Thus, the total error in determination of the thermal-diffusivity coefficient by the proposed method does not exceed 5-7%, which is comparable to the uncertainties of the methods usually employed for studied of specimens which are often difficult or practically impossible to prepare, for example, in the case of aggressive liquid metals.

NOTATION

T	is the temperature;
q_0	is the pulse energy, J;
c_p	is the specific heat, J/kg·°K;
ρ	is the density, kg/m^3;
a	is the thermal diffusivity, m^2/sec;
l	is the thermocouple coordinate;
τ	is the time;
$\tau_{1/2}$	is the time at which temperature signal at point l reaches one half its maximum value.

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THERMISTOR EFFECT IN SWITCHING IN VANADIUM DIOXIDE

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The switching effect in vanadium dioxide is interpreted in terms of a critical temperature on the basis of the temperature dependence of the conductivity for semiconducting VO_2.

It has several times been suggested [1-3] that the temperature dependence of the switching current or voltage for vanadium dioxide is due to change in the mode of switching with the environmental temperature. It has been claimed [1] that the switching in VO_2 occurs on account of the thermistor effect in the range from 223 to 283°K, whereas a semiconductor–metal phase transition occurs at environmental temperatures above 283°K (following [1], we speak in what follows of the thermistor model and the transition model). However, these two models give qualitative agreement between theory and experiment only for certain ranges in the environmental temperature, while the temperature dependence of the switching current or voltage is not described by either of the models for the range 273-314°K.

We have measured the temperature dependence of the switching current and voltage for the range from 160 to 341°K for single-crystal vanadium dioxide; the results are explained via the transition model with a critical temperature on the basis of the temperature dependence of the conductivity of VO_2 in the semiconducting state. We have also measured the specific resistance of VO_2 as a function of temperature.

Curves 1 in parts a and b of Fig. 1 show the switching current and voltage as functions of environmental temperature for single-crystal VO_2; the transition model with a critical temperature has been used [1-3] on the assumption that the conductivity is constant in the metallic state and in the semiconductor state. However,

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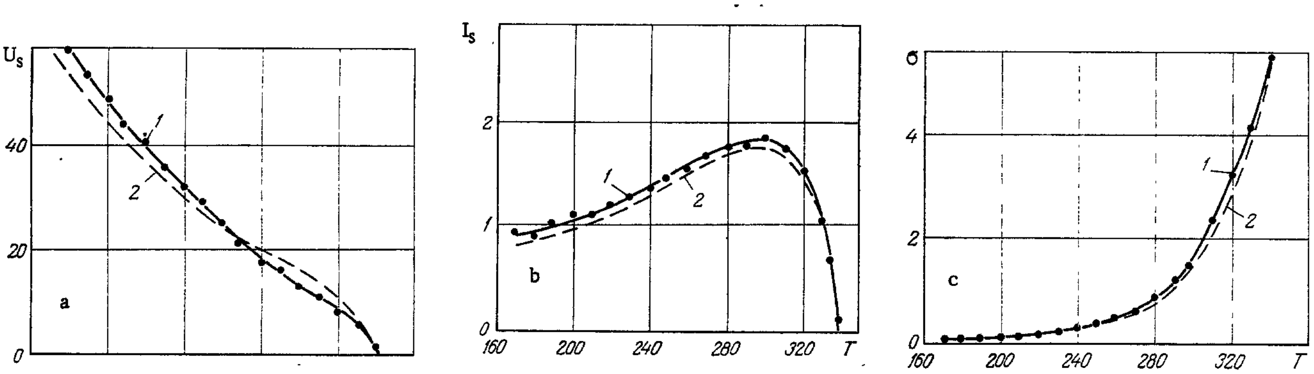

Fig. 1. Dependence of environmental temperature for: a) switching voltage; b) switching current; c) specific resistance: 1) measurement; 2) calculation. U_s, V; I_s, mA; σ, $\Omega^{-1}\cdot m^{-1}$; T, °K.

the actual $\sigma(T)$ curve for VO_2 is different. Curve 1 of Fig. 1c shows the observed relationship between the conductivity and temperature for the single-crystal material. The conductivity of the VO_2 increases suddenly by two orders of magnitude at the semiconductor–metal transition point (T_c = 341°K), and it then remains essentially constant at higher temperatures. The results can be represented as

$$\sigma(T) = \begin{cases} \sigma_0 \exp\{aT\} & \text{for} \quad T \leqslant T_c, \\ \sigma_m & \text{for} \quad T > T_c. \end{cases} \tag{1}$$

The conductivity increases by about a factor 5 between 160 and 341°K, so it is incorrect to assume [1-3] that the conductivity of semiconducting VO_2 is constant. The temperature dependence of the conductivity of VO_2 must be incorporated into the transition model.

An analytic expression for the switching current or voltage as a function of environmental temperature can be derived from the temperature distribution in a cylindrical specimen of VO_2 having thermal conductivity α, length l, and radius r_0, the assumption being that $l \gg r_0$, while α is independent of temperature. These are conditions of cylindrical symmetry, so the temperature distribution is given by

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{U^2\sigma_0}{\alpha l^2}\exp\{aT\} = 0 \tag{2}$$

subject to the boundary conditions

$$\left.\frac{dT}{dr}\right|_{r=0} = 0, \quad T(r = r_0) = T_0. \tag{3}$$

The solution to (2) is [4]

$$T(r) = \frac{1}{a}\ln\frac{8g^2\alpha l^2}{(1+g^2r^2)^2\sigma_0 U^2 a}, \tag{4}$$

where g is a constant of integration. The switching condition is put as

$$U = U_s, \quad \text{if} \quad T(r=0) = T_c. \tag{5}$$

From (3), (4), and (5) we have

$$U_s = \frac{2l}{r_0}\left[\frac{2\alpha}{\sigma a}\{(\exp[a\Delta T])^{\frac{1}{2}} - 1\}\right]^{\frac{1}{2}}, \tag{6}$$

where $\Delta T = T_c - T_0$ and $\sigma_c = \sigma_0 \exp\{aT_c\}$; the switching current is given by

$$I_s = \frac{U_s}{l}\,2\pi\int_0^{r_0}\sigma(T_s(r))\,r\,dr, \tag{7}$$

where $T_s(r)$ is the temperature distribution in the specimen when the applied voltage is U_s. From (4), (6), and (7) we have

$$I_s = 2\pi r_0\left[\frac{2\alpha\sigma_c}{a}\,\frac{(\exp[a\Delta T])^{\frac{1}{2}} - 1}{\exp[a\Delta T]}\right]^{\frac{1}{2}}. \tag{8}$$

We use the following measured values to calculate U_S and I_S: $a = 0.033°K^{-1}$, $\sigma_0 = 7 \cdot 10^{-5}\ \Omega^{-1} \cdot m^{-1}$, $\sigma_C = 5.5\ \Omega^{-1} \cdot m^{-1}$, $l = 10^{-4}$ m, $r_0 = 4.4 \cdot 10^{-5}$ m; the value $\alpha = 0.99\ W \cdot m^{-1} \cdot °K^{-1}$ was taken from [5]. Parts a and b of Fig. 1 (curves 2) show the results; (6) and (8) thus allow one to determine the point of inflection on the $U_S(T)$ curve and the environmental temperature corresponding to maximum I_S:

$$T_{0s} = T_c - \frac{\ln 4}{a} . \tag{9}$$

We found that T_{0S} = 299°K for our measurements; (9) then implies that T_{0S} varies with a. For instance, one can raise or lower T_{0S} by varying a, e.g., by doping the VO_2; i.e., one can obtain a material with a preset temperature dependence for the switching voltage.

Curves 1 and 2 of Fig. 1 (parts a and b) compare the measurements and calculations; switching is clearly described by the transition model with a critical temperature provided that the temperature dependence of the semiconducting form of VO_2 is incorporated, and this gives general agreement between the observations and the calculations within the working temperature range.

NOTATION

U_S	is the switching voltage, V;
I_S	is the switching current, mA;
α	is the conductivity, $W \cdot m^{-1} \cdot °K^{-1}$;
T_C	is the phase-transition temperature, °K;
T_0	is the environmental temperature, °K;
T_{0S}	is the temperature corresponding to maximum switching current, °K;
σ_0	is the electrical conductivity as T → 0, $\Omega^{-1} \cdot m^{-1}$;
σ_m	is the electrical conductivity of the metallic phase, $\Omega^{-1} \cdot m^{-1}$;
a	is the temperature coefficient of electrical conductivity, $°K^{-1}$;
l, r_0	are the sample length and radius, m, respectively.

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