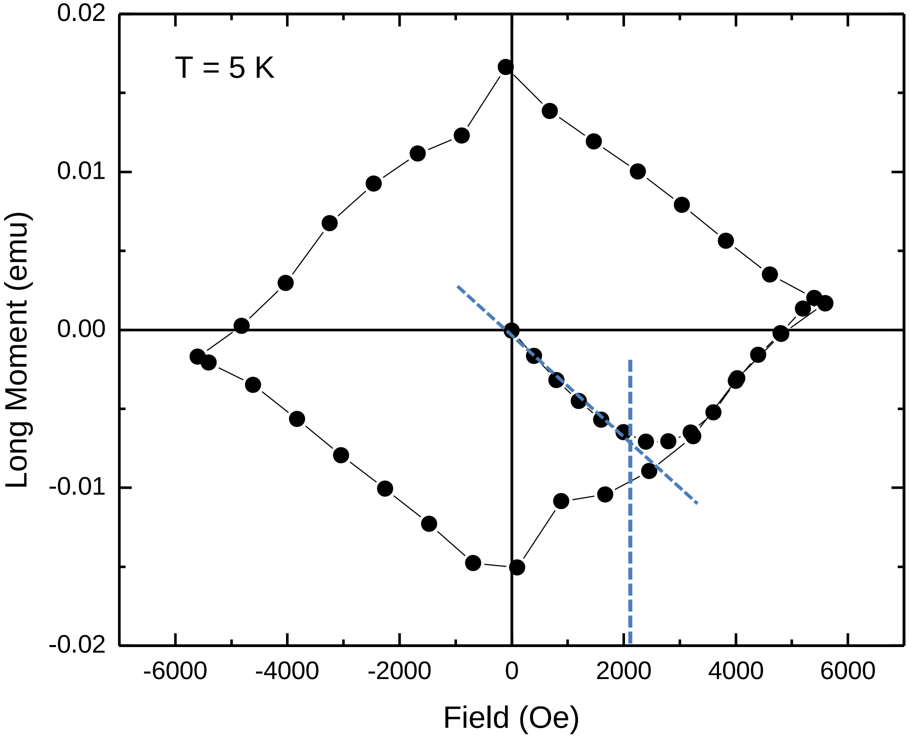




- Theoretical illustration of magnetic field screening by a candidate SIS system. 1
  - Adapted from: A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006)

Test sample

Nb/NbN multilayer

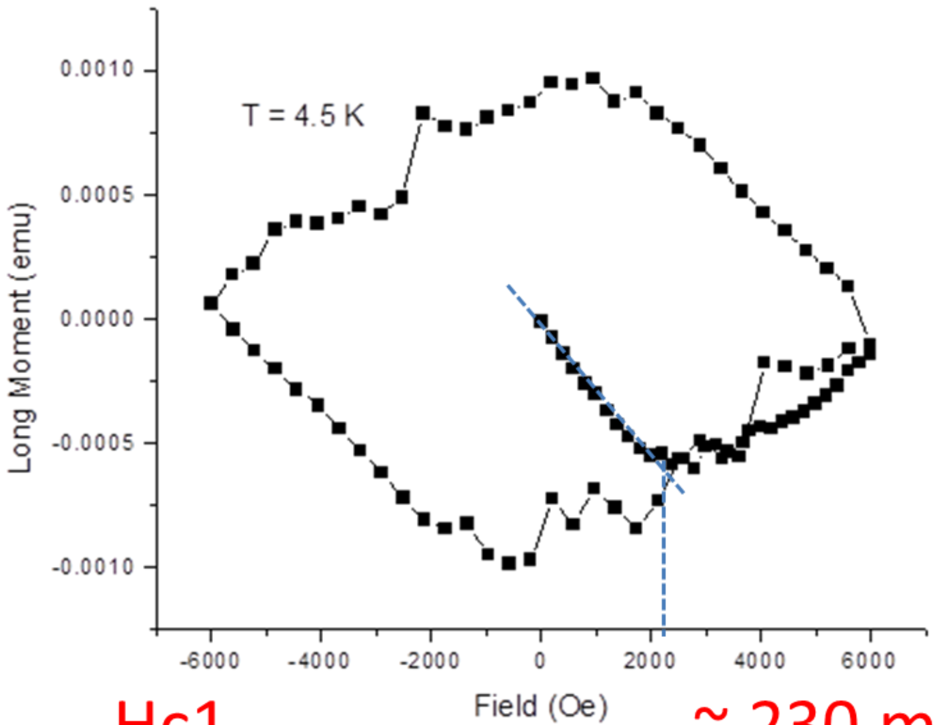


$Hc1_{NbN\text{-}based\text{-}Multilayer} > 200$ mT!

$Hc1_{TFNb} = 180$ mT

$Hc1_{bulk\ Nb} = 200$ mT

Both Nb and NbN in superconducting state



$Hc1_{NbN\text{-}based\text{-}Multilayer}$ ~ 230 mT!

$Hc1_{TFNb}$ = 180 mT

$Hc1_{bulk\ Nb}$ = 200 mT

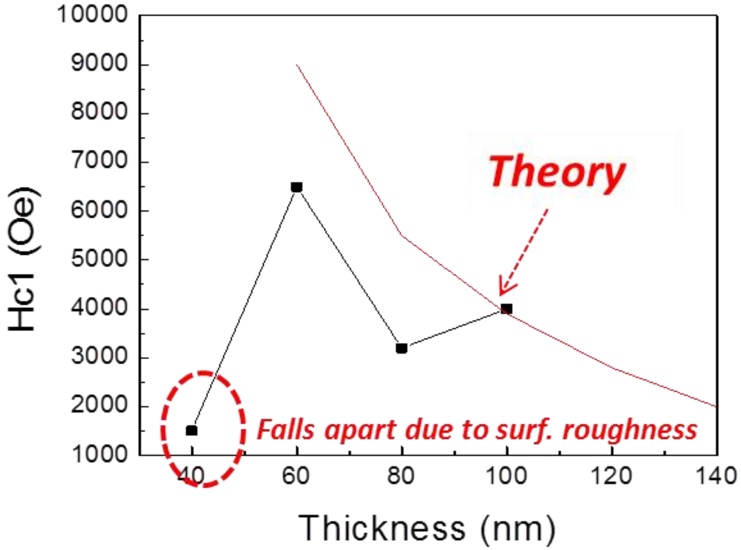
Additional studies: MgB_2 thin films

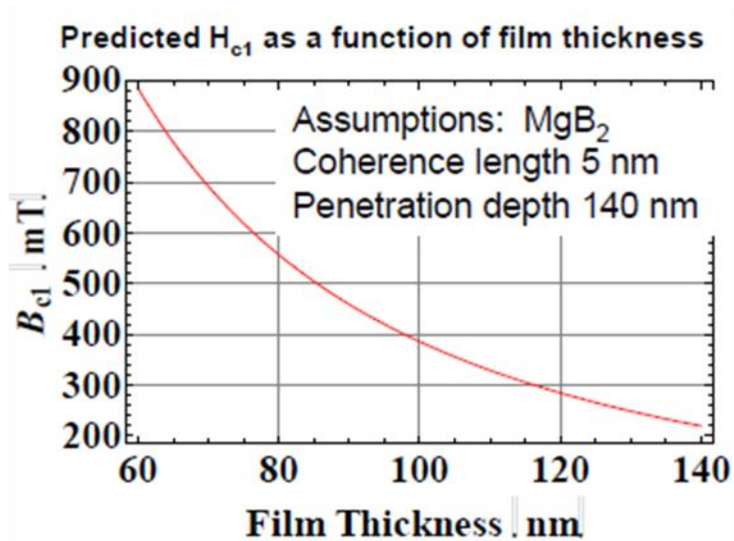
We have initiated investigations on ***MgB$_2$ thin films***.

$$B_{c1} = \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\tilde{\xi}}, \quad d < \lambda$$

[Gurevich, APL 88 (2006) 012511]

"Thickness dependence of superconducting properties in MgB$_2$ thin films", D. Beringer, T. Tan, X. Xi, C. Clavero, C. Reece, A-M. Valente-Feliciano, R. A. Lukaszew, *5th International Workshop on "Thin films applied to Superconducting RF and new ideas for pushing the limits of RF Superconductivity" , Jlab. July 18-20, 2012.*

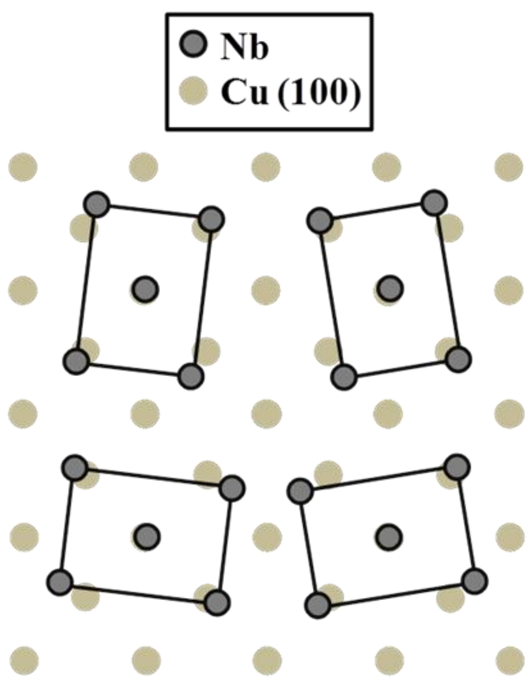


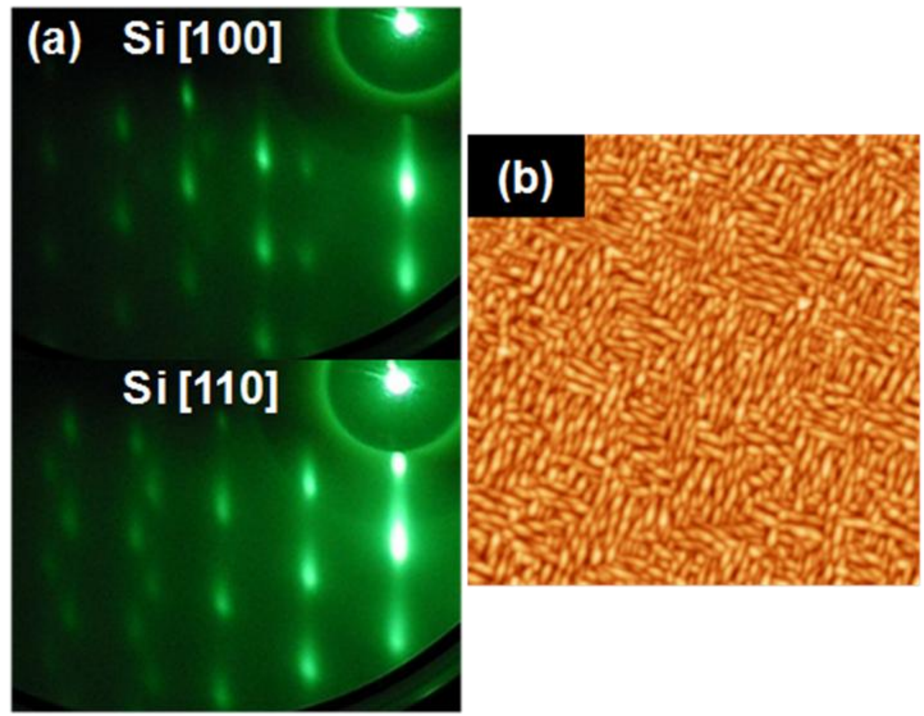


Nb films on Cu (001) surfaces

We have also carried out additional studies on the ***growth of Nb films on Cu substrates***.

Possible Nb/Cu(100) epitaxy:

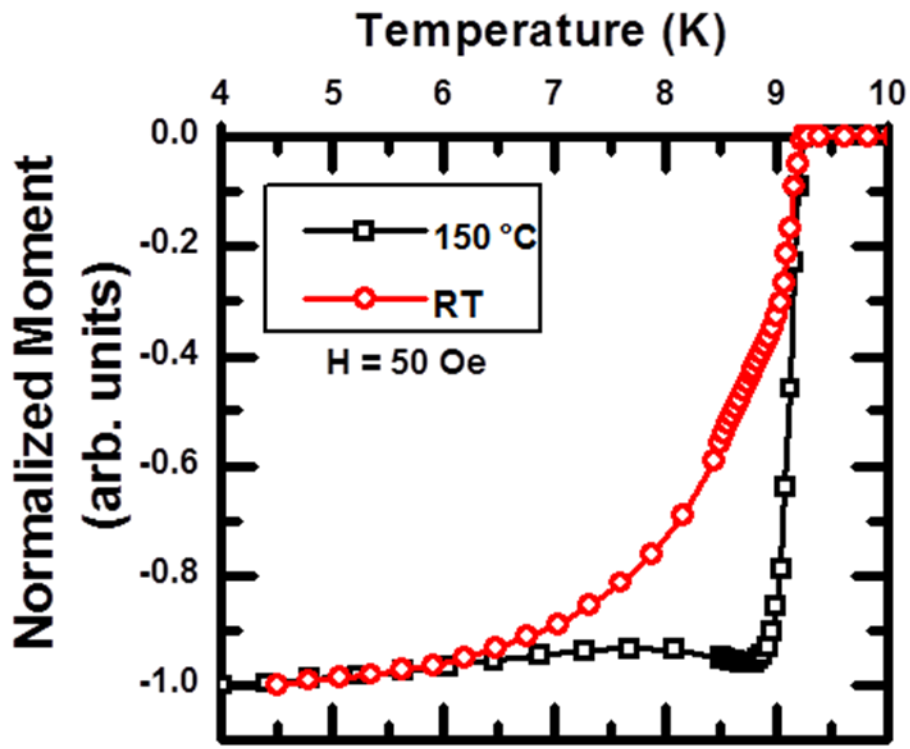




(a) RHEED pattern for Nb(110)/Cu(100)/Si(100) along the Si[100] and Si[110] azimuths. (b) A representative 2 µm x 2 µm AFM scan for Nb films on the Cu template.

SC properties for different growth T

- The films grown at 150 °C have a very sharp transition from the superconducting state to the normal state that begins at ~9 K while films grown at RT have a much more gradual transition.
- Our results suggest that an increased deposition temperature of Nb onto Cu leads to films with higher crystalline quality (grain size) and thus improved superconducting properties (HC1).



***Niobium thin film deposition studies on copper surfaces for superconducting radio frequency cavity applications*, W. M. Roach, D. B. Beringer, J. R. Skuza, W. A. Oliver, C. Clavero, C. E. Reece, and R. A. Lukaszew, *Phys. Rev. ST Accel. Beams* 15, 062002 (2012).**

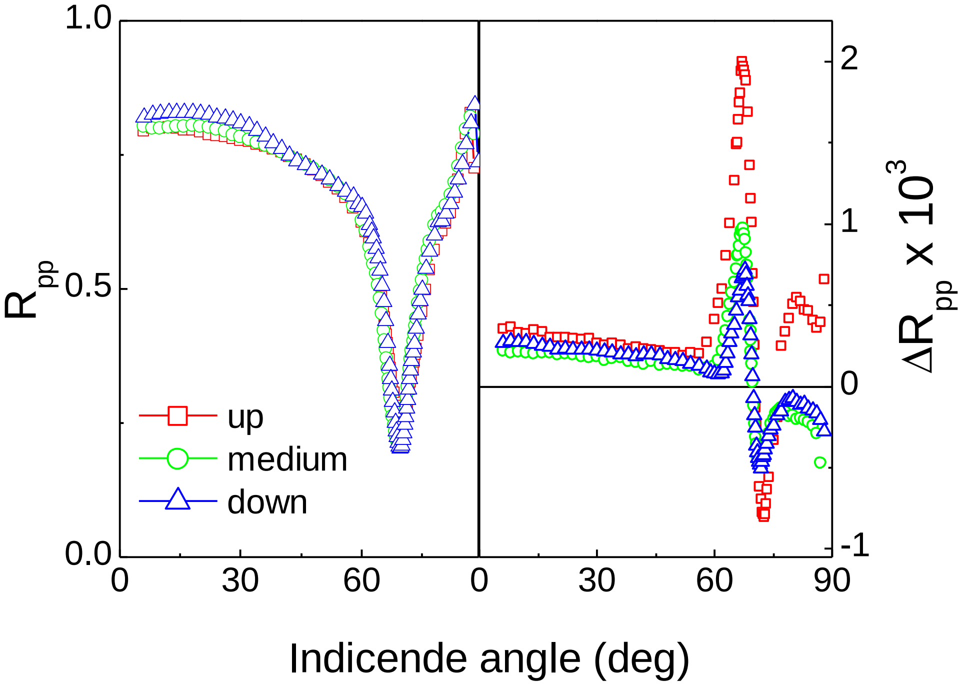
Publications

- Strain Effects on the Crystal Growth and Superconducting Properties of Epitaxial Niobium Ultrathin Films, C. Clavero, D. B. Beringer, W. M. Roach, J. R. Skuza, K. C. Wong, A. D. Batchelor, C. E. Reece, and R. A. Lukaszew, *Cryst. Growth Des*., **12** (5), pp 2588–2593 (2012)
- Niobium thin film deposition studies on copper surfaces for superconducting radio frequency cavity applications, W. M. Roach, D. B. Beringer, J. R. Skuza, W. A. Oliver, C. Clavero, C. E. Reece, and R. A. Lukaszew, *Phys. Rev. ST Accel. Beams* **15**, 062002 (2012).
- Surface impedance measurements of single crystal MgB2 films for radiofrequency superconductivity applications , B. P. Xiao, X. Zhao, J. Spradlin, C. E. Reece, M. J. Kelley, T. Tan, and X. X. Xi, *Supercond. Sci. Technol.* **25**, 095006 (2012).
- Roughness analysis applied to niobium thin films grown on MgO(001) surfaces for superconducting radio frequency cavity applications by D. B. Beringer, W. M. Roach, C. Clavero, C. E. Reece and R. A. Lukaszew, *Phys. Rev. ST Accel. Beams 16, 022001 (2013).*
- NbN thin films for superconducting radio frequency cavities, W M Roach, J R Skuza, D B Beringer, Z Li, C Clavero, and R A Lukaszew, *Supercond. Sci.Technol*. 25, 125016 (2012).
- Study of Nb epitaxial growth onto Cu(111) at sub-monolayer level, by C. Clavero, N. P. Guisinger, S. G. Srinivasan, and R. A Lukaszew, *J. Appl. Phys.* 112, 074328 (2012).
- W. Roach, D. Beringer , Z. Li , C. Clavero , R. A. Lukaszew, “Magnetic Shielding Larger than the Lower Critical Field of Niobium in Multilayers”, *IEEE Trans. Appl. Supercond*. 23, 8600203 (2013).
- D. Beringer, C. Clavero, T. Tan, X. Xi, W. Roach, R. A. Lukaszew, "Thickness Dependence and Enhancement of HC1 in Epitaxial MgB2 Thin Films" accepted for publication *IEEE Transactions in Applied Superconductivity* (2013).

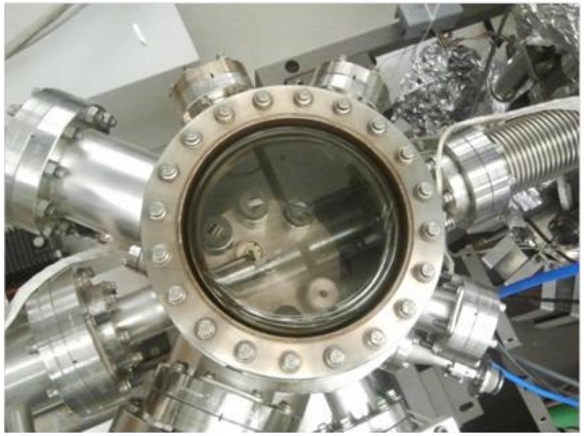
Photocathodes

- In 2012 we initiated a collaborative effort to explore novel schemes to achieve robust photocathodes for next generation accelerators. Two students –K. Yang and Z. Li- are involved in this project.
- This effort is based on the possibility to achieve enhanced QE using metallic films by exploiting surface Plasmon resonance (SPR).
- To achieve incident light k must match the k_{sp}. This can be achieved with oblique light incidence on a patterned surface with a grating.

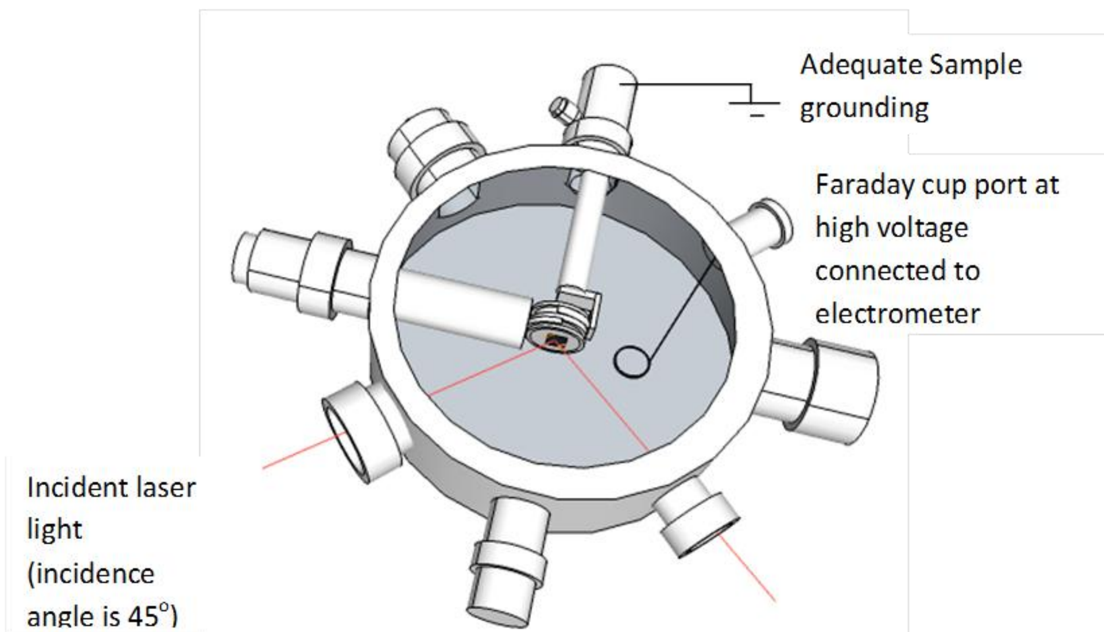
Surface plasmon excitation on metallic films on gratings



(a) Atomic force microscopy image of the grating on the glass/ Co (50 nm) / Au (5 nm) system. (b) reflectivity (left) and transverse magneto-optical Kerr effect ΔRpp=Rpp(H)-Rpp(-H) (right) for glass/ Au (80 nm) / Co (3.5 nm) / Au (dCo) trilayers with dAu= 3, 5 and 7 nm grown on 396 nm pitch gratings.



Left: Top view of the sample-introduction chamber showing all the available ports. *Right:* view of the sample-introduction chamber from the window that we will use to illuminate the sample for the photocurrent experiments.



FEL

- In 2011-2012 I spent a sabbatical research leave from W&M working as a research scientist at the FEL.
- I was able to participate in preliminary VUV tests.
- I was also able to carry out experiments using the FEL THz source. In what follows I will show details on our studies on the metal-insulator transition in VO_2 thin films under IR and THz probing.

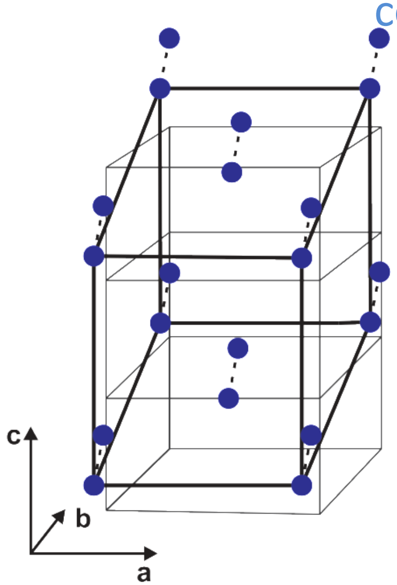
Outline

- Introduction to VO_2
- Experiments
  - ✓Bi-chromatic probing of heat induced MIT
- Results
- Conclusions
- Future plans

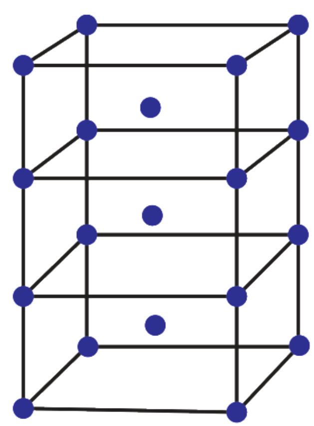
Properties of Vanadium dioxide (VO_2)

- Phase transition induced by
  - heating, around 340K
  - light pulses
  - electric fields
  - etc.

insulator $\underset{\text{cooling}}{\overset{\text{heating}}{\rightleftharpoons}}$ conductor



monoclinic structure (M1)



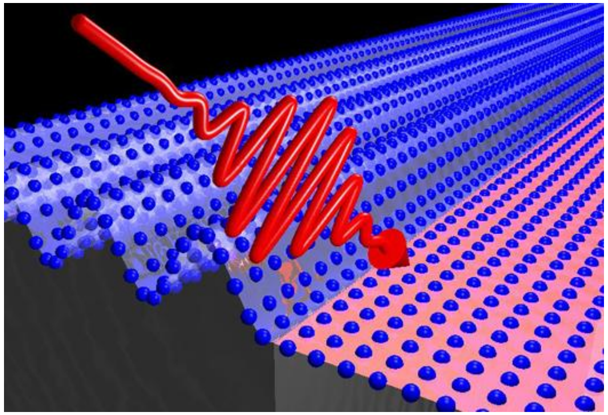
rutile structure (R)

Conductivity change:
- 10^6 for bulk
- 10^5 for thin films

Transmission change: transmission decreases from ~70% down to ~5% in the IR region

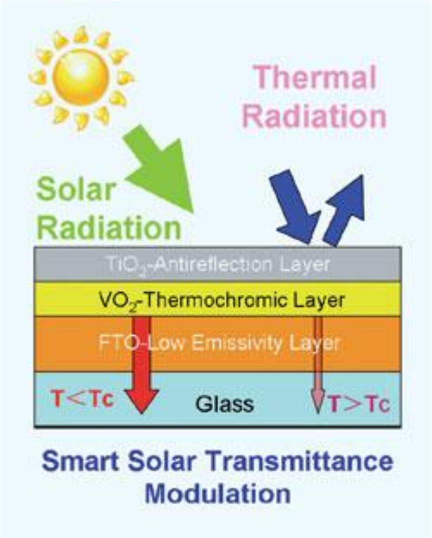
Applications of VO2

- Possible applications:
  - optical/electrical switches and sensors
  - smart window coatings
  - smart barrier for novel transistors
  - plasmonic applications
  - etc.



Copyright © Futurity.org

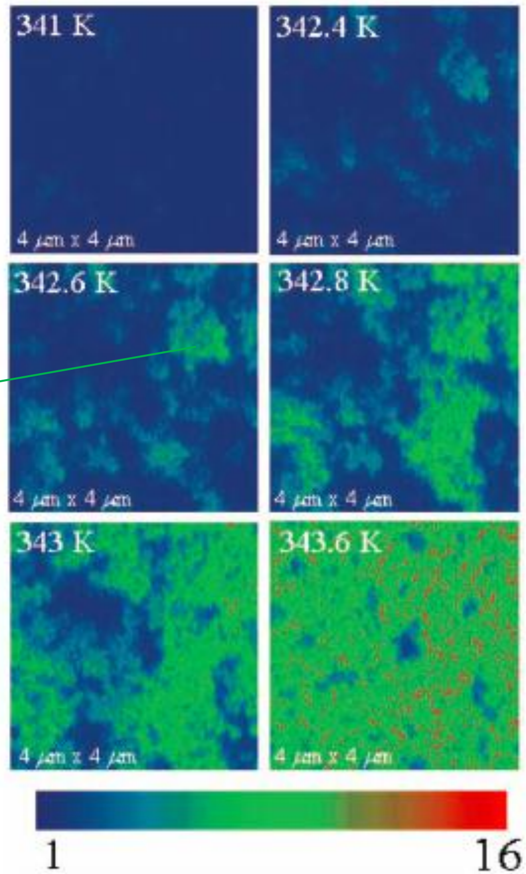
Copyright © Nanowerk



Zongtao Zhang, et.al. ,
Energy Environ. Sci., 2011,4, 4290-4297

- Mechanisms:
  - Peierls (electron-photon)
  - Mott-Hubbard (electron-electron)

Near-field microscopy technique

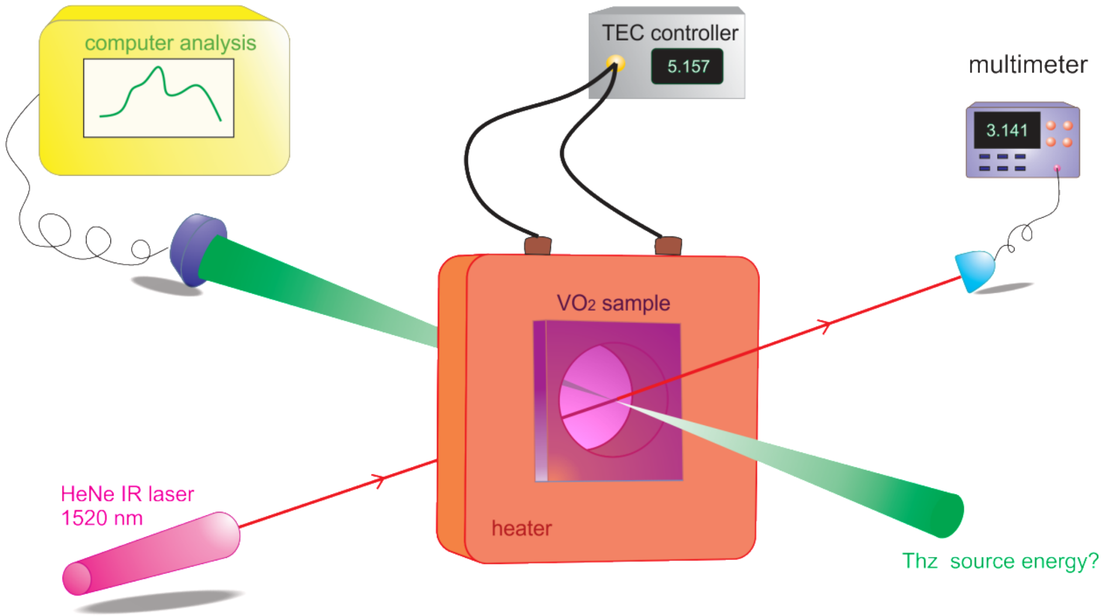


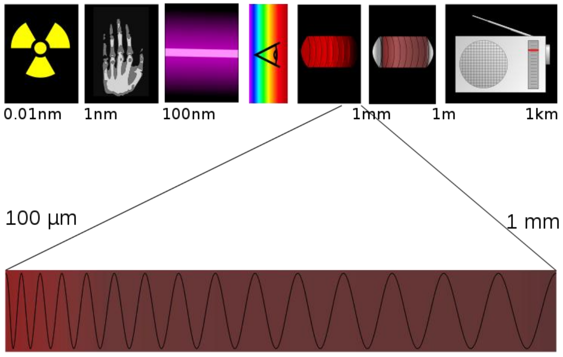
Metallic phase

Images of the near-field scattering amplitude over the same 4-μm-by-4-μm area obtained by s-SNIM
From M. Qazilbash *Science 318, 1750 (2007)*

Far-field detection?

Transmission measurement setup



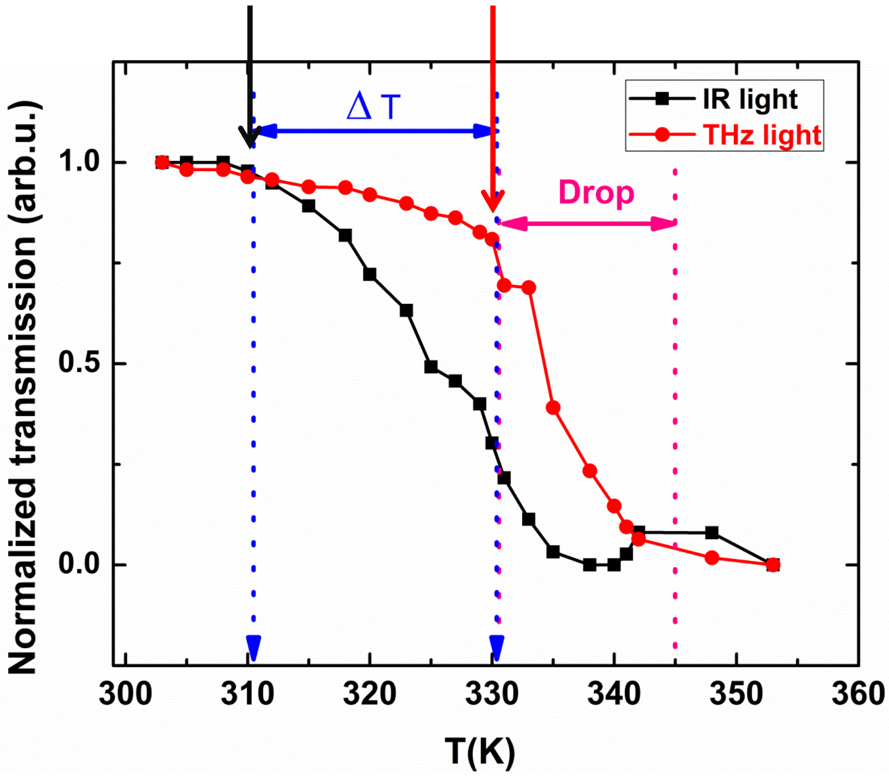


THz range copyright @ wikipedia

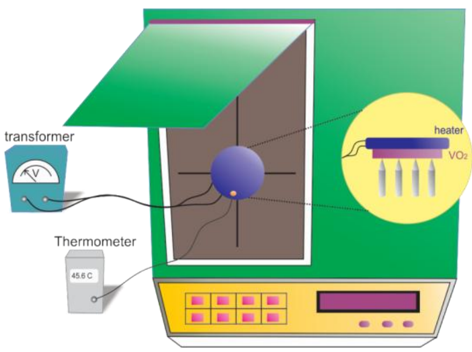
Wavelength Range (THz)	0.1 - 10
Pulse Length (ps)	0.2 - 2
Energy / pulse (microJoules)	2
Repetition Rate	1 Hz - 75 MHz
Total Power (watts)	150

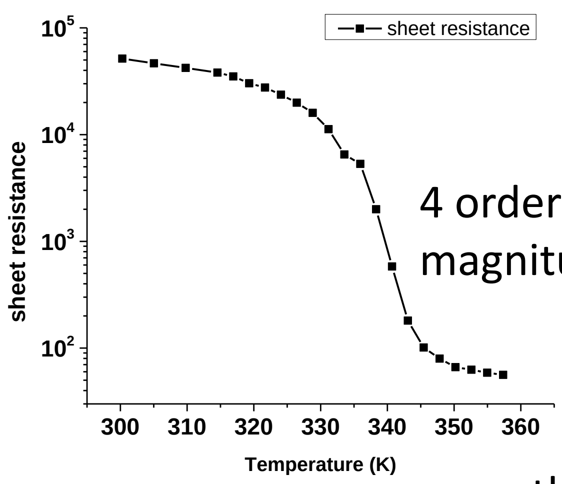
FEL building in Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Experimental results

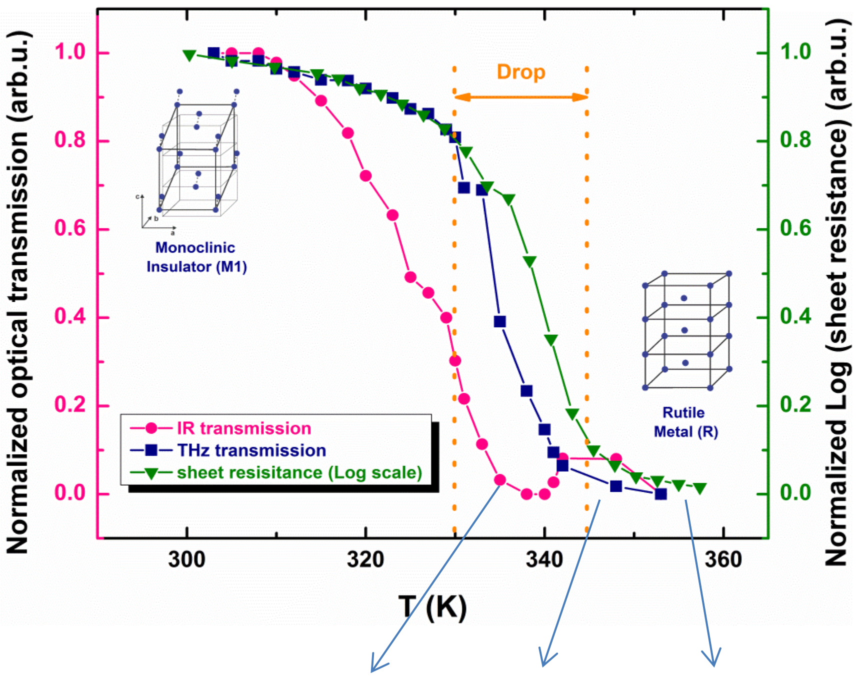


Sheet resistance measurement





4 orders of magnitude change!



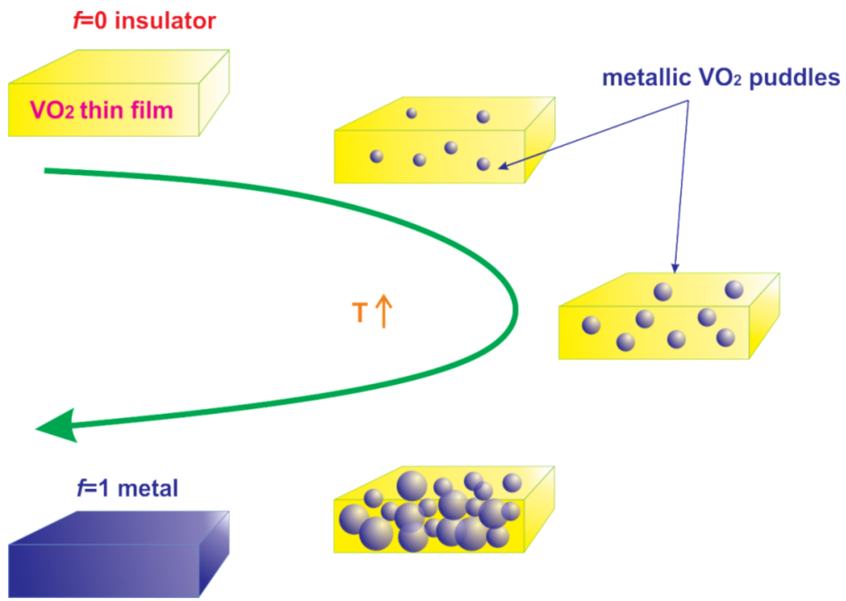
IR 1.5um

THz 300um

DC infinity

the sheet resistance measurement
could be considered as a DC measurement
which is equivalent to an infinite probe wavelength

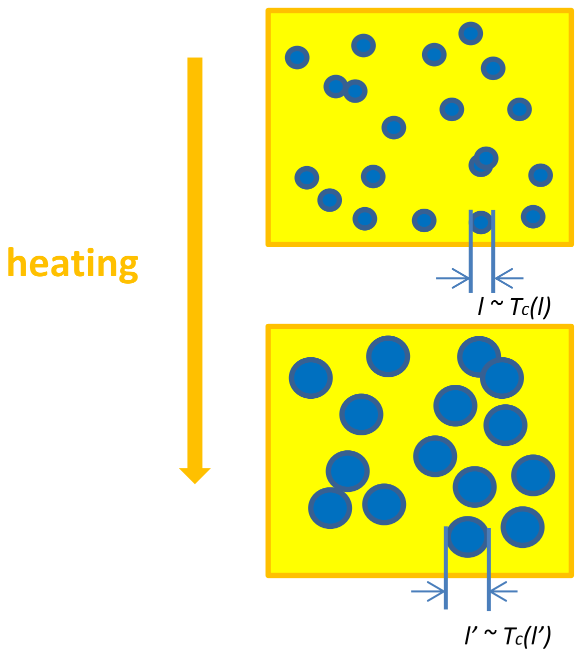
Nucleation model across MIT

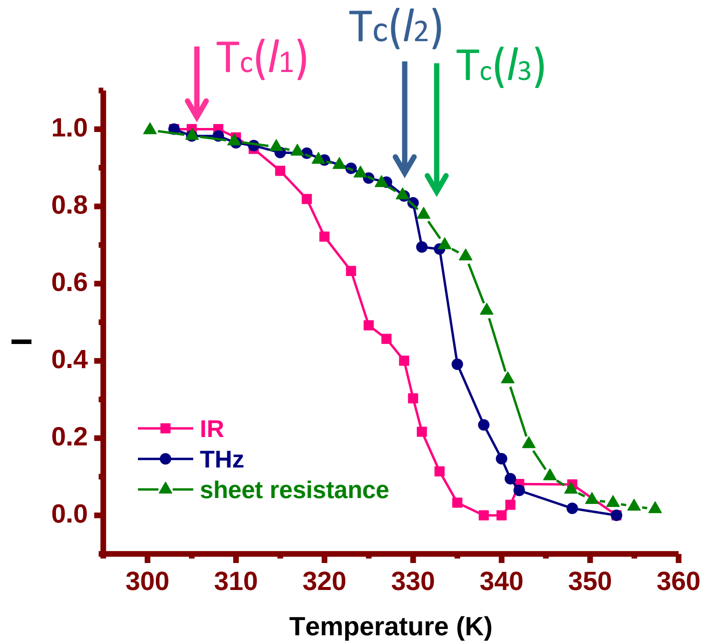


f is volume fraction of the metallic VO_2 puddles in the whole thin film.

When *f*=0, it stands for insulator state,
When *f*=1, it stands for metallic state.

Nucleation model

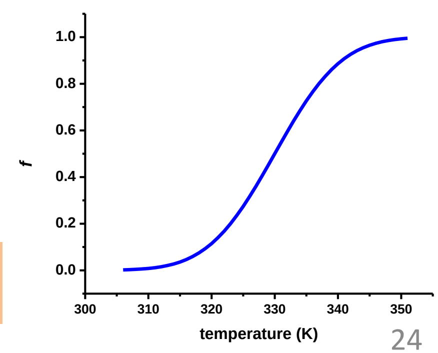




Suppose the numbers of metallic puddles formed at a given size "*l*" follows **Gaussian function**:

$$N(l) = Ae^{-[(l-l_o)/b]^2}$$

$$N(T) = Ae^{-\{[T_C(l)-T_C(l_0)]/b\}^2} = Ae^{-[(T-T_C)/b]^2}$$

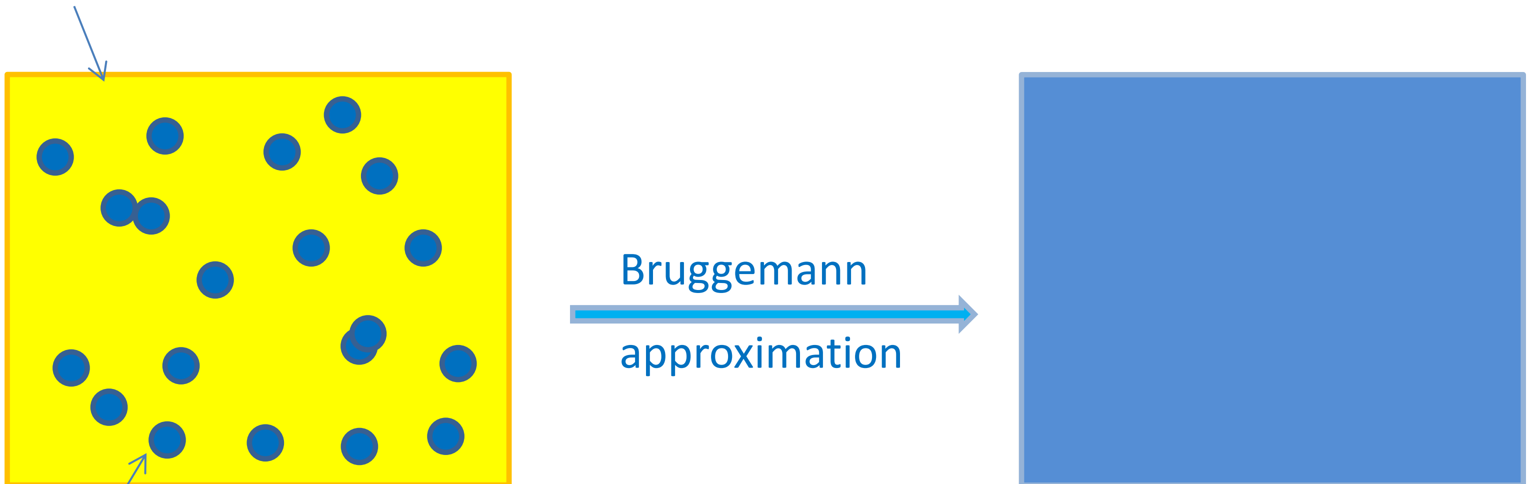


So the metallic phase fraction *f* is: $f = \int N(T)dT = f(A,b,T_c)$

Transmission fitting

$$f = \int N(T)dT = f(A,b,T_c) \qquad N(T) = Ae^{-\{[T_C(l)-T_C(l_0)]/b\}^2} = Ae^{-[(T-T_C)/b]^2}$$

VO2 insulating matrix

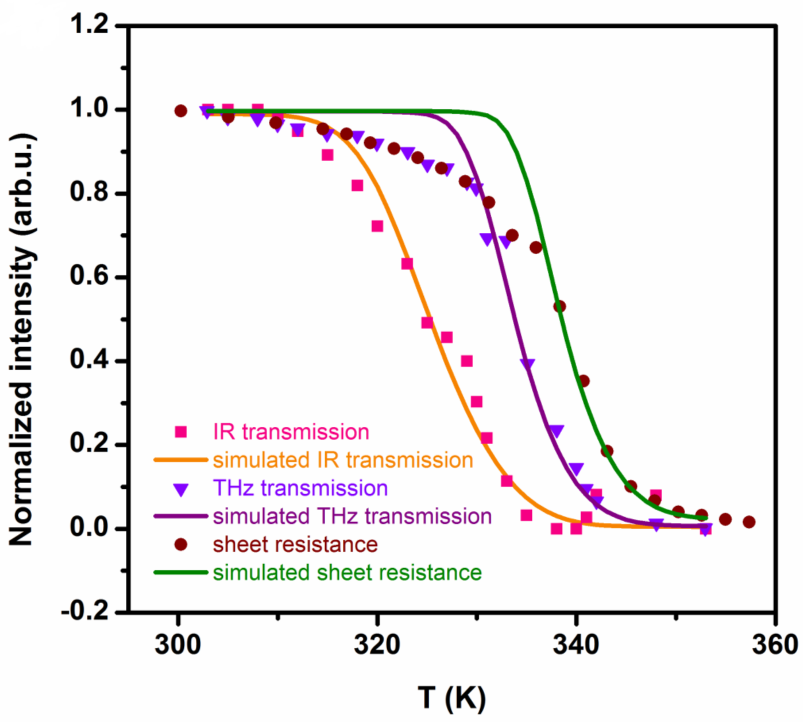


metallic puddles

homogeneous film

$$f\frac{\varepsilon-\varepsilon_{eff}}{\varepsilon+2\varepsilon_{eff}}+(1-f)\frac{\varepsilon_M-\varepsilon_{eff}}{\varepsilon_M+2\varepsilon_{eff}}=0$$

Simulation results

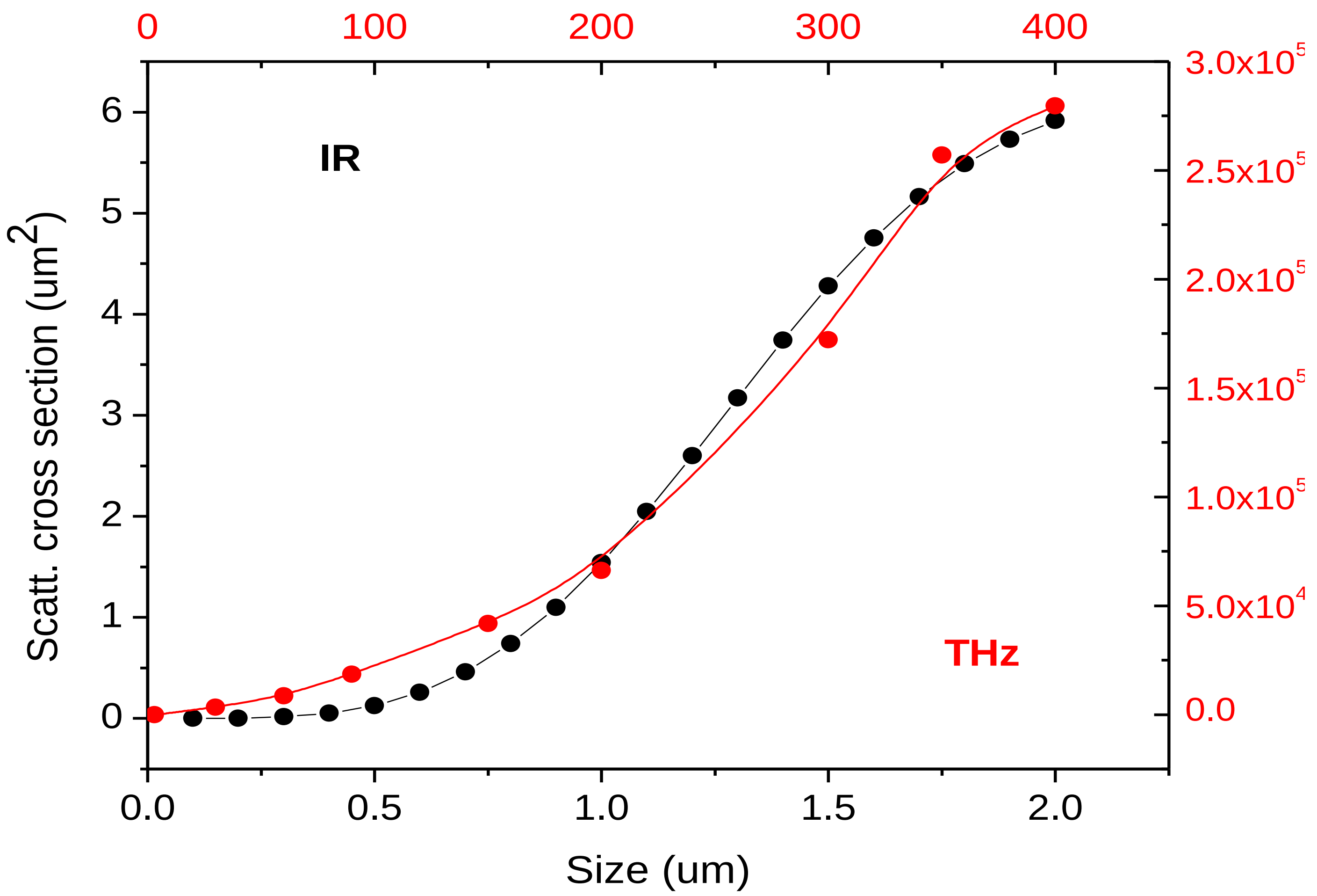


$$f = \int N(T)dT = f(A, b, T_c)$$

$$I(f) = I(A, b, T_c)$$

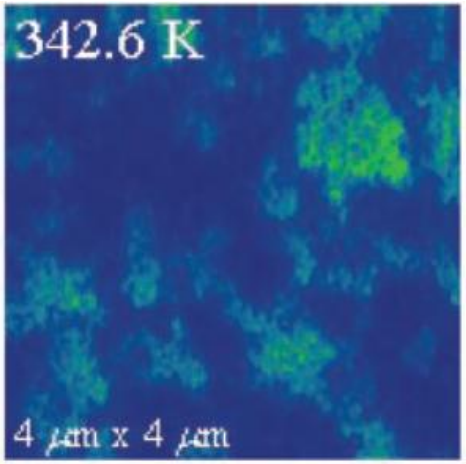
Probe wavelengths	Tc(K)	A,b (fitting parameters)
IR 1.5 um	327.5	A=0.067 b=-0.12 for all of them
THz 300 um	332	
DC (infinity)	336.8	

Mie scattering



Relationship between the probe wavelengths and puddle sizes

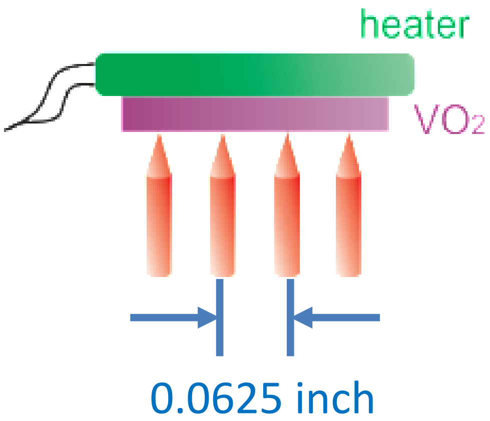
IR



Images From M. Qazilbash *Science* ***318***, *1750 (2007)*

Estimated puddle size
1 um, comparable to the IR wavelength

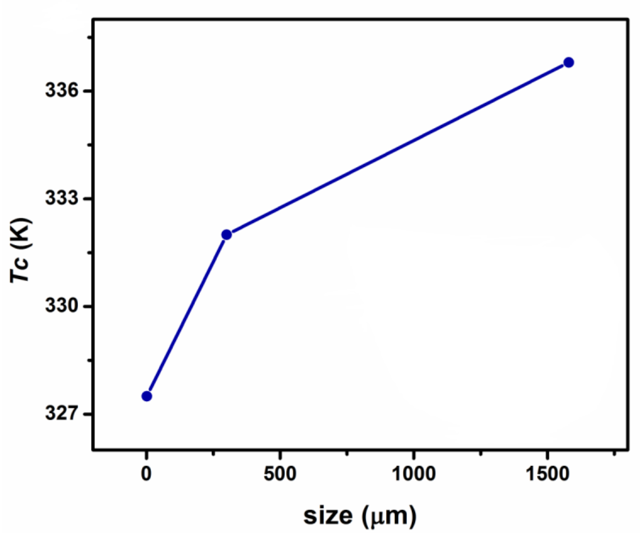
DC



Estimated puddle size
1580 um

Comparison

Probe wavelengths	Puddle sizes	Tc(K)	A,b (fitting parameters)
IR (1.5 um)	1 um	327.5	A=0.067 b=-0.12 for all of them
THz (~ 300 um)	100 - 400 um	332	
DC (infinity)	1580 um	336.8	



Collaborators and Funding

College of William and Mary

Professor R. Ale Lukaszew and her group (Lei Wang)
Professor Irina Novikova and her group (Ellie Radue, Matt Simons)

Jefferson Lab

George Neil, Gwyn P. Williams, J. Michael Klopf,
Michelle Shinn and Scott Madaras

NASA

Eric. I. Madaras

University of Virginia

Professor S. Wolf, Jiwei Lu and Salinporn Kittiwatanakul

Funding

NSF, VMEC, SRC-NRI, Jlab, W&M

Thank you!