Phase Transition in Vanadium Dioxide Nanostructures


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Abstract

Strongly correlated materials exhibit a wide variety of extraordinary optical and electronic properties that can serve as a panacea for industrial applications. We present electronic transport measurements of vanadium dioxide nanostructures, a strongly correlated transition metal oxide system, with a unique thermally driven insulator-metal phase transition also being driven by electrical and optical means thereby making this a very useful material for switching applications. The research aims to address issues such as percolation of nanoscale metallic domains at temperatures near the phase transition. The nucleation and propagation of domains across the transition are studied through a high resolution optical microscope for both electrical and thermal stimulations.

Background

VO$_2$ is a unique material that has two separate transitions that occur in the same instance:

- Mott Transition: A metal-nonmetal phase transition. In VO$_2$, it is characterized by strong electron-electron repulsions.
- Peierls Transition: A structural phase transition characterized by the distoration of the lattice. In VO$_2$, this is characterized by a unit cell change of M1 monoclinic to an R rutile phase.

Both of these transitions are decoupled.

Under conventional band theory you can't predict the existence of many strongly correlated materials, VO$_2$ included.

Depicted in Figure 3 is the combination of the electronic and structural transition. The structural transition is characterized by the dimerization of the vanadium ions resulting in a lattice distortion. The Hamiltonian for any generalized atomic system is given by:

\[ H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_i \left( V_{\text{ion-ion}}(r_i) + \sum_{j<i} V_{\text{ion-ion}}(r_{ij}) \right) \]

Wherein the equation very few analytical solutions exist for solid-state systems, the hydrogen atom and an infinite chain of hydrogen atoms are two examples. Explicitly the Hubbard model accurately predicts the overlapping of valence and conduction bands during the transition and simplifies the Hamiltonian for Mott insulators like VO$_2$.

The Hamiltonian for the Hubbard is given by:

\[ H = -\sum_{\langle i,j \rangle} (c_i^\dagger d_j + c_j^\dagger d_i) + U \sum_i n_i^c n_i^v \]

The experimental setup is shown in Figure 1 and the circuit diagram which was utilized for the transport, imaging, and heating measurements. A resistor was placed in series for both measurements:

- RT: Maintain constant current
- IV: Ensure the safety of the film
Following the characterization we imaged the transition under two different mechanisms:

- Temperature Driven: Excited the MIT using solely thermal stimulation.
- Voltage Driven: At 330K we applied a voltage to excite the phase transition.
Following the imaging: Examine heating effects on the film.
Measuring the current as a function of time near the transition temperature allows us to determine if Joule heating plays a role as a mechanism behind VO$_2$'s MIT.

Theory

The voltage-driven transition is shown in Figure 4 and Figure 5. The RT transition shows us the phase transition changes the resistance by many orders of magnitude. The hysteresis width of the loop is ~10K.

This larger hysteresis width is due to the polycrystalline makeup of the film, giving it a smoother transition.

The IV transition shows the transition appearing at temperatures from 315K to 336K.

The transition becomes less abrupt at higher temperatures and lower voltages are required to excite the transition.

Figure 6 shows a very interesting result. Taking the voltages where the first-order transitions occur and plotting them as a function of temperature we retrieve a linear relation.

Results: Transport

The temperature-driven image is shown in Figure 7. The insulating phase is characterized by the yellow color whereas the green shade displays the domains on opposite sides of the transition. Both images are magnified 25x.

The gold pieces overlaid on the film are the electrical contacts used for transport measurements.

Results: Imaging

The voltage-driven transition is shown in Figure 8. The insulating phase of the five micron piece is shown in detail as the same color as the insulating phase for the temperature-driven.

The left and center images are magnified at 100x whereas the right most image displays the same exact domain formation magnified at 50x.

Conclusions

The VO$_2$ MIT occurs around a temperature of 340K but can also be excited by applying a voltage across.

When the voltage-driven transition is excited at various temperatures it is found empirically that the transition voltage is a linear function of temperature.

The voltage-driven transition imaged results in a green metallic domain between the electrical contacts.

When the current is monitored at a temperature near the transition it is observed that the transition occurs due to heating effects due to the time-dependence.