

CHANGE IN THE ELECTRICAL RESISTANCE OF POROUS $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ THIN FILMS UNDER CYCLIC ALTERNATING DEFORMATION AND TEMPERATURE

Sulaymonov Xusanboy Mannopovich – *Doctor of Philosophy in Physics and Mathematics*

xusanboy.sulaymonov@gmail.com

Fergana State Technical University

G'OVAKLI YUPQA $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ PLYONKALAR ELEKTR QARSHILIGINING TSIKLIK ISHORASI O'ZGARUVCHAN DEFORMATSIYA VA HARORAT TA'SIRIDA O'ZGARISHI

Sulaymonov Xusanboy Mannopovich – *fizika-matematika fanlari bo'yicha falsafa doktori*

Farg'ona davlat texnika universiteti

ИЗМЕНЕНИЕ ЭЛЕКТРИЧЕСКОГО СОПРОТИВЛЕНИЯ ПОРИСТЫХ ТОНКИХ ПЛЕНОК $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ ПОД ДЕЙСТВИЕМ ЦИКЛИЧЕСКОЙ ЗНАКОПЕРЕМЕННОЙ ДЕФОРМАЦИИ И ТЕМПЕРАТУРЫ

Сулаймонов Хусанбой Маннопович – *доктор философии по физико-математическим наукам*

Ферганский государственный технический университет

Tayanch so'zlar: Bi–Sb–Te plyonka, siklik deformatsiya, piezorezistivlik, donalararo to'siq, qarshilik minimum, charchash shikastlanishini nazorat qilish.

Rezyume. G'ovak $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ plyonkalarda siklik ishora almashinuvchi deformatsiyaning qarshilikning haroratga bog'liqligiga ta'siri o'rganildi. Deformatsiya sikllari soni 5×10^5 gacha oshirilganda qarshilik minimumi 333 K dan 408 K gacha siljishi, manfiy qarshilik harorat koeffitsiyentining mutlaq qiymati esa kamayishi aniqlandi. Natijalar g'ovak Bi–Sb–Te plyonkalarini charchash shikastlanishlarini nazorat qilishda qo'llash mumkinligini ko'rsatadi.

Ключевые слова: пленка Bi–Sb–Te, циклическая деформация, пьезорезистивность, межкристаллитный барьер, минимум сопротивления, контроль усталостных повреждений.

Резюме. Исследовано влияние циклической знакопеременной деформации на температурную зависимость сопротивления пористых пленок $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$. При увеличении числа циклов деформации до 5×10^5 температура минимума сопротивления смещается от 333 до 408 K, при этом абсолютная величина отрицательного температурного коэффициента сопротивления уменьшается. Полученные результаты показывают перспективность применения пористых пленок Bi–Sb–Te для контроля усталостных повреждений.

Key words: Bi–Sb–Te thin film, cyclic deformation, piezoresistance, intergranular barrier, resistance minimum, fatigue sensing.

Summary. Porous $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ films were studied under cyclic alternating deformation. The resistance minimum shifted from 333 K to 408 K as the number of deformation cycles increased to 5×10^5 , while the magnitude of the negative temperature coefficient of resistance decreased. The results indicate the potential of porous Bi–Sb–Te films for fatigue-damage sensing.

Introduction. Bismuth telluride and bismuth–antimony telluride remain key near-room-temperature thermoelectric materials and are increasingly used in flexible electronics and sensing systems [1, 2]. In thin-film form, their electrical transport depends strongly on grain boundaries, defects, interfaces and mechanical loading. These effects become especially important on compliant polymer substrates, where repeated deformation can progressively change the intergrain current path without causing immediate electrical failure.

Recent Bi_2Te_3 – BiSbTe flexible films combine high transport performance with substantial mechanical durability, and several device architectures exploit thermoelectric and piezoresistive responses simultaneously [6–12]. Most studies, however, evaluate bending stability through room-temperature resistance or thermoelectric performance. The evolution of the full resistance–temperature characteristic under accumulated cyclic deformation has received less attention, although it is directly relevant to fatigue-damage sensing. Porous polycrystalline films are particularly sensitive because electrical current crosses both crystalline grains and narrow intergranular gaps. Cyclic alternating deformation can modify contact area, effective barrier width and defect populations at these interfaces. Consequently, both the temperature coefficient of resistance (TCR) and the temperature $T_{\min}$ corresponding to the

resistance minimum can encode the accumulated mechanical history [3–5].

The aim of this work is to retain the experimentally established resistance–temperature behavior of porous $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ films while presenting it in an IMRAD framework. Particular attention is paid to the shift of $T_{\min}$ with deformation-cycle number and to a two-component grain/barrier model that explains the observed trend without introducing unsupported experimental parameters.

Materials and Methods. The investigated films were prepared from the $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ solid solution by thermal-vacuum condensation on polyimide-type substrates. Dense films obtained at approximately $T_s \approx 413$ K and $W \approx 400 \text{ Å s}^{-1}$ showed comparatively low strain sensitivity and a resistance–temperature dependence close to that of bulk-like material. Porous high-sensitivity films were obtained near $T_s \approx 363$ K and $W \approx 200 \text{ Å s}^{-1}$; the characteristic micropore dimensions along the current path were of the order of 30–50 Å, and the strain-gauge coefficient exceeded 10^3 . Resistance was measured over 293–455 K before and after cyclic alternating deformation. The cycle number N was increased up to 5×10^5 . The $R(T)$ curves analyzed below resolve the resistance minimum clearly in the experimentally relevant interval. The dense-film curve is used as a control, whereas the

porous-film curves reveal the cumulative influence of deformation on intergranular transport.

Following the model used for highly inhomogeneous strain-sensitive films [4,5], the current path is treated as a series combination of crystalline-grain resistances and intergranular pore/barrier resistances:

$$R_{nl} = \sum_i (R_{k,i} + R_{nop,i}) = R_{kp} + R_{nop} \quad (1)$$

where R_g is the contribution of crystalline grains and R_b is the contribution of intergranular regions. The grain contribution is approximated by a positive-TCR dependence:

$$R_{sp} = R_{sp}^0 [1 + \alpha_{sp} (T - T_0)] \quad (2)$$

where R_g^0 is the characteristic grain resistance at $T_0 = 273$ K. For a porous film, narrow intergranular regions act as finite-width potential barriers. Their resistance is represented by the thermally activated form

$$R_{nop} \approx R_{nop}^0 \cdot \exp(E_{nop} / \kappa T) \quad (3)$$

where E_b is an effective barrier energy and k_B is the Boltzmann constant. Combining the grain and barrier terms gives

$$R_{nl}(T) = R_{sp}^0 [1 + \alpha_{sp} (T - T_0)] + R_{nop}^0 \exp(E_{nop} / \kappa T) \quad (4)$$

The effective temperature coefficient of resistance is then

$$\alpha_{nl} = (\alpha_{sp} \cdot R_{sp}^0 - \frac{E_{nop}}{\kappa T^2} \cdot R_{nop}(T)) / (R_{sp}^0 + R_{nop}^0) \quad (5)$$

The minimum of $R(T)$ occurs when the positive grain contribution and the negative temperature derivative of the barrier contribution compensate. The corresponding condition can be written as

$$T_{\min} = \sqrt{\frac{E_{nop}}{\kappa \alpha_{sp}} \cdot \frac{R_{nop}(T_{\min})}{R_{sp}^0}} \quad (6)$$

or, using the barrier resistance evaluated at the reference temperature, approximately as

$$T_{\min} = \sqrt{\frac{E_{nop}}{\kappa \alpha_{sp}} \cdot \frac{R_{nop}(T_0)}{R_{sp}^0}} \quad (7)$$

Equations (1)–(7) show that an increase in the effective intergranular resistance shifts $T_{\min}$ toward higher temperature when the intrinsic grain parameters change only weakly with deformation. This prediction is tested against the experimental curves in the Results section.

Figure 1 preserves the experimentally reported $R(T)$ behavior. In the undeformed porous film ($N = 0$), resistance decreases with temperature and reaches a minimum near 333 K before increasing again. Mechanical cycling changes both the resistance level and the position of the minimum. $T_{\min}$ shifts to approximately 348 K after 1×10^5 cycles, 363 K after 2×10^5 cycles and 408 K after 5×10^5 cycles. The dense-film control changes much less, confirming that the cumulative response is associated primarily with the porous intergranular current path. The shift of $T_{\min}$ is accompanied by a strong reduction in the magnitude of the negative TCR below the minimum. The initial value is approximately $-5.6 \times 10^{-3} \text{ K}^{-1}$, whereas after 5×10^5 cycles it is about $-2.5 \times 10^{-4} \text{ K}^{-1}$. Thus cyclic deformation does not simply increase resistance; it changes the relative contribution of the two transport components described by Eqs. (1)–(7).

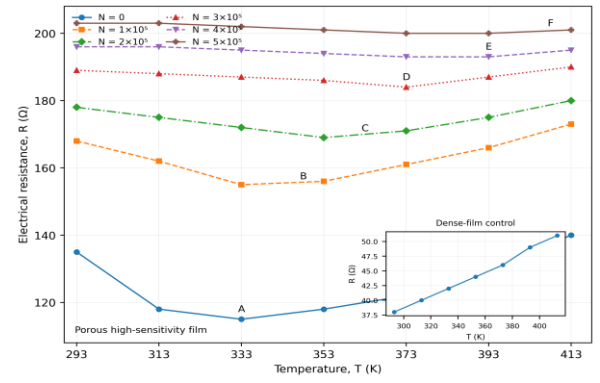


Figure 1. Resistance–temperature characteristics of porous $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ films before and after cyclic alternating deformation. Curves correspond to $N = 0\text{--}5 \times 10^5$ cycles; labels A–F indicate the progressive shift of the resistance minimum. The inset shows the dense-film control. The graph is a clean redraw of the original experimental figure.

Figure 2 summarizes the experimentally stated $T_{\min}$ values. Over the reported

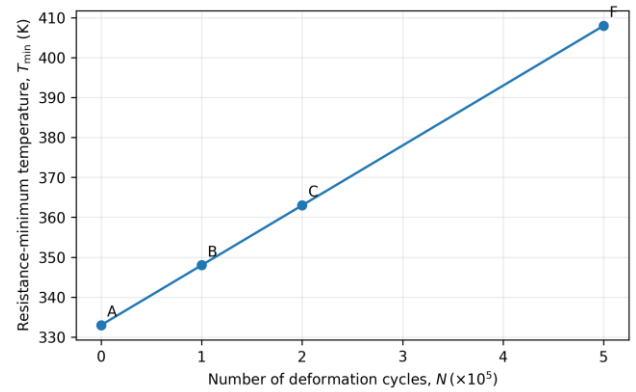


Figure 2. Resistance-minimum temperature $T_{\min}$ as a function of the number of cyclic deformation cycles. Experimental points: 333, 348, 363 and 408 K at $N = 0, 1 \times 10^5, 2 \times 10^5$ and 5×10^5 , respectively. The line is a guide to the eye; no unreported intermediate data are added.

Points, $T_{\min}$ increases monotonically from 333 to 408 K. Because only four numerical values are explicitly available, no intermediate points or error bars are introduced. The trend therefore serves as a compact experimental indicator of accumulated deformation rather than as a complete kinetic law.

Discussion. The central result is the systematic displacement of the resistance minimum with accumulated cyclic deformation. Dense films show only a weak change, whereas porous high-sensitivity films exhibit a pronounced upward shift of $T_{\min}$. This contrast is consistent with the two-component model: the crystalline-grain term has a positive temperature coefficient, while the intergranular barrier term decreases rapidly with increasing temperature. Their competition produces the minimum in $R(T)$. Cyclic loading repeatedly changes local contact pressure and shear at the grain boundaries. Contact wear, local separation, rearrangement of intergrain regions and defect redistribution can increase the effective barrier width or reduce the electrically active contact area. In Eqs. (6) and (7), an increase in R_b therefore raises $T_{\min}$. The simultaneous reduction of $|\text{TCR}|$ supports the same interpretation. The mechanism does not require a large

change in the intrinsic grain resistance; the history-dependent contribution can be concentrated mainly in the intergranular network [3-5].

This interpretation agrees with the broader literature on flexible Bi_2Te_3 - BiSbTe films, where electrical stability under repeated bending is controlled by microstructural continuity, interfaces and defect accommodation [1, 6-11]. Recent dual-mode temperature/pressure devices further show that Bi_2Te_3 -based layers can provide coupled thermal and mechanical readout [8,12]. The present films differ in purpose: instead of minimizing resistance drift, they intentionally exploit cumulative resistance evolution as a record of deformation history.

The temperature regions on the two sides of the minimum have different physical meaning. For $T < T_{\min}$, the overall temperature dependence is governed mainly by the highly inhomogeneous part of the current path: pore- and grain-boundary-associated barriers produce a negative contribution to the TCR because thermally assisted carrier transfer becomes easier as temperature rises. For $T > T_{\min}$, the positive temperature dependence of the crystalline-grain resistance becomes dominant and the $R(T)$ curve turns upward. The minimum therefore marks a crossover between two transport contributions rather than a separate phase transition. This interpretation is consistent with the original observation that the dense-film control follows a much more conventional, nearly bulk-like temperature dependence. The cycle dependence also explains why $T_{\min}$ is more informative than resistance measured at only one temperature. Mechanical cycling increases the effective contribution of intercrystallite regions, so the compensation condition is reached only at a higher temperature. Equations (6) and (7) express this directly through the dependence of $T_{\min}$ on R_b . At large N ,

only a limited population of mechanically active contacts remains available for further rearrangement, so the rate of change can decrease. The original measurements therefore indicate a tendency toward saturation at high cycle number, but the available discrete numerical points are insufficient for fitting a unique saturation law. For this reason Figure 3 shows only the experimentally stated points and does not introduce unmeasured intermediate values.

The practical implication is that $T_{\min}$ may be used as a temperature-readable state variable for fatigue accumulation. A calibrated film attached to a mechanically loaded component could retain the effect of previous cycles and be interrogated later through a limited $R(T)$ scan. At the same time, the present interpretation should remain conservative. Direct microstructural imaging before and after cycling, replicate specimens, controlled strain amplitude and frequency, and repeated heating-cooling tests are required to distinguish mechanical-history effects from thermal annealing and to quantify uncertainty.

Conclusions. Cyclic alternating deformation causes a cumulative modification of the temperature-dependent resistance of porous $(\text{Bi}_{0.3}\text{Sb}_{0.7})_2\text{Te}_3$ films. The resistance minimum shifts from about 333 K in the undeformed state to approximately 408 K after 5×10^5 cycles, while the magnitude of the negative TCR decreases markedly. The retained equations (1)–(7) describe the response as competition between a positive-TCR crystalline-grain contribution and a thermally activated intergranular-barrier contribution. An increase in effective intergranular resistance with cycling explains the observed upward shift of $T_{\min}$. The combined $R(T)$, $T_{\min}$ and TCR behavior supports porous Bi–Sb–Te films as promising cumulative fatigue-sensitive elements, provided that future work adds direct microstructural verification and statistical reproducibility.

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