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L. Konopko, A. Nikolaeva, T. Huber, C. Slobodeniuc, "Tunnel junctions in Bi and Bi0.97Sb0.03 nanoconstrictions," Proc. SPIE 11718, Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies X, 117181R (31 December 2020); doi: 10.1117/12.2571226

Event: Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies 2020, 2020, Online Only

Tunnel junctions in Bi and $Bi_{0.97}Sb_{0.03}$ nanoconstrictions

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ABSTRACT

Here we investigated the field emission effect in nanoconstrictions made on the basis of the microwire in glass insulation. Glass-coated single-crystal microwires of Bi and Bi-Sb were fabricated by the Ulitovsky method; then, using the technique of local laser heating, nanoconstrictions were made. We investigated the field electron emission obtained in Bi and $Bi_{0.97}Sb_{0.03}$ nanoconstrictions at various temperatures and different potentials on the gate electrode. We observed a change in the field emitted electron current depending on the potential on the gate electrode. This difference $\Delta I/I=0.26$ is a manifestation of the change in the microwire tip potential due to the electric field effect.

Keywords: Bi, Bi-Sb, glass-coated microwire, nanoconstriction, field emission, current–voltage characteristic, field effect.

1. INTRODUCTION

Field emission occurs when a strong electric field with an intensity of about 10 MV/cm is applied to the surface of a solid. As a result, the semi-infinite potential barrier at the boundary of the body with the vacuum transforms and acquires a finite width. A decrease in the height of the potential barrier in an external field with intensity U is called the Schottky effect. The combination of these factors leads to a purely quantum-mechanical phenomenon, the possibility of electron tunneling through a potential barrier without energy loss [1]. The theory of field emission processes was developed in 1928-1929 by Fowler and Nordheim [2], after the discovery of the quantum-mechanical tunnel effect. The basic equation derived by them describes the dependence of the field emission current density on the initiating factor - the electric field strength. The main problem is to enhance the electric field at the nanowire tips in order to generate field effect emission, whose physical mechanism is sketched in insert (a) in right panel of Fig. 2. To obtain field emission current from the cathode surface, significant field strengths of at least $3\text{-}5 \cdot 10^7$ V/cm are required. It is almost impossible to create such high electric fields in plane-parallel geometry, since, for example, for a centimeter gap, generation and supply of a very high potential of more than 10 MV is required. Therefore, in order to obtain large field strength on the cathode surface necessary for electron field emission, the emitting surface must be in the region of large curvature and, accordingly, a strong local electric field. As a result, field emission is usually observed only at cathodes in the form of a tip or a blade. Based on the fact that we have already developed a technology for manufacturing nanoconstrictions from glass-coated Bi and Bi-Sb microwires, we decided to contribute to ivestigation of field emission in special prepared glass-coated microwires. In our samples, after laser irradiation, the minimum core diameter can be 50-100 nm, which suggests the generation of a strong local electric field.

2. SAMPLES AND EXPERIMENTAL DETAILS

Individual Bi and Bi-Sb nanowires were prepared using the Ulitovsky technique [3] (see schematic diagram in the left panel of Fig. 1). This technique involves a high-frequency induction coil melting of a Bi or Bi-Sb boule within a borosilicate glass (Pyrex) capsule in an argon atmosphere, a process which simultaneously softens the glass and melts the metal, followed by the drawing of a glass capillary containing the nanowire. The nanowires were cylindrical single-crystals with the $(10\underline{1}1)$ orientation along the wire axis. With the Ulitovsky technique owing to the high frequency stirring and high speed crystallization ($> 10^5$ K/s) involved it is possible to obtain homogeneous monocrystalline $Bi_{0.97}Sb_{0.03}$ nanowires. Bismuth is a semimetal with strong spin–orbit interactions, which has an indirect negative gap

Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies X, edited by
Marian Vladescu, Razvan Tamas, Ionica Cristea, Proc. of SPIE Vol. 11718, 117181R
© 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2571226

($\Delta E = -37$ meV) between the valence band at the T point of the bulk Brillouin zone and the conduction band at the L points [4]. Bismuth has unique properties, such as a low charge carrier concentration and high carrier mobility. Recently, it has been discovered that, in bulk samples, the crystal hinges, rather than the crystal surfaces, host topologically protected conducting modes [5]. The substitution of bismuth with antimony changes the critical energies of the band structure [6]. At concentration x = 0.04, the system turns into a gapless state at the L point. Schematic representation of band energy evolution of $Bi_{1-x}Sb_x$ as function of x is shown in left panel of Fig. 2. We developed a technology for fabrication of nanoconstrictions from Bi and Bi-Sb microwires in glass coating using local laser heating technique. In this method the glass-coated microwire fixed on a moving substrate is heated above the melting temperature by focused infrared laser beam (see right panel of Fig. 1.). However, it is rather difficult to obtain the necessary size of the gap in the glass-coated microwire during laser irradiation. Nanoconstrictions of this type are well protected by a glass cover of the external environment. By the method of cyclic increase in current (Left panel of Fig. 3, inserts (a) and (b)), due to the difference in density ρ in molten and solid states in Bi (ρ_{melt} =10.05 g/cm^3, ρ_{solid} =9.78 g/cm^3), we obtained a break in the thinnest part of the nanoconstriction. To make a tunnel contact, it is necessary to obtain a gap value l less than de Broglie wavelength λ_F, $l \leq \lambda_F$. In Bi and Bi-Sb the de Broglie wavelength of the Fermi electrons, $\lambda_F = h/P_F$, (where h is Planck's constant and P is momentum), is rather large ~ 50 nm. Unfortunately, in the vast majority of cases using this technology, the gap in the nanoconstruction was greater than λ_F.

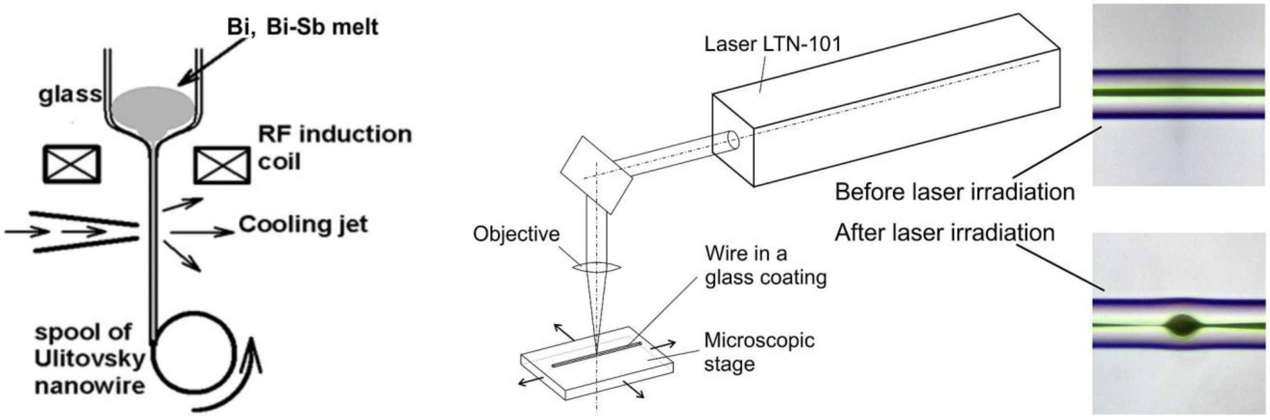

Figure 1. Left panel: Ulitovsky method for preparation of long glass-insulated wires with small diameters. Right panel: Schematic of the installation for manufacturing nanoconstrictions from glass-coated microwires using local laser heating technique.

3. RESULTS AND DISCUSSION

Current – voltage characteristics of Bi nanoconstriction at various temperatures are shown in right panel of Fig. 2. This nanoconstriction was made of bismuth microwire with outer diameter D=21 μm and core diameter d=2.1 μm. The effect of field emission was observed immediately after laser irradiation. As can be seen from the figure, the field emission current at room temperature is much less than at helium temperatures. This can be explained if we take into account that the tips are in a glass capillary. With increasing temperature, the Pirex glass expands linearly ($k=4 \cdot 10^{-6}$ $^oC^{-1}$), which leads to an increase in the distance between the tips and, accordingly, to a decrease in current. Fowler-Nordheim plots ($ln(I/V^2)$ versus l/V) are shown in the insert (b) right panel of Fig. 2. Obtaining a linear dependence of the Fowler-Nordheim plots can be considered as a qualitative confirmation of the effect of field emission in Bi nanoconstriction. The curves of the emission current versus applied voltages (I-V) in $Bi_{0.97}Sb_{0.03}$ nanoconstriction at various temperatures are depicted in left panel of Fig. 3. This nanoconstriction was made of $Bi_{0.97}Sb_{0.03}$ microwire with outer diameter D=37.8 μm and core diameter d=3.7 μm. The effect of field emission in nanocostriction was observed after additional cycling with an increasing current (see inserts (a) and (b)). In this sample, a difference in the field emission current was also observed at various temperatures. Fowler-Nordheim curves confirmed the presence of the effect of field emission (see insert (c)).

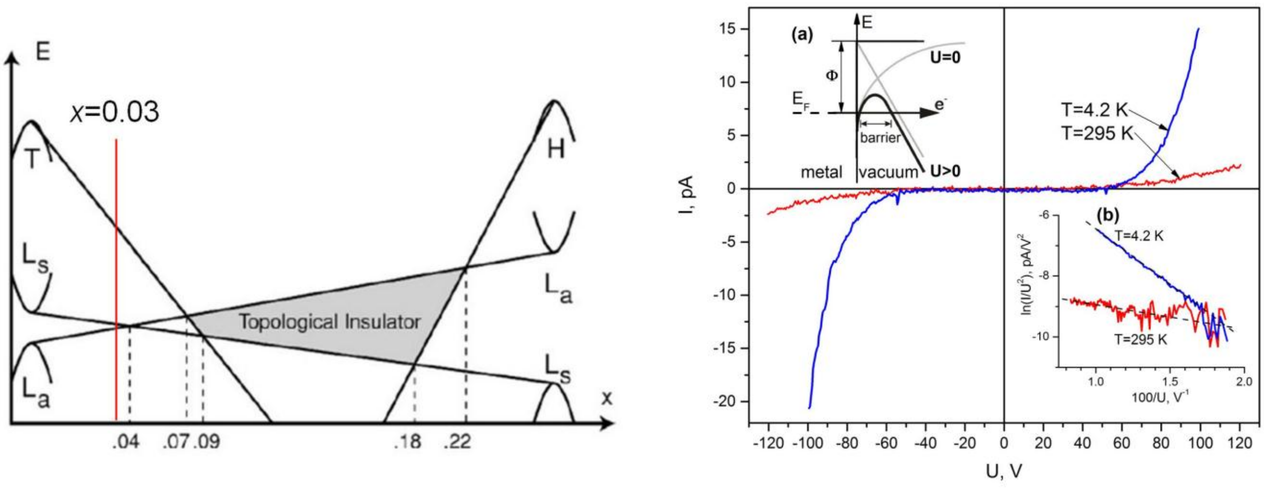

Figure 2. Left panel: Schematic representation of band energy evolution of $Bi_{1-x}Sb_x$ as function of x. Right panel: Field emission current versus electric potential curves of the obtained Bi nanoconstriction at various temperatures. Nanoconstriction was made of bismuth microwire with an outer diameter *D*=21 μm and a core diameter *d*=2.1 μm. Inset (a): electric field emission mechanism at metal/vacuum interface. Inset (b) shows the corresponding Fowler-Nordheim relationships (*ln(I/U^2) - 1/U plot*).

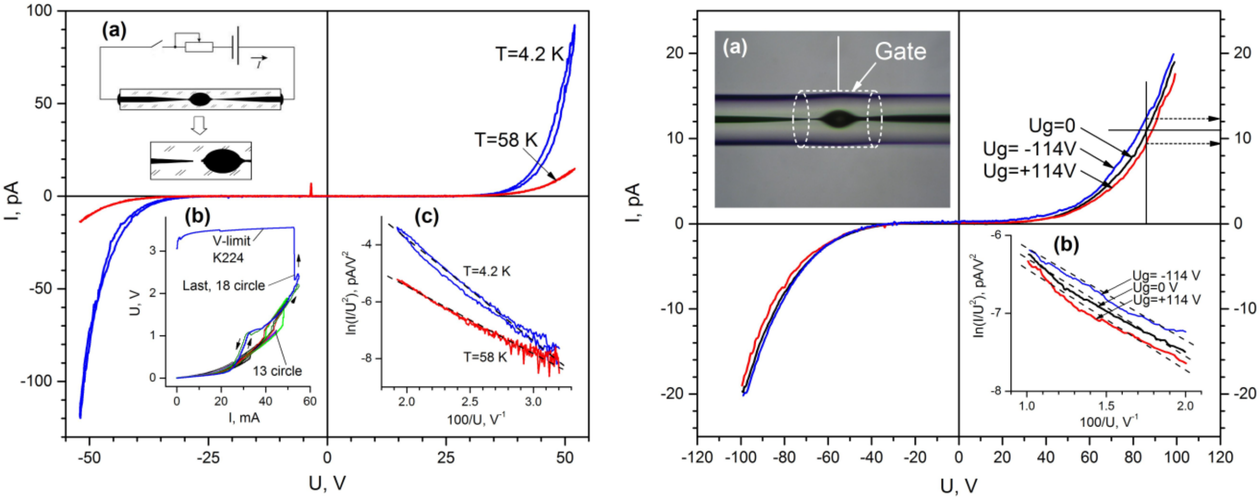

Figure 3. Left panel: Field emission current versus electric potential curves of the obtained $Bi_{0.97}Sb_{0.03}$ nanoconstriction at various temperatures. Nanoconstriction was made of $Bi_{0.97}Sb_{0.03}$ microwire with an outer diameter *D*=37.8 μm and a core diameter *d*=3.7 μm by laser heating technique (without formation of a break). Then, the increasing current circulation through the nanoconstriction at 4.2 K eventually led to the formation of a break. Inset (a): Scheme of the formation of a break in the nanoconstruction. Inset (b): *U-I* characteristics during the formation of a gap in a nanoconstruction. Inset (c) shows the corresponding Fowler-Nordheim relationships (*ln(I/U^2) - 1/U plot*). Right panel: Field emission current versus electric potential curves of the obtained $Bi_{0.97}Sb_{0.03}$ nanoconstriction at various potentials on the gate electrode, *T*=1.5 K. Inset (a): Schematic of the sample; The gate electrode was made with silver paint. Inset (b) shows the corresponding Fowler-Nordheim relationships (*ln(I/U^2) - 1/U* plot).

Current – voltage characteristics of $Bi_{0.97}Sb_{0.03}$ nanoconstriction (base on $Bi_{0.97}Sb_{0.03}$ microwire with outer diameter D=38 µm and core diameter d=3.7 µm) at temperature T=1.5 K and various potentials on gate electrode (U_g=±114 V) are shown in right panel of Fig. 3. The effect of field emission was observed immediately after laser irradiation. By putting silver paint to the surface of the nanoconstriction, a gate electrode was made (see insert (a)). We applied different potentials to the cylinder gate electrode in order to obtain the dependence of the field emission current on the gate voltages. The electric field effect on Bi films and nanowires leads to a significant bending of the zones on the surface [7, 8], which affects the height of the potential barrier at the tip and, accordingly, leads to a change in the field emission current. The change in the field emission current, depending on the gate potential, is quite large ($\Delta I/I$ = 0.26). The Fowler-Nordheim curves also confirmed the presence of field emission effect (see insert (b)). When comparing the results, it turns out that the effect of field emission in nanocostriction, which was observed after additional cycling with increasing current, led to much greater field emission current.

4. CONCLUSIONS

We investigated the field emission effect in nanoconstrictions made on the basis of the microwire in glass insulation. Glass-coated single-crystal microwires of Bi and Bi-Sb were fabricated by the Ulitovsky method; then, using the technique of local laser heating, nanoconstrictions were made. We investigated the field electron emission obtained in Bi and $Bi_{0.97}Sb_{0.03}$ nanoconstrictions at various temperatures and different potentials on the gate electrode. Fowler-Nordheim curves confirmed the presence of the effect of field emission. The electric field effect on Bi nanowires leads to a significant bending of the zones on the surface, which affects the height of the potential barrier at the tip and, accordingly, leads to a change in the field emission current. The change in the field emission current, depending on the gate potential (U_g=±114 V), is quite large ($\Delta I/I$ = 0.26). When comparing the results, it turns out that the effect of field emission in nanocostriction, which was observed after additional cycling with increasing current, led to much greater field emission current..

ACKNOWLEDGEMENTS

This work was supported by Moldova State Project # 20.80009.50007.02, NSF through STC CIQM 1231319, the Boeing Company and the Keck Foundation.

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