Publication information

Title	Interface effect in Nb-Bi ₂ Te ₃ hybrid structure
Author(s)	Liu, Hongchao; He, Hongtao; Li, Baikui; Liu, Shiguang; He, Qinglin; Wang, Gan; Sou, Iam Keong; Wang, Jiannong
Source	Applied Physics Letters , v. 103, (15), October 2013, article number 152601
Version	Published version
DOI	http://dx.doi.org/10.1063/1.4824651
Publisher	American Institute of Physics (AIP) Publishing

Copyright information

This article may be downloaded for personal use only. Any other use requires prior permission of the author and AIP Publishing. The following article appeared in "Liu, H., He, H., Li, B., Liu, S., He, Q., Wang, G., Sou, I.K., & Wang, J. (2013). Interface effect in Nb-Bi₂Te₃ hybrid structure, Applied Physics Letters, 103(15), article number 152601." and may be found at <http://dx.doi.org/10.1063/1.4824651>

Notice

This version is available at HKUST Institutional Repository via <http://hdl.handle.net/1783.1/61994>

If it is the author's pre-published version, changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published version.

Interface effect in Nb-Bi₂Te₃ hybrid structure

Hong-Chao Liu, Hong-Tao He, Bai-Kui Li, Shi-Guang Liu, Qing Lin He, Gan Wang, Iam-Keong Sou, and Jiannong Wang

Citation: *Applied Physics Letters* **103**, 152601 (2013); doi: 10.1063/1.4824651

View online: <http://dx.doi.org/10.1063/1.4824651>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/103/15?ver=pdfcov>

Published by the AIP Publishing

Articles you may be interested in

Interfacial roughness and proximity effects in superconductor/ferromagnet CuNi/Nb heterostructures

J. Appl. Phys. **118**, 213905 (2015); 10.1063/1.4936789

Response to "Comment on 'Anomalous capacitance response induced by the superconducting gap in an Au/BiFeO₃/La_{1.84}Sr_{0.16}CuO₄/LaSrAlO₄ heterostructure'" [Appl. Phys. Lett. 105, 246103 (2014)]

Appl. Phys. Lett. **105**, 246104 (2014); 10.1063/1.4897991

Fluctuation-induced conductivity analyses of Be-doped (Bi_{0.25}Cu_{0.25}Li_{0.25}Ti_{0.25})Ba₂Ca₂Cu₃O_{10-δ} superconductors in the critical regime and beyond

J. Appl. Phys. **111**, 033917 (2012); 10.1063/1.3681325

Single electron transistors with Nb/AlO_x / Nb junctions

J. Vac. Sci. Technol. B **21**, 775 (2003); 10.1116/1.1560213

Magnetic memory effect in YBa₂Cu₃O_{7-x} / (BiDy)₃(FeGa)₅O₁₂ heterostructures

J. Appl. Phys. **83**, 7327 (1998); 10.1063/1.367835

NEW Special Topic Sections

NOW ONLINE
Lithium Niobate Properties and Applications:
Reviews of Emerging Trends

AIP Applied Physics Reviews

Interface effect in Nb-Bi₂Te₃ hybrid structure

Hong-Chao Liu,¹ Hong-Tao He,^{1,2} Bai-Kui Li,¹ Shi-Guang Liu,¹ Qing Lin He,¹ Gan Wang,^{1,2} Iam-Keong Sou,¹ and Jiannong Wang^{1,a)}

¹Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China

²Department of Physics, The South University of Science and Technology of China, Shenzhen, Guangdong 518055, China

(Received 10 September 2013; accepted 24 September 2013; published online 7 October 2013)

An array of Nb strips was fabricated on a Bi₂Te₃ thin film. Transport measurements show that an upturn of the resistance occurs below the Nb superconducting transition temperature. Corresponding to this resistance upturn, a differential resistance peak around zero bias and a prominent negative magnetoresistance at low magnetic fields are observed. The resistance upturn, differential resistance peak, and negative magnetoresistance can be suppressed by increasing measurement current, temperature, and applied magnetic field. We explain these phenomena in terms of an energy barrier effect induced by the Nb superconducting gap and the suppression of Andreev reflection due to the low transparency at the Nb-Bi₂Te₃ interface. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4824651>]

As a new material, topological insulators (TIs), especially the 3D TIs represented by bismuth compounds Bi₂Se₃ and Bi₂Te₃, attracts lots of attentions in recent years.^{1,2} Due to their strong spin-orbit coupling, 3D TIs have unique metallic surface states with spin-momentum locking property, and these Dirac-cone-like surface states have been observed by angle-resolved photoemission spectroscopy (ARPES).^{3,4} Due to the time reversal symmetry, the surface states are robust against non-magnetic impurities and show a strong weak antilocalization effect in transport measurement.^{5–7}

Recently, theory predicts that, through the superconducting proximity effect (SPE), a singlet s-wave superconductor can induce a non-trivial chiral p-wave state inside a TI due to its strong spin-orbit coupling, and this state will host Majorana bound states at vortices.⁸ This prediction has led extensive studies of the SPE in various superconductor-TI interfaces^{9–11} and superconductor-TI-superconductor junctions.^{12–19} In the study of Sn-Bi₂Se₃ interface, a double-gap structure and zero-bias conductance peak has been revealed below the superconducting transition temperature of Sn and ascribed to SPE-induced new superconducting phase in Bi₂Se₃.⁹ In Bi₂Se₃ nanoribbons contacted with two superconducting tungsten electrodes the flow of a supercurrent has been demonstrated through the W-Bi₂Se₃-W junctions together with the multiple Andreev reflections in the differential conductance spectra.¹² Later, dc and ac Josephson effect, i.e., the Fraunhofer-like magnetic field dependence of the critical current and the appearance of Shapiro steps under microwave excitation, has also been observed in Nb-Bi₂Te₃-Nb¹⁸ and Nb-HgTe-Nb junctions.¹⁵ In addition, the transport study of the Al-Bi₂Se₃-Al junction reveals an “unconventional” Josephson effect.¹⁶ The magnetic field modulation of the critical current deviates obviously from the conventional Fraunhofer pattern, showing aperiodic distributed minima. However, in the studies of the

In-Bi₂Se₃-In system²⁰ and the Sn-Bi₂Se₃ interface,⁹ distinct from the conventional SPE, a resistance upturn has been observed with decreasing temperatures below the superconducting transition temperature, which so far has not been conclusively explained. All these results not only demonstrate the rich physics revealed in the study of SPE in TIs, but also call for further investigation of this topic, which will lead to the final realization of Majorana fermions in TIs. In this Letter, we report our transport studies on the Nb-Bi₂Te₃ hybrid structure where an array of Nb strips with inter-separation of 150 nm gap is formed on the surface of a Bi₂Te₃ thin film. A resistance upturn at temperatures below the Nb superconducting transition temperature, a differential resistance peak around zero bias, and negative magnetoresistance (NMR) at low magnetic fields are observed. The resistance upturn and NMR can be suppressed by increasing measurement current, while the differential resistance peak disappears with increasing temperature and applied magnetic field. These phenomena can be well understood in terms of the low transparency interface between Nb and Bi₂Te₃ film and the occurrence of superconducting gap in Nb.

The 20 nm-thick Bi₂Te₃ thin film used in the experiment was grown by molecular beam epitaxy on a (111) semi-insulating GaAs substrate with an undoped ZnSe buffer layer. Hall measurement determined that electron concentration and mobility were $1.6 \times 10^{19} \text{ cm}^{-3}$ and $300 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at 2 K, respectively. A Bi₂Te₃ Hall bar with dimension of $50 \mu\text{m} \times 9 \mu\text{m}$ was fabricated using standard photolithographic processes. A series of Nb strips with dimension of $5 \mu\text{m} \times 8.5 \mu\text{m}$ and inter-separation of 150 nm were formed on top of the Bi₂Te₃ Hall bar by electron-beam lithography and lift-off techniques. The 40 nm-thick Nb strips was deposited by electron-beam evaporation. The Nb-Bi₂Te₃ hybrid structure is schematically illustrated in Fig. 1(a). Its corresponding scanning electron microscope image displayed in Fig. 1(b) shows the uniformity of the strips and gaps. Between two voltage probes, there are ten Nb strips. The transport measurement of the structure was conducted in a

^{a)}Author to whom correspondence should be addressed. Electronic mail: phjwang@ust.hk

FIG. 1. (a) Schematic drawing of Nb-Bi₂Te₃ device structure. (b) Scanning electron microscopy image of the part of the device: Nb strips on the Bi₂Te₃ Hall bar, the gap between two adjacent Nb strips is 150 nm.

Quantum Design physical property measurement system (PPMS).

Fig. 2 shows the temperature dependent resistance, $R(T)$ curves, from 300 to 2 K of the Nb-Bi₂Te₃ device (left black curve) and the Bi₂Te₃ Hall bar (right red curve) measured with 2 μ A current in standard four-probe method. As can be seen, the resistance of Bi₂Te₃ Hall bar is nearly 5 times that of Nb-Bi₂Te₃ device at low temperatures. As the resistivity of Nb (10^{-7} $\Omega\cdot\text{m}$) is much smaller than that of Bi₂Te₃ (10^{-5} $\Omega\cdot\text{m}$), the region of Bi₂Te₃ covered by Nb strips is effectively shorted out. Taking into account of the device geometry and only considering the series resistance of the Nb strips and the Bi₂Te₃ portions between the Nb strips, the total resistance between the two voltage probes is estimated to be around 200 Ω at 5 K, which is much smaller than the measured value of ~ 1 k Ω as shown in Fig. 2. This indicates that the Nb-Bi₂Te₃ interface has large resistance and is not transparent. Therefore, the system studied can be effectively modeled as $20 \times$ Bi₂Te₃-interface-Nb junctions connected in series, as indicated by the top inset of Fig. 2. Each Bi₂Te₃-interface-Nb junction is just like the conventional normal metal-insulator-superconductor (NIS) junction.²¹ The bottom inset of Fig. 2 shows the $R(T)$ curve below 7 K of the Nb-Bi₂Te₃ device. A sharp resistance drop occurs at 4.3 K, corresponding to the superconducting phase transition of the Nb strips. Although the superconducting transition temperature (T_c) of a bulk Nb material is 9.3 K, the T_c of a bare Nb

FIG. 2. Temperature dependent resistance, $R(T)$, of Nb-Bi₂Te₃ device (black curve) and bare Bi₂Te₃ Hall bar (red curve) ranging from 300 to 2 K. The top inset gives the equivalent circuit of the Nb-Bi₂Te₃ device. The bottom inset is the enlarged $R(T)$ curve of Nb-Bi₂Te₃ device from 2 to 7 K.

thin film in this experiment is measured as 4.3 K which is limited by its thin thickness of 40 nm. Unlike a two-step resistance drop in a conventional SPE,¹² a turning point appears at $T_G = 3.5$ K below which temperature the resistance increases rapidly with further decrease of temperature. We note that the resistance of the Bi₂Te₃ Hall bar also increases with decreasing temperature below 8 K ($\sim 0.3\%$ relative to the minimum resistance) as shown in Fig. 2, so this is not responsible for the prominent resistance upturn ($\sim 6\%$) observed in Nb-Bi₂Te₃ device.

To identify the origin of the resistance upturn below T_G , we have measured the differential resistance spectra of our sample at different temperatures, as shown in Fig. 3(a). At $T = 2$ K, a prominent differential resistance peak is clearly observed in the vicinity of zero bias, with two dips located at $V = \pm 22$ mV. As temperatures increase, the peak weakens gradually, and finally disappears around T_G . In addition, the differential resistance peak shows a similar dependence on the applied magnetic field H , as shown in Fig. 3(b). According to the previous studies of conventional NIS junctions,²¹ Andreev reflection is strongly suppressed in our device due to the low transparency of its interface. In order to conduct through the interface between the Bi₂Te₃ layer and the superconducting Nb strips, electrons must overcome an energy barrier Δ arising from the superconducting gap (2Δ) of Nb. This results in the observed differential resistance peak around zero bias, as well as two dips appearing at $\pm \Delta$.²¹ It should be noted that the superconducting gap of Nb cannot be estimated directly from the observed dip position at ± 22 mV in Fig. 3, since our device consists of $20 \times$ Bi₂Te₃-interface-Nb junctions and the series resistance of the Bi₂Te₃ portions between the Nb strips. But based on the BCS theory, we can calculate the superconducting gap of Nb from the measured T_c : $2\Delta = 3.52k_B T_c \sim 1.3$ meV. We note that similar differential resistance peaks have been reported in the study of Sn-Bi₂Se₃ interface⁹ and of Nb-HgTe-Nb junction,¹⁵ where the low-transparency interface is believed to be the cause of such differential resistance peaks.

Now the $R(T)$ curve in the bottom inset of Fig. 2 can be explained as follows. When the temperature decreases to T_c , the Nb strips undergo a superconducting phase transition, giving rise to the sharp drop of resistance in the $R(T)$ curve. With temperatures further decreased below T_G , the superconducting gap of Nb becomes large enough to generate an effective energy barrier Δ at the interface, as indicated by the differential resistance peak below T_G as shown in Fig. 3(a).

FIG. 3. Measured differential resistance, dV/dI , versus bias voltage (a) at indicated different temperatures under zero magnetic field; (b) under indicated different perpendicular magnetic fields at 2 K. The curves are offset for clarity and the measuring current is $2 \mu\text{A}$.

When the applied bias across each Nb-Bi₂Te₃ interface is much smaller than the gap Δ , the electrons must acquire sufficient thermal energy to overcome the barrier Δ to conduct through the interface. At lower temperatures, it is therefore more difficult for the electrons to conduct through the interface. This explains the resistance upturn in $R(T)$ curve below T_G shown in the bottom inset of Fig. 2, as well as the increase of the magnitude of the differential resistance peak with decreasing temperatures in Fig. 3(a). In addition, with fixed applied bias and measurement temperature, increasing the applied magnetic field will decrease the superconducting gap of Nb 2Δ , or the energy barrier Δ , and the resultant differential resistance peak is thus expected to decrease as well, as shown in Fig. 3(b).

The above discussion implies that larger measuring current, i.e., larger bias across the device can reduce the effective energy barrier at the Nb-Bi₂Te₃ interface. The resistance upturn below T_G is thus expected to be suppressed with large enough measuring current applied. This is indeed observed in our device, as shown in Fig. 4(a). The resistance upturn is reduced as the measuring current increases from $2 \mu\text{A}$. It is strongly suppressed when the current is above $30 \mu\text{A}$. The inset of Fig. 4(a) shows the differential resistance spectrum as a function of current at $T = 2 \text{ K}$ and $B = 0 \text{ T}$. Note that the differential resistance dips appear around $\pm 23 \mu\text{A}$. With applied current above the dip region, no effective energy barrier exists at the interface. Therefore, only when the measuring current is smaller than the dip current, the resistance upturn is observed at low temperatures.

It is noted that similar resistance upturn below T_c has been reported in the In-Bi₂Se₃-In junction²⁰ and the

FIG. 4. (a) $R(T)$ curves with indicated different measuring currents at 0 T. The inset shows the dV/dI versus current at 2 K and 0 T. (b) Magnetoresistance curves with indicated different measuring currents at 2 K.

Sn-Bi₂Se₃ interface.⁹ But different mechanisms have been proposed. In the former case, the resistance upturn is ascribed to the spin-flip scattering occurred when the cooper pairs in superconducting indium penetrate into spin-momentum-locked Bi₂Se₃ surface states, while the low transparency of the Sn-Bi₂Se₃ interface is believed to be responsible for the resistance upturn in the latter case but lack of detailed analysis and justification. Our experimental results clearly show that the observed resistance upturn in our device arises from the low transparency of Nb-Bi₂Te₃ interface, in agreement with the study of Sn-Bi₂Se₃ interface. Due to the low transparency of interface, Andreev reflection is strongly suppressed and no SPE or supercurrent is observed in our devices above 2 K, the lowest temperature reachable for our PPMS. But further decreasing the temperature might lead to the observation of SPE, as shown in the study of Sn-Bi₂Se₃ interface⁹ and Nb-HgTe-Nb junctions¹⁵ where the interfaces are also suffered from low transparency. SPE is observed in these two systems only when the temperature is lower than 1.2 K and 25 mK, respectively.

Furthermore, as shown in Fig. 4(b), a prominent NMR is observed in magnetoresistance measurements at low magnetic fields with $T = 2 \text{ K}$ and the measuring current of $2 \mu\text{A}$. The appearance of such an NMR can be ascribed to the energy barrier caused by Nb superconducting gap at the

Nb-Bi₂Te₃ interface. As the magnetic field increases, the superconducting gap of Nb shrinks and this leads to the decrease of interface energy barrier. Therefore, the resistance is expected to decrease with increasing magnetic fields, i.e., NMR appears. But the further increase of the magnetic field will destroy the superconductivity of Nb eventually. As a result, the device displays a sharp increase of MR around 3 T, which is the upper critical field of Nb at 2 K. Fig. 4(b) also shows that the magnitude of NMR becomes smaller at larger measuring currents. This is because larger measuring current will effectively reduce the interface energy barrier as discussed in Fig. 4(a) where the magnitude of resistance upturn is reduced with large measuring current applied. These indicate that NMR and the resistance upturn in $R(T)$ have the same physical origin and their magnitudes are correlated. With the strong suppression of NMR above 20 μ A, a resistance dip begins to appear in small magnetic fields, which is the weak antilocalization effect arising from the Bi₂Te₃ films.^{5,6}

In conclusion, we have studied in detail the resistance upturn observed in the Nb-Bi₂Te₃ hybrid structure and analyzed the influences of measuring current, temperature, and magnetic field on this resistance upturn. Our experimental results clearly indicate that the observed resistance upturn in our device arises from the low transparency and the energy barrier induced by Nb superconducting gap at the Nb-Bi₂Te₃ interface.

We wish to thank Dr. H. Z. Lu and Professor S. Q. Shen for fruitful discussions. This work was supported in part by the Research Grants Council of the HKSAR under Grant Nos. 605011, 604910, and SEG CUHK06, and in part by the National Natural Science Foundation of China under Grant No. 11204183. The electron-beam lithography facility was supported by the Raith-HKUST Nanotechnology Laboratory at MCPF (SEG HKUST08).

- ¹M. Z. Hasan and C. L. Kane, *Rev. Mod. Phys.* **82**, 3045 (2010).
- ²X. L. Qi and S. C. Zhang, *Rev. Mod. Phys.* **83**, 1057 (2011).
- ³Y. Xia, D. Qian, D. Hsieh, L. Wray, A. Pal, H. Lin, A. Bansil, D. Grauer, Y. S. Hor, R. J. Cava, and M. Z. Hasan, *Nat. Phys.* **5**, 398 (2009).
- ⁴Y. L. Chen, J. G. Analytis, J.-H. Chu, Z. K. Liu, S.-K. Mo, X. L. Qi, H. J. Zhang, D. H. Lu, X. Dai, Z. Fang, S. C. Zhang, I. R. Fisher, Z. Hussain, and Z.-X. Shen, *Science* **325**, 178 (2009).
- ⁵J. Chen, H. J. Qin, F. Yang, J. Liu, T. Guan, F. M. Qu, G. H. Zhang, J. R. Shi, X. C. Xie, C. L. Yang, K. H. Wu, Y. Q. Li, and L. Lu, *Phys. Rev. Lett.* **105**, 176602 (2010).
- ⁶H. T. He, G. Wang, T. Zhang, I. K. Sou, G. K. L. Wong, J. N. Wang, H. Z. Lu, S. Q. Shen, and F. C. Zhang, *Phys. Rev. Lett.* **106**, 166805 (2011).
- ⁷H. Z. Lu, J. Shi, and S. Q. Shen, *Phys. Rev. Lett.* **107**, 076801 (2011).
- ⁸L. Fu and C. L. Kane, *Phys. Rev. Lett.* **100**, 096407 (2008).
- ⁹F. Yang, Y. Ding, F. Qu, J. Shen, J. Chen, Z. Wei, Z. Ji, G. Liu, J. Fan, C. Yang, T. Xiang, and L. Lu, *Phys. Rev. B* **85**, 104508 (2012).
- ¹⁰G. Koren, T. Kirzhner, E. Lahoud, K. B. Chashka, and A. Kanigel, *Phys. Rev. B* **84**, 224521 (2011).
- ¹¹P. Zareapour, A. Hayat, S. Y. F. Zhao, M. Kreshchuk, A. Jain, D. C. Kwok, N. Lee, S. W. Cheong, Z. Xu, A. Yang, G. D. Gu, S. Jia, R. J. Cava, and K. S. Burch, *Nat. Commun.* **3**, 1056 (2012).
- ¹²D. Zhang, J. Wang, A. M. DaSilva, J. S. Lee, H. R. Gutierrez, M. H. W. Chan, J. Jain, and N. Samarth, *Phys. Rev. B* **84**, 165120 (2011).
- ¹³B. Sacépé, J. B. Oostinga, J. Li, A. Ubalini, N. J. G. Couto, E. Giannini, and A. F. Morpurgo, *Nat. Commun.* **2**, 575 (2011).
- ¹⁴F. Yang, F. Qu, J. Shen, Y. Ding, J. Chen, Z. Ji, G. Liu, J. Fan, C. Yang, L. Fu, and L. Lu, *Phys. Rev. B* **86**, 134504 (2012).
- ¹⁵L. Maier, J. B. Oostinga, D. Knott, C. Brüne, P. Virtanen, G. Tkachov, E. M. Hankiewicz, C. Gould, H. Buhmann, and L. W. Molenkamp, *Phys. Rev. Lett.* **109**, 186806 (2012).
- ¹⁶J. R. Williams, A. J. Bestwick, P. Gallagher, S. S. Hong, Y. Cui, A. S. Bleich, J. G. Analytis, I. R. Fisher, and D. Goldhaber-Gordon, *Phys. Rev. Lett.* **109**, 056803 (2012).
- ¹⁷F. Qu, F. Yang, J. Shen, Y. Ding, J. Chen, Z. Ji, G. Liu, J. Fan, X. Jing, C. Yang, and L. Lu, *Sci. Rep.* **2**, 339 (2012).
- ¹⁸M. Veldhorst, M. Snelder, M. Hoek, T. Gang, V. K. Guduru, X. L. Wang, U. Zeitler, W. G. van der Wiel, A. A. Golubov, H. Hilgenkamp, and A. Brinkman, *Nat. Mater.* **11**(5), 417–421 (2012).
- ¹⁹J. Shen, Y. Ding, Y. Pang, F. Yang, F. Qu, Z. Ji, X. Jing, J. Fan, G. Liu, C. Yang, G. Chen, and L. Lu, e-print [arXiv:1303.5598v3](https://arxiv.org/abs/1303.5598v3).
- ²⁰J. Wang, C. Chang, H. Li, K. He, D. Zhang, M. Singh, X.-C. Ma, N. Samarth, M. Xie, Q. K. Xue, and M. H. W. Chan, *Phys. Rev. B* **85**, 045415 (2012).
- ²¹G. E. Blonder, M. Tinkham, and T. M. Klapwijk, *Phys. Rev. B* **25**, 4515 (1982).