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Photomemristive switching in bismuth selenide crystals

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An effect of optical switching of resistive states in structures based on chalcogenide Bi_2Se_3 compounds with copper and graphene electrodes was discovered. Authors proposed a physical model which describes the processes occurring during switching. The obtained results indicate the possibility of using the studied photomemristive structures as artificial synapses for neuromorphic computing, which weighting coefficients can be set both electrically and optically.

Keywords: chalcogenides; photomemristors; resistive switching; photomemristive states.

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Introduction

The high energy efficiency of biological "computing and detection systems" compared to the enormous energy consumption of modern computing and detection devices developed by humans to detect and analyze big data related to visual information stimulates great interest to research of operational principles of neuromorphic systems. Today, detection and processing of visual information is carried out using the Von Neumann architecture, where sensory, memory, and computing units are divided. This requires converting the optical signal into an electrical one, transmitting it to the computer, to the memory and back. Machine learning algorithms in such systems are implemented at the software level, which undoubtedly results in the poor quality of the issue solution and increases energy costs and the time for processing visual data. The development and implementation of “analog” artificial synapses and neurons is a critical task to improve energy efficiency and accelerate processing speed of electrical [1–3] and optical signals [4–6].

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Chalcogenide memristors, control of resistive states by electric field

Layered chalcogenide materials such as bismuth selenide Bi_2Se_3 consist of two layers of Bi and three layers of Se (so-called quintuples, which are about 1 nm thick). These layers are linked together by Van der Waals bonds. This allows bulk crystals to be split along these layers, allowing to obtain very high-quality microscopic structures with quite simple methods. The possibility of memristive switching in bismuth selenide crystals (E_g = 0.3–0.8 eV) was previously demonstrated [7, 8].

From Bi_2Se_3 crystals obtained by the Bridgman method, cleavages were prepared along the quintupule layers, with characteristic dimensions of 3–4 mm along the layers and 200–300 µm across, which were then transferred to a copper substrate served as the lower electrode. The transferred crystals were pressed mechanically onto the substrate using a beryllium bronze rod, which served as the top electrode. Samples were also made from layered Bi_2Se_3 crystals obtained by exfoliating a bulk crystal with adhesive tape and transferred to a Si/SiO_2 substrate, followed by the production of gold electrodes for them using electron beam lithography (Fig. 1, left). The obtained structures were studied for their current-voltage characteristics (CVC) and the time parameters of electrical and optical switching using a Keithley 2450 source meter, a GW Instek AFG 73021 arbitrary waveform generator, a LeCroy WaveSurfer 24Xs-A oscilloscope, and laser excitation at a wavelength of 650 nm.

The structure produced with Au-Bi_2Se_3-Au gold electrodes exhibited a linear CVC without resistive switching features (Fig. 1, right). The absence of resistive switching and an ohmic CVC were also observed in the structure with silver electrodes made to the edges of the crystal using RS PRO Silver Conductive silver glue.

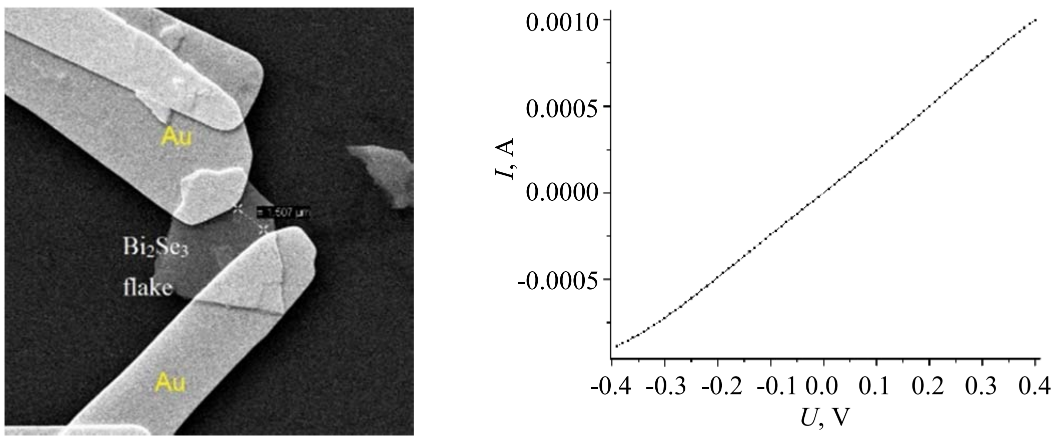

Fig. 1. Layered Bi_2Se_3 crystals transferred onto a Si/SiO_2 substrate (by exfoliating the bulk crystal with adhesive tape) with gold electrodes produced with electron beam lithography (left) and the CVC of the Au/Bi_2Se_3/Au structure (right)

The vertical structure with copper electrodes Cu-Bi_2Se_3-BeCu showed a change in resistance in a range of values from R_{high} = 100 Ohm to R_{low} = 5 Ohm. The reproducibility of the resistance value was about 10 %, which made it possible to obtain 9 memristive states (Fig. 2) of the sample when it was treated by electrical pulses. Thus, it was shown that memristive states in a vertical structure can be achieved with an "active" copper electrode. Based on these experimental data, X-ray diffraction analysis and analysis of previously published data, it was concluded that the observed resistive switching is caused by the migration of active metal compounds, percolation of these compounds into Van der Waals gaps [9] and transport of point structural defects (such as selenium vacancies) in the surface modified layer [10]. The application of an electric field of one polarity results in formation of a conductive channel, which is maintained when the external electric field is switched off, and is destroyed when treated with an electric field of reverse polarity.

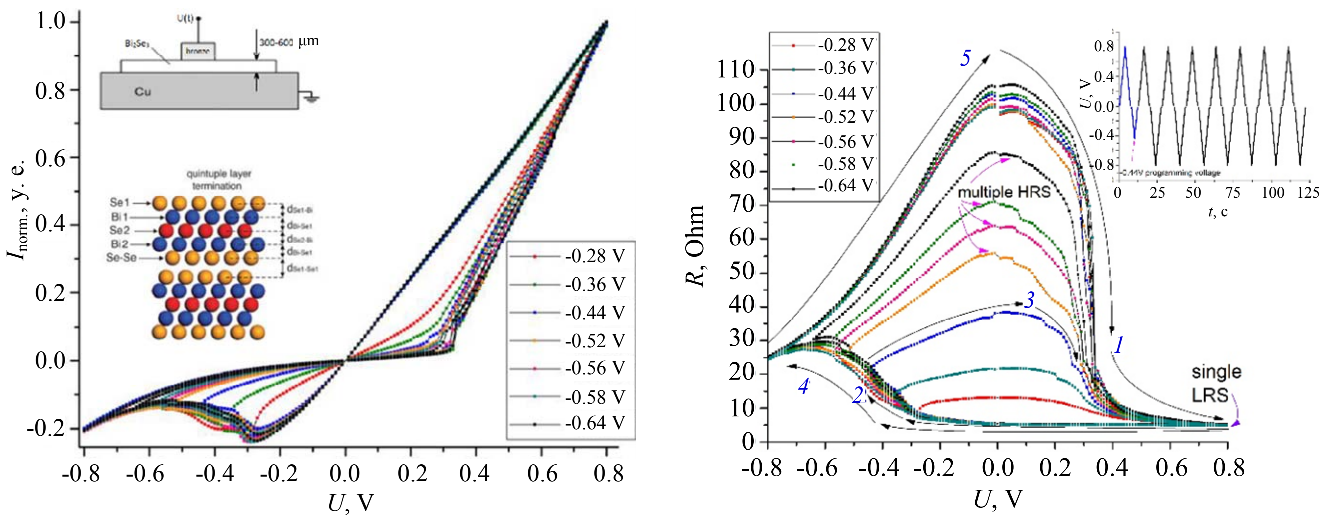

Fig. 2. Control of resistive states of the Cu-Bi_2Se_3-BeCu structure by an electric field. structure CVC (left). Inserts: Layout view of the sample (top left) and the structure of Bi_2Se_3 (bottom left). Dependence of the resistance of the Cu-Bi_2Se_3-BeCu structure on the bias voltage (right). Insert: Time sweeping of offset voltage

Optical response

The optical response of the Cu-Bi_2Se_3-BeCu structure was also investigated (Fig. 3). The sample treated by optical radiation (650 nm laser), turned into a low-resistance state at different bias voltages. When the optical pulse was turned off, the structure "electrically" returned to the resistance value caused by the electric field. Transitions to intermediate optical states, as we assume, are possible when the radiation parameters (wavelength, pulse duration) vary.

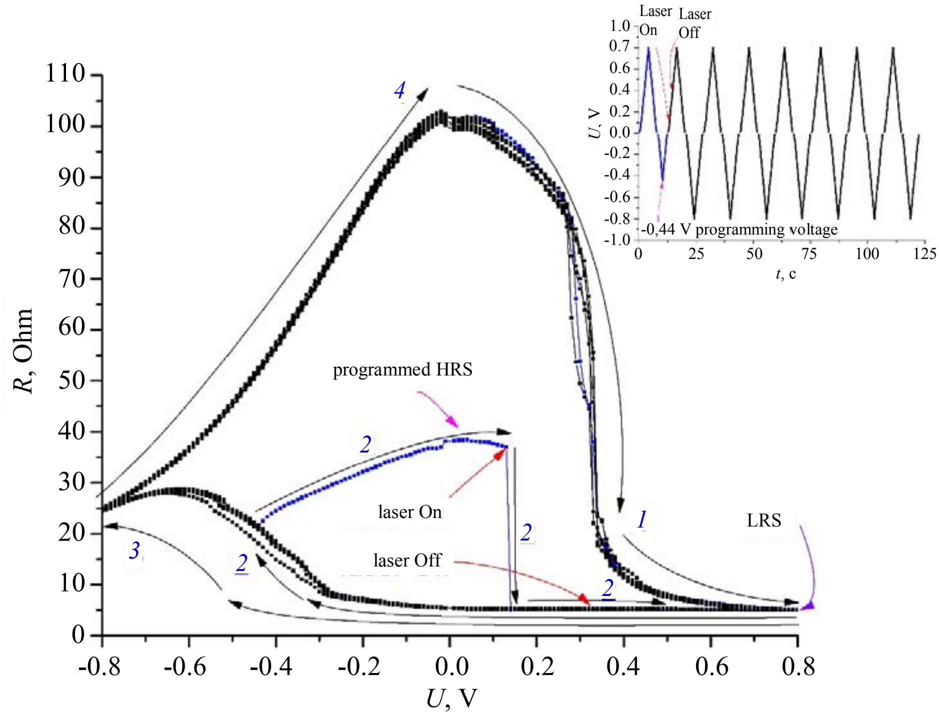

Fig. 3. Control of resistive states of the Cu-Bi_2Se_3-BeCu structure electrically and optically. Inset: time sweeping of bias voltage of the structure with programming and optical excitation by 650 nm laser

Active electrode made of oxidized graphene

The studied vertical Bi_2Se_3 structures demonstrated photomemristive properties in the presence of an active electrode, when the current flows across the quintupole layers and the modified layer formed on the Bi_2Se_3 surface. For optical applications [11], vertical structures with a transparent active electrode are of particular interest. In this work, such electrode was made of oxidized graphene (OG), which can serve as a source of oxygen modifying the surface layer of the structure when exposed to an electric field or optical radiation [6].

Figure 4 shows the dependence of the resistance of the produced Au/Bi_2Se_3/OG structure on the bias voltage under electrical and optical excitation. The top electrode to the structure was made from OG transferred onto a plastic substrate (Fig. 4, insert). The structure with the OG clamping electrode exhibited resistive properties similar to those of the Cu-Bi_2Se_3-BeCu structure, but less stable, which may be due to the defective structure of the thin OG clamping layer. This did not allow HRS programming to be performed. From cycle to cycle, the HRS instabilityexceeded 20 % (LRS 1 ~150 kOhm was more stable). This parameter can be improved by enhancing the contact between graphene and Bi_2Se_3 by direct transfer of the graphene electrode to the crystal surface, which requires refining the transfer technique to low-dimensional structures.

Upon optical excitation, the Au/Bi_2Se_3/OG structure switched to a low-resistance state LRS 2 (~100 kOhm), lower than LRS 1, to which the structure was switched from HRS by an electric field. Still the LRS 2 state did not turn to HRS in this range of bias voltages, indicating that it may depend on duration, intensity, and wavelength of the laser pulses used. The obtained results were reproduced on several fabricated structures, all of them, having similar CVC and R(U), switched reversibly by an electric field from HRS to LRS 1 and irreversibly by optical excitation from HRS to LRS 2. This indicates a more complex mechanism of resistive switching in such heterostructures during their optical excitation under changing electric field. A system of coordinated control of the duration and intensity of optical and electrical pulses will allow such experiments to be carried out in more details.

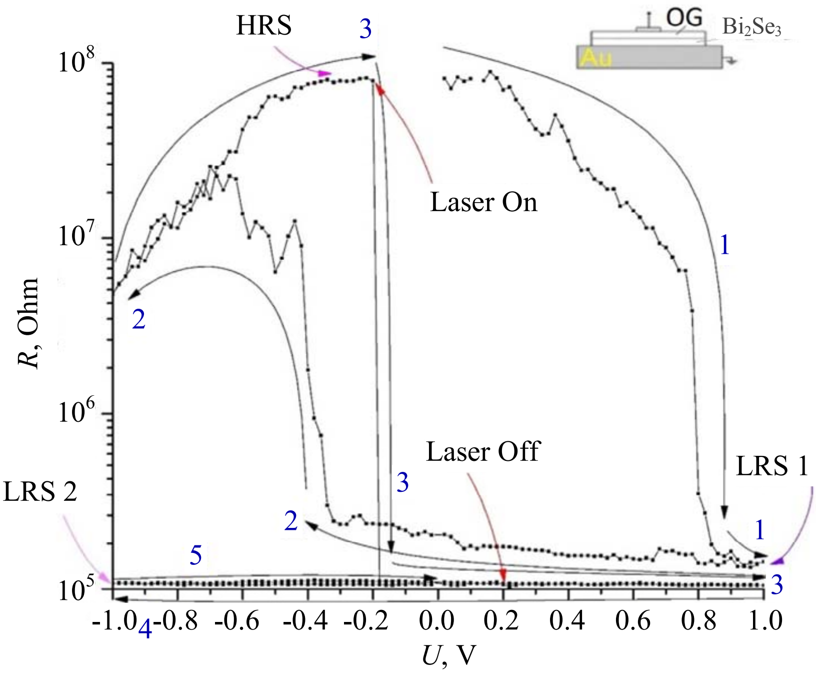

Fig. 4. Control of resistive states of the Au/Bi_2Se_3/OG structure electrically and optically. Insert: schematic representation of the sample under study

Conclusion

Authores produced and studied two types of structures, Cu/Bi_2Se_3/BeCu and Au/Bi_2Se_3/OG, showing resistance plasticity under electrical and optical excitation. The obtained results indicate the potential of memristive structures based on layered Bi_2Se_3 chalcogenides for the implementation of artificial synapses for neuromorphic computing and optical signal processing in photosensors.

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