Percolation noise at the metal–insulator transition of nanostructured VO_2 films [a)]

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I. INTRODUCTION

Thermochromism in VO_2 is associated with a first-order metal–insulator transition (MIT) at $T_c \approx 68$ ºC,[1] and VO_2 is capable of transforming between a low-temperature (monoclinic, M1) semiconducting state and a high-temperature (rutile, R) metallic-like state. Thin films are of intense current interest for numerous applications such as glazings for energy-efficient buildings and a large number of (opto)electronic, bolometric, and sensing devices.[2–5]

In single crystals of VO_2, the MIT is characterized by sharp real-space phase boundaries between the R and M1 structures and by the fact that these boundaries can propagate along the crystallographic *c*-axes,[6] *i.e.*, the transition is non-percolating in nature. Thin films of VO_2 are normally distinctly different, however, and the MIT is gradual with metallic-like regions growing in extent as the sample temperature T_s approaches T_c from below and with semiconducting regions disappearing as T_s becomes increasingly larger than T_c.[7,8–13] The percolative character of the MIT in VO_2 films has been emphasized several times.[9,14–17] The percolation is not only of theoretical interest but also relevant for the energy-savings potential for VO_2-type films used in energy-efficient fenestration.[18]

Percolation enhances macroscopic resistance fluctuations, as is well known,[19] and such fluctuations have been investigated in some prior studies[20–23] especially with regard to bolometer performance.

II. EXPERIMENTS

VO_2 films with grain-like features at the 50 nm length scale were prepared by reactive DC magnetron sputtering onto heated sapphire substrates and were used to make 100-nm-thick samples that were 10 μm wide and 100 μm long.

The thermochromic properties of the VO_2 micro-bridge was verified by measurements of electrical resistance R_s during heating and cooling in the $20 < T_s < 80$ ºC interval. The temperature recording had to rest at least for 10 minutes at each setting in order to stabilize the T_s and resistance readings. Figure 1 shows that R_s changes by a factor ~2000 in the range between ~50 and ~70 ºC and that the transition displays thermal hysteresis amounting to ~7 ºC. The origin of the hysteresis may be stress build-up and release and associated effects of super- and sub-cooling. Energetically, this can be represented by a system of microscopic double-potential wells connected with pinning forces via interactions with the substrate.

After installing a home-made temperature control that provided about a million times less temperature fluctuations (in the nano-Kelvin range) than commercial units (in the milli-Kelvin range), we were able to measure power density spectra *S*(*f*) of resistance noise around T_c and to demonstrate unambiguous $1/f$ behavior, thus proving that the measured noise was not due to temperature fluctuations.

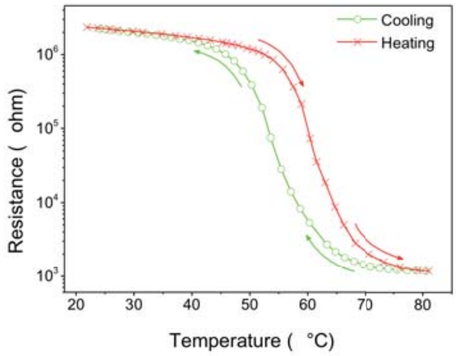

FIG. 1. Resistance hysteresis upon heating and cooling of a VO_2 film.[a)]

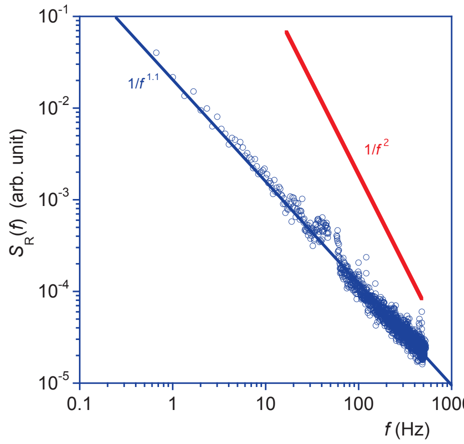

FIG. 2. Resistance noise spectrum of a VO_2 film. The data show $1/f$-like performance even at the middle of the resistive transition.[a)]

At 10 Hz, we performed a scaling analysis of the normalized noise *versus* the resistance, where temperature was a hidden parameter. The normalized spectrum scaled as

$$\frac{S_R}{R_s^2} \propto R_s^x \ , \tag{1}$$

where S_R is the resistance noise spectrum and R_s is the sample resistance. The noise exponent x was –2.6 for $T_s < T_c$ and +2.6 for $T_s > T_c$.

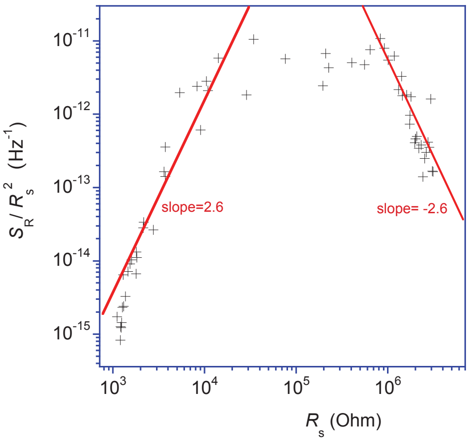

FIG. 3. Scaling plot of the normalized resistance noise spectrum for a VO_2 film.[a)]

III. UNSOLVED PROBLEMS

Theoretical models and experiments of conductor–insulator and conductor–superconductor transitions fail to produce the empirical noise exponents at both[19] or one side[24] of the transition, except for the *Pennetta–Trefan–Reggiani* (PTR) model[25] where the positive exponent was empirically obtained by computer simulations[25] and the negative exponent follows [a] from duality arguments in two dimensions. But there are open questions:

(*i*) How is the $1/f$ noise spectrum generated, especially near the percolation threshold, in such small systems?

(*ii*) Is there an analytic solution of the PTR model to produce these exponents?

(*iii*) Are the noise exponents universal in periodic lattices, or do they depend on the type of resistor lattice?

(*iv*) Which assumptions of the healing–recovering dynamics are essential to get these noise exponents?

(*v*) Is duality indeed enough to explain the negative exponent in two dimensions or extra assumptions are needed?

(*vi*) What are the exponents in three dimensions, *i.e.*, can we expect a dimensional crossover in thicker films?

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