Peculiarities of the electro- and magnetoresistivity of WTe$_2$ and MoTe$_2$ single crystals before and after quenching

Cite as: AIP Advances 11, 015226 (2021); https://doi.org/10.1063/9.0000182
Submitted: 15 October 2020 . Accepted: 25 November 2020 . Published Online: 11 January 2021

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Paper published as part of the special topic on 65th Annual Conference on Magnetism and Magnetic Materials

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Peculiarities of the electro- and magnetoresistivity of WTe$_2$ and MoTe$_2$ single crystals before and after quenching

ABSTRACT

WTe$_2$ and MoTe$_2$ single crystals were grown, some of them were quenched, and the following properties were studied: electroresistivity in the temperature range from 1.8 to 300 K, magnetoresistivity at temperatures from 1.8 to 300 K in magnetic fields of up to 9 T. On the one hand, quenching leads to dramatic changes in the behaviour and value of the electroresistivity of MoTe$_2$; the type of the electroresistivity changes from "semiconductor" to "metallic", and the electroresistivity values of MoTe$_2$ before and after quenching differ by 8 orders of magnitude (!) at low temperatures. On the other hand, quenching is shown not to lead to significant changes in the behaviour and value of the electroresistivity of WTe$_2$. A relatively small increase in the electroresistivity of quenched WTe$_2$ at low temperatures can be associated with the scattering of current carriers by structural defects. The magnetoresistivity of MoTe$_2$ increases from 7 to 16% in a field of 9 T at a temperature of 12 K as a result of quenching. The magnetoresistivity of WTe$_2$ is shown to reach $\sim$1700% in a field of 9 T at 2 K. The behaviour of the magnetoresistivity of non-quenched samples is typical for compensated conductors with a closed Fermi surface.

Topological Weyl semimetals (TWSs) based on transition metal dichalcogenides (TMDs) are of great interest both from fundamental and applied points of view (Refs. 1–6). Such materials have promising prospects for use in spintronics and micro- and nanoelectronics due to unusual electronic and magnetic properties owing to their unique band structure, such as extremely large magnetoresistance, high charge carrier mobility, and spin-polarized transport. In particular, quasiparticles in the bulk of TWSs are massless Weyl fermions. They can be controlled much faster than ordinary charge carriers due to "zero" effective mass. The unique spin-polarized surface states in TWSs are called Fermi arcs. TMD WTe$_2$ and MoTe$_2$ were found to exhibit the TWS features (Refs. 3 and 4). Moreover, the physical properties of MoTe$_2$ are known to strongly depend on the type of crystal structure that can be tuned by heat treatment (Refs. 7–9). MoTe$_2$ undergoes a transition from the diamagnetic semiconductor phase to the paramagnetic semimetallic one under certain conditions. Hence, it is of interest to track these changes in MoTe$_2$ and investigate how quenching affects the crystal and electronic structure of the WTe$_2$ compound, in particular, the electro- and magnetoresistivity. Therefore, the purpose of this work is to study the electro- and magnetoresistivity of WTe$_2$ and MoTe$_2$ single crystals before and after quenching.

II. EXPERIMENTAL

WTe$_2$ single crystals were grown by the chemical vapour transport method using Br$_2$ as a transport agent according to the procedure described in Ref. 8. In order to study the effect of quenching on...
the crystal structure and electronic transport of obtained samples, some single crystals were sealed in a quartz ampoule, then heated to 910°C, held at this temperature for 1 hour, and quenched in water.

X-ray diffraction analysis revealed that MoTe$_2$ crystallizes in a hexagonal structure with the lattice parameters $a = 3.540(7)$ Å and $c = 13.983(5)$ Å. The parameter $c$ changes noticeably after quenching to $\sim 13.81$ Å. Such values of the parameter $c$ before and after quenching are close to its values for $\alpha$-MoTe$_2$ (hexagonal) and $\beta$-MoTe$_2$ (monoclinic), respectively (Refs. 10–12), that may indicate the structural transition that occurred during quenching. While WTe$_2$ crystallizes in an orthorhombic structure with the lattice parameters $a = 3.435(8)$ Å, $b = 6.312(7)$ Å and $c = 14.070(4)$ Å. No significant changes in the crystal structure of WTe$_2$ after quenching are observed.

The chemical composition of the samples and microstructure of their surface were investigated using a FEI Inspect F scanning electron microscope (SEM) equipped with an EDAX attachment for X-ray microanalysis. Figure 1 shows the SEM images of MoTe$_2$ and WTe$_2$ before and after quenching. In the case of MoTe$_2$ (figure 1a, c), we can observe an increase in the layering of the sample after quenching. The layer thickness is approximately 1.5 μm. In the case of WTe$_2$ (figure 1b, d), an increase in the number of defects of the sample after quenching can be noted.

The temperature dependences of the electro- and magnetoresistivity were measured by the standard method (see, e.g. Refs. 13 and 14) in the temperature range from 1.8 to 300 K in magnetic fields of up to 9 T. The measurements were carried out using the PPMS-9 system (Quantum Design) in Collaborative Access Center “Testing Center of Nanotechnology and Advanced Materials” of IMP, UB of RAS.

### III. RESULT AND DISCUSSIONS

Figure 2 shows the temperature dependences of the electoresistivity $\rho_0(T)$ of MoTe$_2$ (figure 2a) and WTe$_2$ (figure 2b) before and after quenching.
and after quenching in the temperature range from 1.8 to 300 K. The dependence $\rho(T)$ of non-quenched MoTe$_2$ (figure 2a) is seen to have a “semiconductor” type with a very large resistivity value of more than $10^4$ Ohm cm at low temperatures, whereas the resistivity is less than 1 Ohm cm at temperatures above 50 K. The dependence $\rho_0(T)$ of quenched MoTe$_2$ shows a “metallic” behaviour with a resistivity value of $\sim (1.1-6.8)\times10^{-3}$ Ohm cm, that is 8 orders of magnitude (!) less than the resistivity of MoTe$_2$ before quenching at low temperatures. Thus, quenching leads to the dramatic change in the electroresistivity of MoTe$_2$. The analysis of the behaviour of electroresistivity of MoTe$_2$ before and after quenching is presented in Ref. 15. The dependence $\rho_0(T)$ of WTe$_2$ (figure 2b) has a “metallic” type with a resistivity value of $\sim (0.2-8.6)\times10^{-4}$ Ohm cm, monotonically increasing with temperature according to a law close to quadratic at low temperatures, reaching a linear dependence at high temperatures, $\approx 1$ at high temperatures, which can be due to the scattering of current carriers by structural defects in WTe$_2$ tends to 1 at high temperatures, and after quenching in the temperature range from 1.8 to 300 K. Quenching is seen to do not lead to significant changes in the behaviour and value of the electroresistivity of WTe$_2$. The MR was calculated by the formula

$$\Delta \rho_{xx}/\rho_0 = (\rho_{xx} - \rho_0)/\rho_0 \times 100\%,$$

where $\rho_0$ is the electroresistivity without a magnetic field, $\rho_{xx}$ is the resistivity in magnetic fields of up to 9 T. The dependence $\Delta \rho_{xx}/\rho_0(B)$ of MoTe$_2$ before quenching is close to quadratic and about $7\%$ in a field of 9 T (figure 4a). The quadratic dependence $\Delta \rho_{xx}/\rho_0(B)$ is known to be characteristic of compensated conductors with a closed Fermi surface Ref. 16. Quenching is seen to lead to an increase in the MR to $\sim 16\%$, and along with the quadratic field contribution, the linear term also appears. The linear on a magnetic field contribution to the MR can be due to the appearance of open electron orbits perpendicular to the direction of the electric current in reciprocal space Ref. 16. Figure 4b shows the field dependence of the MR of WTe$_2$. The MR increases with a field and reaches $\sim 1700\%$ at 2 K in a field of 9 T. The analysis of the dependence $\Delta \rho_{xx}/\rho_0(B)$ of WTe$_2$ revealed that, since the MR changes according to a law close to quadratic in fields of up to 9 T, such a behavior of the MR is typical for compensated conductors with a closed Fermi surface in the region of strong effective magnetic fields Ref. 16.

It should be noted that the magnitude of the MR of WTe$_2$ is 2 orders of magnitude higher than that of the MR of MoTe$_2$ (Figure 4). This is largely due to the difference in the “electrical” purity of the crystals, i.e. Residual Resistance Ratio (RRR), where RRR = $\rho_{xx}/\rho_0 B_0 K$. For WTe$_2$, RRR $\approx 43$, and for MoTe$_2$ after quenching, RRR $\approx 6$. Thus, in the case of the WTe$_2$ single crystal, the range of magnetic fields of up to 9 T, where the close-to-quadratic magnetic field dependence of the MR is observed, refers to the region of high effective magnetic fields with $\omega \tau > 1$ (a is the cyclotron frequency, $\tau$ is the relaxation time) with a strong dependence on $B$ and a large MR Ref. 16. A similar strong dependence $\Delta \rho_{xx}/\rho_0(B)$ with a large MR was observed in the Ref. 17. For the MoTe$_2$ single crystal after quenching, magnetic fields of up to 9 T are apparently intermediate, where $\omega \tau \sim 1$, with the weaker dependence $\Delta \rho_{xx}/\rho_0(B)$ and the significantly lower MR.
IV. CONCLUSIONS

The studies of the electro- and magnetoresistivity of WTe\textsubscript{2} and MoTe\textsubscript{2} single crystals before and after quenching allow us to draw the following conclusions. On the one hand, quenching leads to the dramatic changes in the behaviour and value of the electroresistivity of MoTe\textsubscript{2}: the type of the electroresistivity changes from “semiconductor” to “metallic”, and the electroresistivity value of MoTe\textsubscript{2} decreases by 8 orders of magnitude (!) from $\sim 10^5$ to $\sim 10^{-3}$ Ohm cm at low temperatures. On the other hand, quenching is shown to do not lead to significant changes in the behaviour and value of the electroresistivity of WTe\textsubscript{2}: the type of the temperature dependence of the electroresistivity is “metallic”, and its value increases from $0.2 \cdot 10^{-4}$ to $8.6 \cdot 10^{-4}$ Ohm cm in the temperature range from 1.8 to 300 K. A relatively small increase in the electroresistivity of quenched WTe\textsubscript{2} at low temperatures can be associated with the scattering of current carriers by structural defects, which are also reflected by the data of scanning electron microscopy. The MR of MoTe\textsubscript{2} increases from 7 to 16% in a field of 9 T at a temperature of 12 K as a result of quenching. The MR of WTe\textsubscript{2} is shown to reach $\sim 1700$% in a field of 9 T at 2 K. The behaviour of the MR of non-quenched samples is typical for compensated conductors with a closed Fermi surface.

ACKNOWLEDGMENTS

The research was carried out within the state assignment of Ministry of Education and Science of the Russian Federation (theme “Spin”, No. AAAA-A18-118020290104-2), supported in part by RFBR (Project No. 20-32-90069) and the Government of the Russian Federation (Decree No. 211, Contract No. 02.A03.21.0006).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES