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Criterion Of Electric Current Thermal Switching In Solids

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ABSTRACT

Considering the heat-balance equation for the solid sample overheated through the Joule effect its normalized current–voltage characteristic has been obtained. On this basis there is established a universal correlation between ambient-temperature resistivity of material and the voltage of thermal switching: when the resistivity decreases by a factor of $\sim$ 2 the current switches on. According to criterion, the switching effect observed in β-rhombohedral boron near the room-temperature reveals a purely thermal nature.

KEYWORDS

Electric current in solids;
Thermal switching;
β-rhombohedral boron.

INTRODUCTION

Electric current switching phenomena in the bulk of solids or at the solid-state barrier-junctions are known for a long time but still are a subject of intensive studies (see e.g.[1–4]). This is not only by the wide field of their technical applications in controlling, measuring, cutting out, rectifier, memory, protective etc systems but also for the diversity of switching mechanisms that can take place in solids. Among them the thermal switching is one of the most interesting. This kind of the electric current instability is explained by the heat generated due to the current passage in the material with a negative resistivity-temperature coefficient. However, the effect in pure form is difficult-to-find.

On the one hand thermal switching is almost impossible in metals as they commonly have a positive resistivity-temperature coefficient. Point is that due to the electron-phonon scattering, the mobility of the quasi-free electrons is a decreasing function of temperature while their concentration remains constant. On the other hand the ionic mechanism of conduction peculiar to dielectrics for the most part can lead only to the irreproducible thermal breakdown accompanied by the irreversible structural changes in material.

As to the current switching observed in semiconductors it mainly termed as a thermo-electrical or electro-thermal effect. In the former case the ther-

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mal switching plays the role of an assistor for the avalanche breakdown which occurs at voltages exceeding a certain threshold value and means the steep increase of current with voltage. The avalanche current is connected with impact ionization of the localized or band electron states otherwise not participating in the electrical conduction at given temperature. In the latter case the current carriers in semiconductor may be multiplied by their injection from the electrodes or due to the electric field effect. So, the almost pure thermal effect has chance to be appeared only in semiconductors and only under the special conditions favorable to such kind of switching.

Earlier we mapped[5,6] the detailed temperature-field within the sample overheated through the electric current. Obtained theoretical current–voltage characteristic provided a good fit to the measured ones at the physically reasonable sets of parameters. However, its analytical form is too complicated in order to be normalized and in this manner find a clear criterion whether the thermal switching take place or not in given conditions. For reasons of this now we return to same problem aiming to consider simplified but more general model of the overheated sample at the certain averaged temperature.

In the next section we will theoretically find the normal form of current–voltage characteristic for the semiconductor sample resistivity of which uniformly reduces due to Joule heating and obtain the corresponding switching point. Then criterion of the thermal switching will be tested for β-rhombohedral boron revealing the appropriate(hopping-type) mechanism of conductivity. And finally, there will be made some remarks concerning the accuracy of the formulated criterion.

Theorizing

Below the static current vs. voltage characteristic will be calculated under the assumption of a pure temperature effect. In such case a good approximation of the current dependence of the sample' steady resistance near the fixed ambient temperature T is given by

$$R(I) = R(1 - \alpha \Delta T(I)) \quad (1)$$

where R and $\alpha > 0$, respectively, are the resistance of the sample and absolute value of its thermal coefficient at the ambient temperature while is $\Delta T(I)$ the rise in temperature at current I through the sample. According the Ohm's law $U = R(I)\, I$ is the voltage across the sample. Consequently, the Joule power input UL equals

$$W_{Input} = R(1 - \alpha \Delta T(I))\, I^2 \quad (2)$$

If $\Delta T(I) << T$ the power lost is proportional to $\Delta T(I)$,

$$W\ Input = \lambda \Delta T(I) \quad (3)$$

where λ is the effective heat-transfer coefficient including not only thermal conduction through the electrodes but also the thermal radiation from the lateral surfaces of the sample.

In steady state (i.e. for a stable operating point) the condition $W_{Input\,=}\ W_{Input}$ must be held what means the heat-balance equation in form of

$$R(1 - \alpha \Delta T(I))\, I^2 = \lambda \Delta T(I) \quad (4)$$

With $I^2_S = \lambda/\alpha R$ and with use of eqs. (1) and (4) we obtain

$$\Delta T(I) = 1\, I^2/ I^2_S/\alpha\, I^2/I^2_S \quad (5)$$

and

$$R(I)/R = 1/\ 1 + I^2/I^2_S \quad (6)$$

Then with the $US = RI_S / 2$ equation (6) yields relation between the normalized voltage U / U_S and normalized current I / I_S:

$$½\ U/US = I/I_S/1 + I^2/I^2_S \quad (7)$$

For the relaxation point where (normalized) differential resistance of sample

$$1/R\ DU/dl = 1 - I^2/I^2_S/(1 + I^2/I^2_S)^2 \quad (8)$$

equals zero we found $I = I_S$ and $U = U_S$ (see eq. (7)). Hence, temporary application of the voltage higher than U_S to the sample transforms a state of high resistance to a state of poor resistance which is then retained even at a lower voltage. So, the arrangement under the consideration operates as a current switch and, according to Eq. (6), the switching point has to be attained by a current through the sample which causes a decrease in its resistance by a factor of $.R/R(I_S) = RI_S/U_S = 2$.

Figure 1: Normalized current–voltage characteristic of the thermal switch

The eq. 7 can be solved for the current value. There exist two roots. First branch

$$\frac{I}{I_S} = \frac{U_S}{U} - \sqrt{\frac{U_S^2}{U^2} - 1} \quad (9)$$

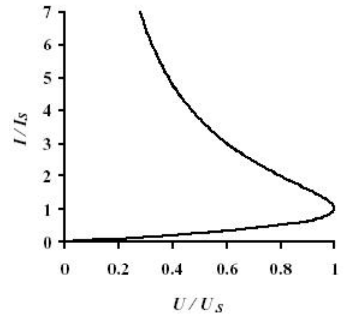

Figure 1: Normalized current–voltage characteristic of the thermal switch

Expresses current as a function of voltage below the switching point. If the voltage vanishes the $U \to 0$current also $I \to 0$ and in accordance with is Ohm's law $I \to U/R$. First branch of the current–voltage characteristic from the point (U_S, I_S) is followed by a second one

$$\frac{I}{I_S} = \frac{U_S}{U} + \sqrt{\frac{U_S^2}{U^2} - 1} \tag{10}$$

Where the differential resistance is increasing in absolute value and negative. Now at $U \to 0$ the current is inversely of voltage $I \to R_S^2/U$ and, consequently, unrestrictedly large $I \to \infty$.

The normalized theoretical curve calculated from eqs.(9) and (10) is shown in the figure 1.

Testing

At the room temperature ($T \approx 300$ K) chemically pure β-rhombohedral boron is characterized by the high resistivity (~10^7 Ω⁻cm) and the large and negative resistivity-temperature coefficient (with absolute value of $\alpha \approx 0.0587\ K^{-1}$). The nature of bipolaron-hopping conductivity realized in this material[7] seems suitable for observation of the thermal switching. (1) As there are practically no free current carriers the breakdown via impact ionization in boron is strongly excluded. (2) Due to the high resistance of sample the overheating sufficient for the thermal switching is reached at relatively low voltage which is impossible to induce an electric field ionization of the low-lying hopping levels or inject free carriers from the electrodes before the switching point. (3) And what is more, because of large absolute value of resistivity-temperature coefficient the raise in temperature should to be small to develop thermal effect into the electrical one via thermal excitation of the trapped carriers. By reasons of this the switching in β-rhombohedral boron about the room temperature is expected to be predominantly a heat effect.

For the measurements of the current–voltage characteristic of β-rhombohedral boron it was used two specimens of the almost identical geometry which were cut out from super-pure (Wacker-Chemie, claimed purity 99.9999 wt. % B) vacuum-deposited and zone-refined macro-crystalline rod. Their surfaces were mechanically polished and then formed amorphous surface-layers were etched in boiling nitric acid solution. Tail-end surface cleaning was made using solution containing alkaline potassium before distilled water flushing. Such treatment excludes any kind of surface conductivity or surface breakdown frequently characterizing the high-resistivity materials.

The pairs of symmetrical layer-electrodes were formed by the vacuum sputtering of silver onto the opposite flat surfaces of the tested specimens. In addition to the electrical connection they also provided the good heat dissipation. These devices were clamped between flawless steel probes the contact pressure of which was sufficiently high to guarantee the negligible series resistances.

Display of I-U characteristics of β–rhombohedral boron was obtained by the semiconductor devices' curve tracer. The switching effect has been investigated using static(D.C.) and so-called normal (sinusoidal A.C. of line frequency 50Hz) regimes.

When very slowly increased voltages are applied to the specimen, it is observed at first only a slight increase in current; but, above a certain voltage, the current suddenly raises sharply while the voltage drop at the specimen diminishes asymptotically tending to zero. The obtained characteristics are symmetric with respect to current direction. If the time for the measurement of the individual points is sufficiently long(to reach the steady state), the return curves closely approach the initial ones for increasing current. The differences between the characteristics determined with D.C. and A.C. are only slightly marked below the switching point. Therefore, the switching time is quite large (much greater than period of current oscillations in line 0.02 s). The detected characteristics were fully reproducible as switching does not caused any irreversible changes

TABLE 1 : Switching parameters of the tested β-rhombohedral boron specimens

Specimen	R, Ω	I_S A	U_S, V	$R\,I_S\cdot U_S$
1	$2.00\cdot10^{7}$	$1.20\cdot10^{-4}$	$1.22\cdot10^{3}$	1.97
2	$2.00\cdot10^{7}$	$1.30\cdot10^{-4}$	$1.28\cdot10^{3}$	2.03

in the specimens' structure or any kind of electrostatic memory. It should be mentioned that all these are the features inhered to the thermal effect.

The values of switching current and switching voltage measured in static regime for the tested boron specimens are presented in TABLE 1. One can see that in both of cases there are found switching factors, 1.97 and 2.03, almost equal 2. So, it is obtained quite good agreement between experiment and our theory for current–voltage characteristic and, therefore, we can confidently explain this effect in -rhombohedral boron as a process of thermal switching.

CONCLUSION

The proposed generalized model of the solid sample overheated by electric current is based upon two approximations: (1) The raise in temperature is relatively small in comparison with ambient temperature; (2) There are no temperature variations across the sample. Let us consider their influence on the obtained criterion of thermal switching.

If the averaged raise in temperature of the sample is not small in comparison with ambient temperature the linear approximations for resistance and output power no longer are valid. For instance, the radiation part of the latter should be presented as ~ $((T+T(I))^4-T^4)$. But, necessity of overheating at Δ T(I)T to reach the thermal switching means that absolute value of resistivity-temperature coefficient of material is very low which obviously tends to thermal or some kind of electrical breakdown masking thermal switching phenomenon.

If the temperature-field within the sample at a non-zero current is not uniform the Thomson and Peltier heats are generated in the bulk and at the electrodes, respectively. These are a first-order effects according to the current value (~I) while the Joule one is a second order effect (~I^2). Thus, their heat densities are small in comparison with Joule heat density generated at any given point. Moreover, if the sample and electrodes are symmetrically shaped the temperature-distribution is also symmetrical with respect to midpoint and in particular the temperatures of both electrodes are the same. In such case the Thomson heat release inside the one half of sample is exactly compensated by the Thomson heat absorption inside another one. Analogously, the Peltier heat release and absorption at the electrodes are compensated by each other.

Thus, if the current switching in solid has a pure thermal nature it should satisfy obtained criterion: resistivity of material at the switching current makes up almost the half of its Ohmic resistivity (i.e. in the low current limit). The thermal switching factor may fluctuate from the value of 2 only negligibly (as in the tested case of β-rhombohedral boron) because of varying contact resistances and also possibly due to variation in heat dissipation.

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