Characterization of Vanadium Dioxide by Scanning Probe Microscopy

Thomas P. Campbell[1], Robert E. Marvel[2], Benjamin W. Schmidt[3], Richard F. Haglund, Jr.[2,4]

[1]Institute of Engineering, Murray State University, [2]Interdisciplinary Graduate Program in Materials Science, Vanderbilt University, Nashville, TN ,
[3]Director, VINSE Labs, Vanderbilt University, [4]Physics Department, Vanderbilt University, Nashville, TN

INTRODUCTION

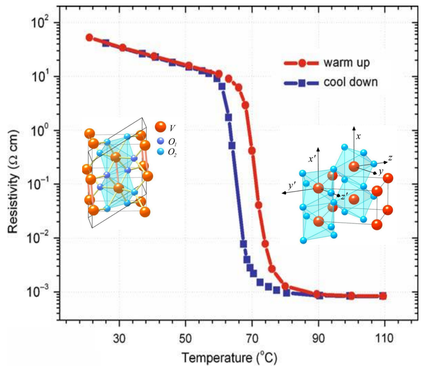
Vanadium dioxide (VO_2) experiences a metal-to-insulator transition from a monoclinic, semiconductor phase to a rutile, metallic phase at approximately 70° C. During this transition, a vast change in physical, thermal, electrical, and optical properties are observed.

This transition can be initiated by:

- Temperature change
- Electric field
- Optical pumping
- Mechanical stress

In films, this transition does not occur all at once

- Grains switch individually
- 'Puddles' of metallic VO_2 form during transition



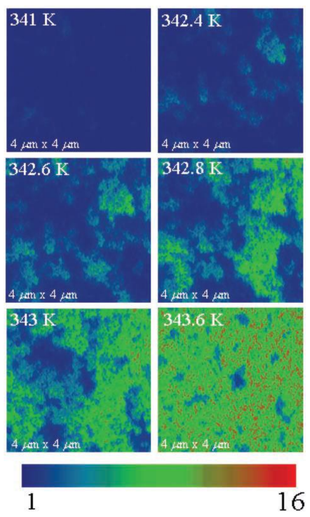
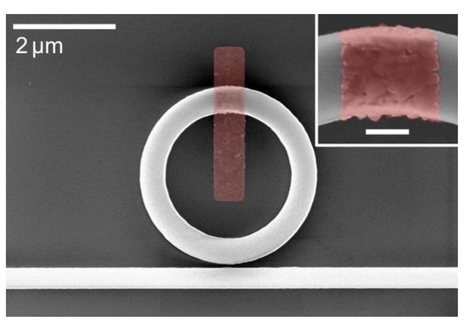


Figure 1 (Above): Electrical Conductivity of VO_2 with respect to temperature -Volker Eyert, Ann. Phys. (Leipzig) 11 (2002) 9
Figure 2 (Right): SNIM images of partially switched VO_2 at different temperatures through the phase transition
- M. M. Qazilbash et al, Science 318, 1150124 (2007)

APPLICATIONS OF VO_2

The VO_2 phase transition makes it an attractive material for many applications:

- Passive thermal cooling devices
- Waveguide couples
- Optical modulators
- Resonators (below)
- Ultrafast field effect transistors



At right:
SEM image of a Silicon micro ring resonator, consisting of a Silicon absorber (radius of 1.5 μm) with a 500 nm length patch of VO_2 (colored red) which can be switched optically.

Ryckman et al, Optics Express, 10753 (2013)

SCANNING PROBE MICROSCOPY

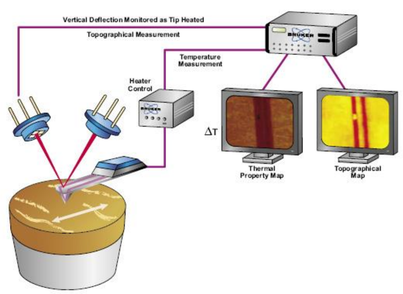
VO_2 thin films that are part of nanoscale device architectures often cannot be characterized by typical optical transmission or reflection measurements. Scanning probe microscopy techniques such as tunneling and thermal microscopy offer a viable alternative.

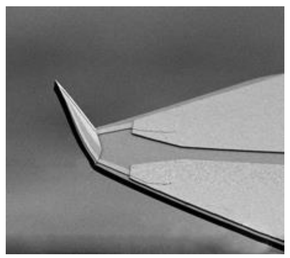
Advantages of scanning probe microscopy:

- High lateral and vertical resolution
- Many SPM techniques can be used with the same instrument
- Probing can take place in air instead of vacuum
- Scans can collect multiple types of data at once

SCANNING THERMAL MICROSCOPY (SThM)

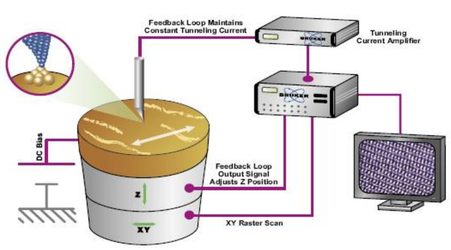
Scanning thermal microscopy uses a physical probe consisting of a cantilever and a sharp (<100 nm radius) tip. This tip is actually a very small thermocouple, allowing the user to collect temperature data and topography data simultaneously.



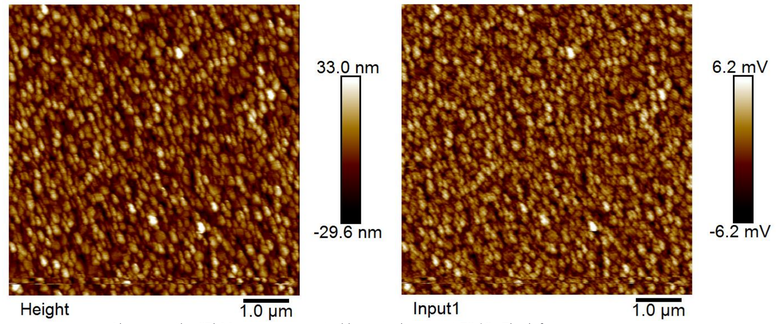


SCANNING TUNNELING MICROSCOPY (STM)

Scanning tunneling microscopy utilizes a sharp etched or precision-cut tungsten wire to probe the sample surface. A DC bias voltage is held between the tip and sample surface, and the tip is brought into very close proximity with the sample (approx. 1 nm). This allows a measureable tunneling current to flow into the tip. As the tip moves horizontally across the surface, it is adjusted vertically to maintain a consistent current, and a detailed electron density contour map is obtained.

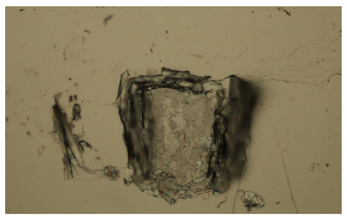


RESULTS



Above are the SThM images generated by a single scan at 73 °C. The left image is the topography image, and right is the thermocouple voltage.

- The height map and thermal image above allow us to compare topography and potential phase coexistence
- The metallic phase is more thermally conductive than the insulator phase of VO_2 which allows more heat to flow from the sample to the probe tip
- Surface-to-tip heat flow is strongly influenced by topography
- In the valleys between grains, the probe tip is in contact with more surface area, allowing more heat to flow



- No usable STM images were acquired
- The probe left scarred areas (image at left, 20 μm wide) on the sample surface.
- A sharper tip or a vacuum may be required

CONCLUSIONS AND FUTURE WORK

- In the future, we plan to use scanning probe microscopy to explore the percolation of the vanadium dioxide phase transition in thin films.
- SThM seems a viable method for distinguishing metallic from insulator VO_2, as the phases have differing thermal conductivities.
- STM will potentially give us the highest resolution images, and is the only technique that will allow metallic VO_2 nanopuddles to be seen.

ACKNOWLEDGEMENTS

The authors thank Vanderbilt University, the Vanderbilt Institute of Nanoscale Science and Engineering (VINSE), all members of the Haglund group, and Dr. Bo Choi for his valuable insight into STM.

This research is funded by the National Science Foundation grant DMR-1263182.