Thermal switching effect in $\beta$-rhombohedral boron

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

1. 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 (e.g., see [1-4]). This is not only because of the wide field of their technical applications in controlling, measuring, cutting out, rectifying, 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. Because of the electron-phonon scattering, the mobility of the quasi-free electrons is a decreasing function of temperature, whereas their concentration remains constant. On the other hand, the ionic mechanism of conduction, peculiar to dielectrics, can lead only to the irreproducible thermal breakdown accompanied by the irreversible structural changes in the material.

As for current switching observed in semiconductors, it is termed as a thermo-electrical or electro-thermal effect. In the former case, the thermal switching assists 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 related 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 can appear only in semiconductors and only under the special conditions favourable to such kind of switching.
Both crystalline (β-rhombohedral) and amorphous boron can be considered as most probable candidates for realization of the current thermal switching. There are numerous studies on electrical current instabilities in boron (see [5-14] and others). They had shown that at low temperatures, switching reveals an electric character, but above ~ 250 K contribution of the heat generated by the current flow becomes important [11]. In [15], new measurements of the electric field dependence of electrical conductivity in β-rhombohedral boron were presented and discussed according to the various theories (the classical model of hot electrons, the Poole–Frenkel model, models of non-thermally activated hopping by Mott and Shklovskii, the model of the field dependence of small polaron mobility, space charge limited currents) together with a critical review of the previous measurements.

In general, three ranges of the $I - E$ dependence are distinguished ($I$ is the electric current and $E$ is the mean electric field strength in the sample): (i) Ohmic behaviour $I \sim E$; (ii) non-Ohmic behaviour and temperature-dependent field dependence; and (iii) non-Ohmic behaviour $I \sim E^2$ independent of temperature, which reveals a change in the transport mechanism rather than an “electrical breakdown”. These results have confirmed hopping as the prevailing transport mechanism in high-purity β-rhombohedral boron at room temperature, at least up to fields of about 8 kV / cm. Resistance of the samples of lesser purity usually had been assumed high enough to exclude the Joule heating below the room temperature. On the contrary, in [15] it was found that in high-purity β-rhombohedral boron, already at room temperature and at fields of about 1.5 kV / cm, the samples are significantly heated. In [15], Joule heating was considered problematic and was avoided by means of accommodation of a sample in the evacuated chamber of a close-cycle refrigerator equipped with an additional heater.

In the present work, we consider the different case, when the sample temperature is not fixed and the thermal switching can freely develop. Earlier we mapped [16-17] the detailed temperature field within the sample overheated through the electric current and found that theoretical current–voltage characteristic provided a good fit to the measurements. However, the suggested analytical formulas were too complicated, and it was not clear whether or not the thermal switching takes place under given conditions.

It seems that for a long time this interesting problem was left behind. Here we return to same task aiming to consider simplified, but more general model of the overheated sample at the certain averaged temperature and analyze current–voltage characteristics available for boron.

2. Criterion of thermal switching

Below the static current vs. voltage characteristic will be constructed under the assumption of a pure temperature effect in semiconductor sample, resistance of which uniformly reduces due to Joule heating. In such case, a good approximation of the current dependence of the sample’s steady resistance near the fixed ambient temperature $T$ is given by

$$ R(I) = R_0 \left(1 - \alpha \Delta T(I) \right) $$

Here $R_0$ and $\alpha > 0$, respectively, are the resistance of the sample and absolute value of its temperature coefficient at the ambient temperature, and $\Delta T(I)$ is the rise in temperature at current $I$ flowing through the sample. According to the Ohm’s law, $U = R(I)I$ is the voltage across the sample. Consequently, the Joule power input $UI$ equals to

$$ W_{\text{input}} = R_0 (1 - \alpha \Delta T(I))I^2 . $$

If $\Delta T(I) \ll T$ the power loss is proportional to $\Delta T(I)$,

$$ W_{\text{output}} = \lambda \Delta T(I) . $$

Here $\lambda$ is the effective heat-transfer coefficient, which in general includes not only thermal conduction through the electrodes, but also the thermal radiation from the sample’s lateral surfaces.

In steady state (i.e., for a stable operating point) the condition $W_{\text{input}} = W_{\text{output}}$ must be held meaning the heat-balance equation
With \( I_s^2 = \frac{\lambda}{\alpha R_0} \) and equations (1) and (4) we obtain

\[
\Delta T(I) = \frac{I^2}{I_s^2} - 1
\]

and

\[
R(I) = \frac{1}{1 + I^2 / I_s^2}.
\]

Then, with \( U_s = R_0 I_s / 2 \) the equation (6) yields relation between the normalized voltage \( U / U_s \) and normalized current \( I / I_s \):

\[
\frac{1}{2} \frac{dU}{U_s} = \frac{1 - I^2 / I_s^2}{(1 + I^2 / I_s^2)^2}
\]

For the relaxation point, where (normalized) differential resistance of sample \( R_0 \) equals to zero, we found \( I = I_s \) and \( U = U_s \) (see equation (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 then is retained even at a lower voltage. So, the arrangement under the consideration operates as a current switch and, according to equation (6), the switching point has to be attained by a current through the sample, which decreases its resistance by a factor of \( R_0 / R(I_s) = R_0 I_s / U_s = 2 \).

The equation (7) can be solved for the current value. There exist two roots. The first branch expresses current as a function of voltage below the switching point. If the voltage vanishes \( U \to 0 \) the current also \( I \to 0 \) and, in accordance with Ohm’s law, \( I \to U / R_0 \). The first branch of the current–voltage characteristic from the point \( (U_s, I_s) \) is followed by the second one

\[
\frac{I}{I_s} = \frac{U_s}{U} + \frac{U_s^2}{U^2} - 1
\]

where the differential resistance is negative and increases in absolute value. Now at \( U \to 0 \) the current depends inversely of the voltage \( I \to R_0 I_s^2 / U \) and, consequently, unrestrictedly large \( I \to \infty \).

The normalized theoretical curve calculated from equations (9) and (10) is shown in the figure 1.
Figure 1. Normalized current–voltage characteristic of the thermal switch.

If the averaged rise in temperature of the sample is not small in comparison with ambient temperature then the linear approximations for resistance and output power are no longer valid. For instance, the radiation part of the power should be presented as \( -((T + \Delta T(I))^4 - T^4) \). However, necessity of overheating at \( \Delta T(I) \geq T \) to reach the thermal switching means that absolute value of resistivity-temperature coefficient of the 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 then Thomson and Peltier heat contributions are generated in the bulk and at the electrodes, respectively. These are first-order effects vs. the current \( \sim I \), while the Joule heat is a second order effect \( \sim I^2 \). 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 then the temperature distribution is also symmetrical with respect to midpoint and the temperatures of both electrodes are the same. In such case, Thomson heat release inside one half of a sample is exactly compensated by Thomson heat absorption inside another one. Analogously, 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 the obtained criterion: resistivity of material at the switching current makes up almost the half of its Ohmic resistivity, i.e., the low current limit.

3. Testing of boron samples

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

The pairs of symmetrical 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 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. The \( I - U \) characteristics were displayed by the semiconductor device curve tracer. The switching effect has been investigated using static (DC) and so-called normal (sinusoidal AC of line frequency 50 Hz) regimes.

When very slowly increasing voltage was applied to the specimen, at first, there was only a slight increase in current; but, above a certain voltage, the current rose sharply while the voltage drop at the specimen decreased asymptotically to zero. The obtained characteristics are symmetric with respect to the 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 DC and AC are only slightly marked below the switching point. Therefore, the switching time is quite large (much greater than period of AC oscillations 0.02 s). The detected characteristics were fully reproducible as switching did not cause any irreversible changes in the specimens’ structure or any kind of electrostatic memory. It should be mentioned that all these features are inherent to the thermal effect.

**Table 1.** Switching ratios for tested boron specimens.

| Specimen                | \( R_0 I_s / U_s \) | References |
|-------------------------|----------------------|------------|
| Pure macrocrystalline \( \beta \)-B (1) | 1.97                | This work  |
| Pure macrocrystalline \( \beta \)-B (2) | 2.03                | This work  |
| Polycrystalline \( \beta \)-B       | 1.87                | [7]        |
| Amorphous B (1)           | 2.18                | [9]        |
| Amorphous B (2)           | 2.00                | [10]       |
| Amorphous B (3)           | 2.04                | [10]       |

Table 1 presents the values of switching ratio \( R_0 I_s / U_s \), i.e. ratio of resistances at zero and switching currents measured in static regime for two tested \( \beta \)-rhombohedral boron specimens. The values of the mean electric field strength at the switching points are 6.1 and 6.4 kV/cm, respectively, less than the suggested [15] upper limit 8 kV/cm of the hopping conductivity region. Thus, up to switching, these samples indeed are characterized with a negative resistivity-temperature coefficient. One can see that in both cases, the switching factors 1.97 and 2.03 almost equal 2, which is also true for some earlier results listed in the table. The thermal switching ratio can deviate from 2 because of varying contact resistances and also possibly due to variations in heat dissipation. Thus there is a good agreement between experiment and proposed theory for current–voltage characteristic. We can confidently explain the current instability effect observed in boron at room temperature as a process of thermal switching.

4. **Conclusions**
Finally, let us consider the probable reasons of thermal nature of current switching in \( \beta \)-rhombohedral boron. At room temperature \( (T = 300 \text{ K}) \) chemically pure material is characterized by the high resistivity (~ \( 10^7 \, \Omega \text{cm} \)) and the large and negative resistivity-temperature coefficient \( (\alpha \approx 0.0587 \, /\text{K}) \). The nature of hopping conductivity realized in boron seems suitable for observation of the thermal switching: (i) as there are practically no free current carriers, the breakdown via impact ionization is excluded; (ii) due to the high sample resistance, the overheating sufficient for the thermal switching is reached at relatively low voltage, which can not induce an electric field ionization of the low-lying hopping levels or inject free carriers from the electrodes before the switching point; (iii) because of the large absolute value of resistivity-temperature coefficient, the rise in temperature should to be small for the thermal excitation of the trapped carriers. Therefore, the switching in \( \beta \)-rhombohedral boron near the room temperature is predominantly a heat effect.

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