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Evaporation of a sessile droplet resting on a thin vanadium dioxide film

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Abstract. The paper is devoted to the study of the evaporation of water sessile drops resting on a smooth surface consisting of a vanadium dioxide thin film (~150 nm) covering a sapphire substrate. Vanadium dioxide is considered because of the promising applications it is expected to have in new technologies for heat waste recuperation. Water drops are deposited on the substrate heated at different temperatures from 20 to 80°C, and the time dependence of the droplet shape is registered with the use of shadow imaging. This reveals that the three-phase contact line remains pinned during most of the drop lifetime, while the wetting contact angle as well as the drop volume are continuously changing. With the help of image processing, the vaporization rate of the drop is calculated. It is found that it is almost constant with time, and increases exponentially with the temperature of the substrate, well in agreement with theoretical models developed to describe the evaporation of drops with a pinned contact line.

INTRODUCTION

Heat and mass transfer across solid/fluid interface is significant for numerous application areas [1–4]. For example, droplet interactions with a solid surface are encountered in heat waste recuperation systems, in spray cooling of hot surfaces which is an efficient technology for heat dissipation. It is clear, that for further improvement of these techniques, a gain in physical insights concerning the interaction of a liquid droplet with a solid surface and a surrounding vapor is required.

Vanadium dioxide (VO_2), because of its remarkable properties, is a promising material for its usage as a basic element in different smart applications in green technologies [5]. This material exhibits a fully inversible metal-insulator phase transition close to 67°C. The phase change is accompanied by a significant electrical conductivity rise of about four orders of magnitude. The variation of the physical properties close to the temperature of phase transition gives the possibility for fabricating various easy-tunable devices. Specifically, the substantial jump-like changing of thermal emissivity [6] and thermal conductivity [6] could lead to vanadium dioxide applications in next generation of thermal devices, like thermal diodes or thermal transistors [7]. However, from another side, the external conditions could impact drastically on the material properties because of such sharp phase transition. Therefore, the prediction of the vanadium dioxide behavior under different conditions is critical for further improvement of devices stability and reliability.

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In this paper, we investigated the evaporation of a water droplet deposited on a thin vanadium dioxide nanofilm on a sapphire substrate. The evolution of the droplet shape with the time is observed experimentally for different temperatures of the solid surface. More specifically, the droplet volume, the radius of the solid/liquid contact line as well as the wetting angle were registered and analyzed in detail. Finally, an analytical model for the description of the drop evaporation is also compared to the measurements.

MATERIALS AND METHOD

A 150 nm thick VO_2 film was deposited by pulsed laser deposition on a substrate of sapphire-C (001). A V_2O_5 target was used for ablation with a KrF excimer laser at 248 nm. Oxygen pressure and temperature of the substrate were optimized to obtain the VO_2 phase. X-ray diffraction analysis revealed a (010) preferred orientation. SEM and AFM analysis show a smooth surface with a roughness RMS below 2 nm on a 1×1 μm^2 surface.

The phase transition occurring in the studied material was emphasized by Raman spectroscopy. Specifically, Fig. 1 demonstrates the characteristic of Raman spectra measured from the studied sample at room temperature (Fig. 1a) and above phase transition at 80 °C (Fig. 1b). As one can see, the phase transition significantly changes the Raman spectrum. Additionally, it should be mentioned, that the phase transition was fully reversible, meaning that the spectrum returns to the initial one after cooling down to the room temperature.

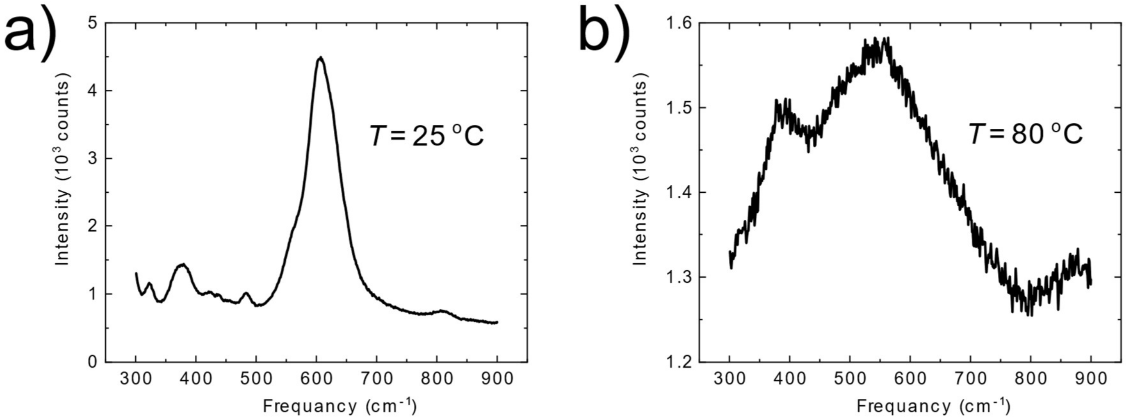

FIGURE 1. Raman spectra registered before (room temperature) and after (T = 80 °C) phase transition from the vanadium dioxide film grown on the sapphire substrate

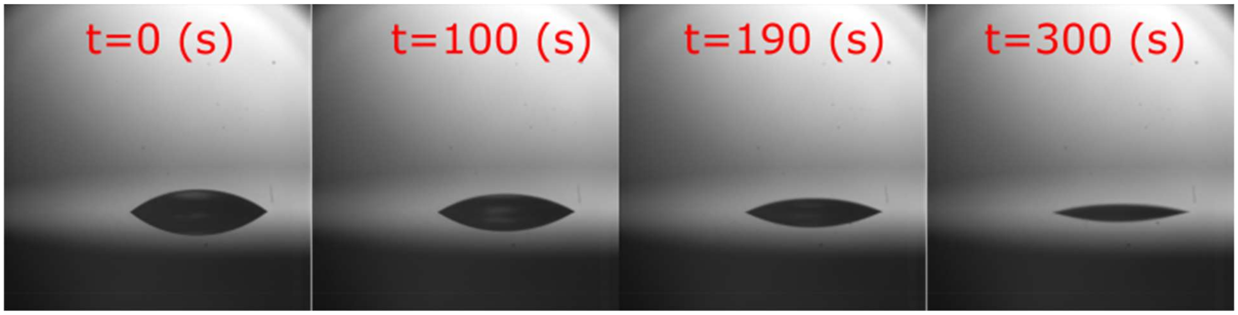

FIGURE 2. Images of the droplet located on the VO_2 thin film at different times for a surface temperature of 40 °C.

The droplets have a fixed initial volume which is adjusted accurately with the use of a microsyringe. Images of the droplet shape are recorded by the camera every 10s with the use of a backlit illumination (shadowgraphy). As an example, Fig. 2-4 show temporal sequences of images taken at surface temperatures equal to 40 °C, 60 °C, and 80 °C. Dataset are provided in the following for different temperatures of the substrate from 25 °C to 80 °C with step equals to 5 °C. Image processing allows us to extract the main features of the droplet geometry like its central height h and its contact radius R and the contact angle θ.

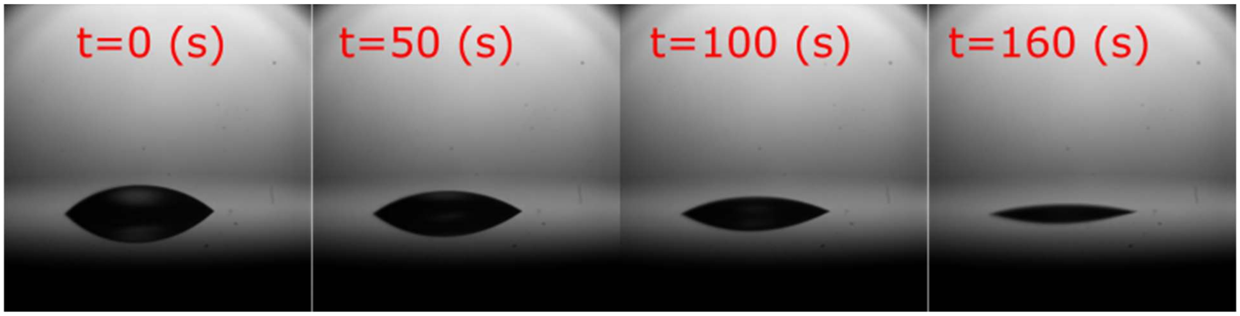

FIGURE 3. Results of shape of the droplet located a VO_2 thin film at different time for a temperature of 60 °C.

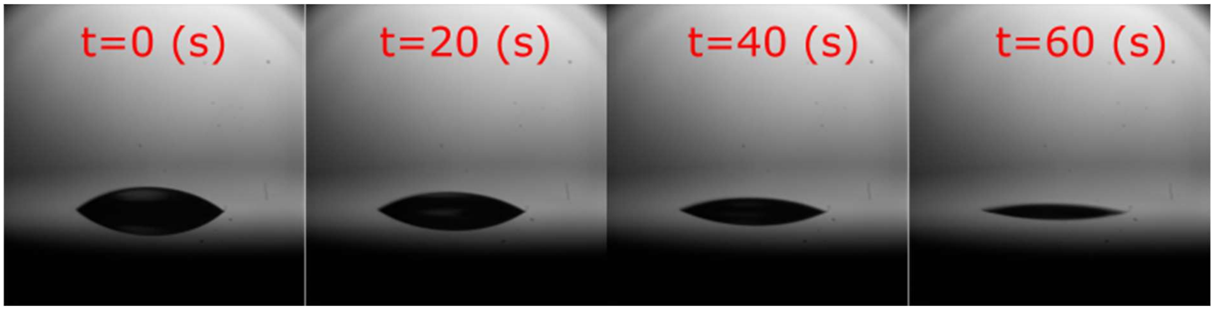

FIGURE 4. Results of shape of the droplet located a VO_2 thin film at different time for a temperature of 80 °C.

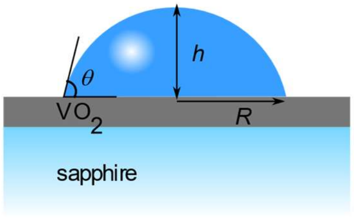

FIGURE 5. Sketch-view of the considered geometry.

RESULTS AND DISCUSSION

Fig. 6 shows typical time evolutions of the droplet height and the radius of contact line for the same experimental cases presented in Fig. 4. As one can see, droplet height is decreasing almost linearly with time. At the same time, the contact radius remains constant during almost the whole droplet lifetime, which means that the triple contact line remains pinned. More generally, the evolution of an evaporating sessile drop can follow several regimes: constant contact line radius (like in the present study), constant contact angle and a regime with a sliding and jumping contact line. This regime depends on the wetting properties of the surface, in particular when the receding (minimal) contact angle is low (practically 0 in the case of the VO_2 surface) the triple contact line can remain pinned until the very end of the evaporation period.

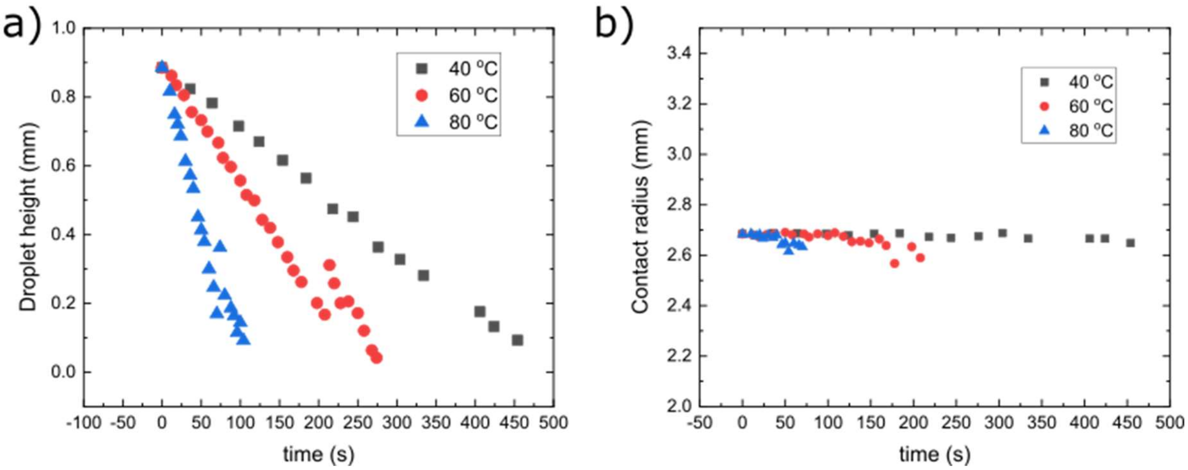

FIGURE 6. Time evolutions of height (a), contact radius (b) of a droplet resting on the VO_2 sample heated at 40 °C, 60°C and 80°C.

Assuming that the drop shape corresponds to a spherical cap, the drop volume can be calculated with the following equation [8]:

$$V(t) = \frac{\pi h(t)\left(3R^2 + h^2(t)\right)}{6}, \tag{1}$$

where $h(t)$ is the droplet height, R is the radius of the contact line. Fig. 7 presents the evolution of the droplet volume as a function of time. Such evolutions can be fitted well with the use of a linear law. The evaporation rate, defined as the slope of V(t) is presented in Fig. 8 as a function of the surface temperature. As one can see, the effect of the surface temperature can be described with an exponential-like growth.

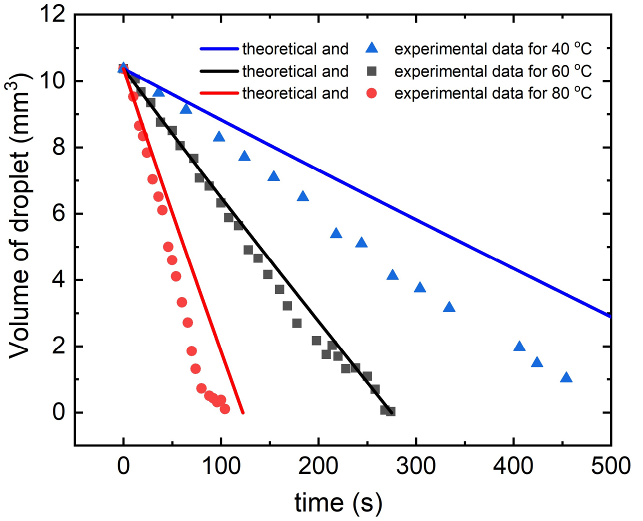

FIGURE 7. The dependencies of a volume droplet with time (temperatures of heater equal to 40 °C, 60 °C, 80 °C)

The drop evaporation can be modelled within the frame of the quasi-steady theory[8]. For the sake of simplicity, it is assumed here that the vapor mass transport is mainly driven by pure diffusion in the ambient air, and also that the liquid temperature is uniform and equals to that of the solid surface. With these above assumptions and for the evaporation regime of constant contact radius observed in the experiments, the evaporation can be evaluated with the following equation [9]:

$$\frac{dV}{dt} = -\frac{\pi r D \Delta\rho f(\theta)}{\rho_w}, \tag{2}$$

where V is the droplet volume, ρ_w is the density of liquid water, r is the droplet radius, D is the diffusion coefficient of vapor in air, $f(\theta) = 1.3 + 0.27\,\theta^2$ is a function of the contact angle ($\theta = 2 \cdot \mathrm{atan}(h/R)$), $\Delta\rho = \rho_s - \rho_\infty$ is the mass concentration difference between the region close to the liquid/vapor interface and the ambient air (ρ_∞). *Equilibrium* between *liquid* and *vapor* phases allows to have:

$$\rho_\infty = \frac{HP_{sat}(T_\infty)M_w}{RT_\infty} \tag{3}$$

$$\rho_s = \frac{P_{sat}(T_s)M_w}{RT_s}, \tag{4}$$

where H is the humidity, M_w is the molar weight of a water molecule, R is the universal gas constant, T_s and T_∞ are the temperature of sample and ambient one respectively. P_{sat} is the saturation pressure which is a function of the temperature following the Antoine equation in the following form [10]

$$P_{sat}(T) = A \cdot \exp\left(B - \frac{C}{D+T}\right), \tag{5}$$

where A, B, C and D are constants.

The substitution of Eqs.(3)-(5) in Eq. (1) gives us the expression for the evaporation rates as a function of temperature. Thus, one can reveal the exponential increase found experimentally. Therefore, one can use the following approach for the prediction of evaporation rates for different temperatures. The simulated curve is presented in Fig. 8 with the solid line. As one can see, the theoretical dependence represents quite well general trend. Nevertheless, the simulated curve under-estimates the experimental data. This may arise because of the present of the natural convection which increases the evaporation rate.

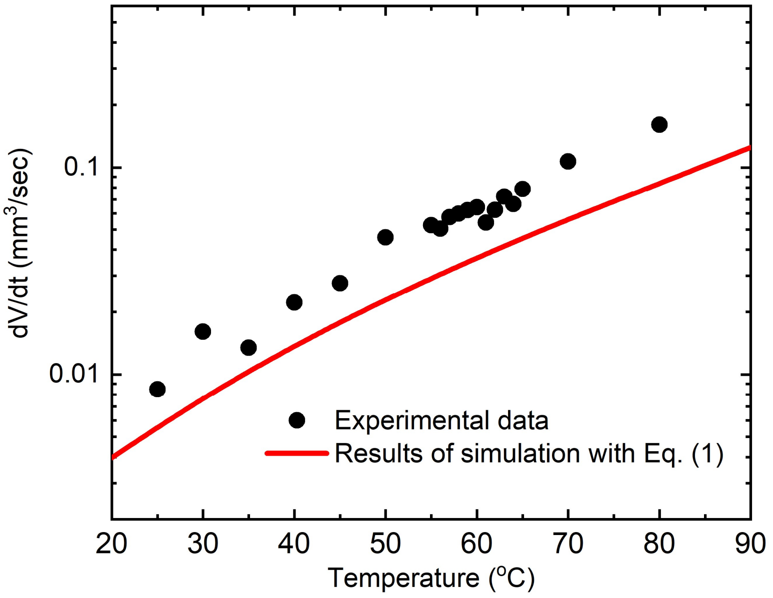

FIGURE 8. The dependence of evaporation rate as a function of the sample temperature. The dots correspond to experimental data, while the solid line corresponds to results of simulation with Eq. (1).

CONCLUSIONS

In this paper, we considered features of a droplet evaporation of a thin film of vanadium dioxide. We deposited a spherical droplet on the substrate heated at different temperatures. The dependence of the droplet shape was detected as a function of time with the use of a high-speed camera. Specifically, we measured the height, contact radius and the wetting angle of the droplet. We revealed the constant contact radius evaporation regime. In this regime, the volume of the droplet changes linearly with time. Thus, we evaluated the rate of change of the droplet volume as a function of temperature. We found that this dependence can be described with an exponential law increase. This tendency was explained with the use of an analytical approach, with which the experimental data were correlated.

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