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研究課題名（和文）Graphene-based high temperature two-dimensional topological insulator for realizing Majorana fermions

研究課題名（英文）Graphene-based high temperature two-dimensional topological insulator for realizing Majorana fermions

研究代表者
Ｔｕ　Ｈａｎ（Tu, Ngoc Han）

国立研究開発法人理化学研究所・創発物性科学研究センター・特別研究員

研究者番号：００８６２３２７

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研究成果の概要（和文）：我々は、グラフェンとBi2-xSbxTe3-ySey薄膜（BSTS）を組み合わせたファンデルワールスヘテロ構造に注目している。われわれは、グラフェンが10～30 nmの範囲の厚さの高品質BSTS薄膜を成長させるのに適したプラットフォームであることを示した。BSTS膜の厚さが10 nmを下回ると、グラフェンとBSTS超薄膜の界面における近接効果によるスピン軌道相互作用の増大が、界面に沿ったヘリカルエッジ状態の出現をサポートする。

研究成果の学術的意義や社会的意義
The development of a highly controllable fabrication method for 2D-TIs holds significant potential for the next generation of electronic devices. Moreover, helical edge states is an idea platform to discovery Majorana fermions that can become a future material for quantum computer.

研究成果の概要（英文）：We focus on van der Waals heterostructures combining graphene with Bi2-xSbxTe3-ySey thin film (BSTS), one of the best three-dimensional topological insulators 3D-TIs). We have shown that graphene is a good platform for growing high quality BSTS films with thicknesses in the range of 10 to 30 nm. When the thickness of the BSTS films is below 10 nm, the proximity effect induced enhancement of the spin-orbit interaction at the interface of graphene and BSTS ultrathin films supports the emergence of helical edge states along the edge.

研究分野：Physics

キーワード：Topological insulators　Graphene　van der Waals　helical edge states

１．研究開始当初の背景

Two-dimensional topological insulators (2D-TIs), known as quantum spin Hall insulators, exhibit insulating properties with a bandgap in the bulk but have the helical edge states along the edge. In these edge states, backscattering is forbidden, allowing the creation of innovative devices [1]. The first 2D-TI to be experimentally realized is the semiconductor quantum well of HgTe/CdTe [2] and then InAs/GaSb [3] by molecular beam epitaxy, where the observation temperature of the helical edge states is as low as tens of millikelvin. The next generation of 2D-TIs is the monolayer of WTe_2, [4] a transition metal dichalcogenide (TMDC), which is experimentally observed around 100K. On the other hand, the difficulty of structural control to the 1T' phase, the overwhelmingly low yield of monolayer films, and the atmospheric instability of this material bring many difficulties to the sample fabrication process. Therefore, the development of a highly controllable fabrication method for two-dimensional topological insulators holds significant potential for the next generation of electronic devices. Moreover, helical edge states in 2D-TI is an idea platform to discovery Majorana fermions by fabricating an interface with a s-wave superconductor [5] that can become a future material for quantum computer.

２．研究の目的

We focus on van der Waals (vdW) heterostructures combining graphene with Bi2-xSbxTe3-ySey thin film (BSTS), one of the best three-dimensional topological insulators (3D-TIs). Heterostructures of Dirac materials such as graphene and 3D-TIs provide interesting platforms to explore exotic quantum states of electrons in condensed matter. We have shown that graphene is a good platform for growing high quality BSTS films with thicknesses in the range of 10 to 30 nm. When the thickness of the BSTS films is below 10 nm, the proximity effect induced enhancement of the spin-orbit interaction at the interface of graphene and BSTS ultrathin films supports the emergence of helical edge states along the edge.

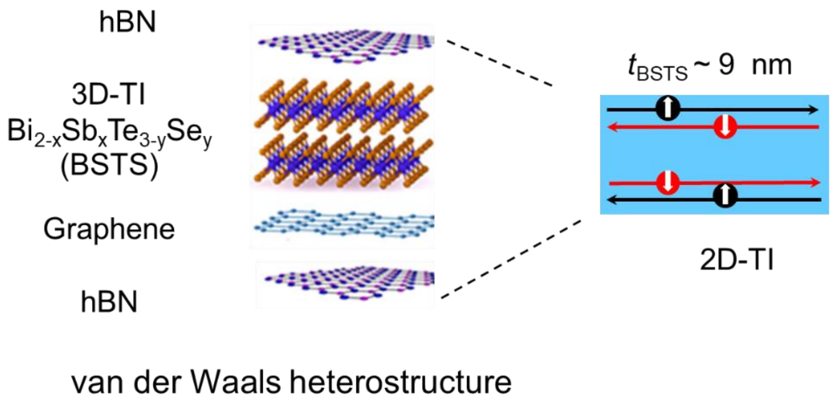

Figure 1. Gaphene-3D TI Van der Waals heterostrucrure

３．研究の方法

We have developed a technique to grow and control the properties (thickness, composition) of BSTS films on CVD monolayer graphene by physical vapor deposition method. We also investigated a dry stacking method that would allow us to produce a high-quality van der Waals heterostructure of hBN/TI-graphene/hBN, thus improving the quality and stability of the samples. We observed the signature of the helical edge states with a suitable thickness of BSTS film to induce hybridization between the top and bottom surface by non-local transport properties and magnetoresistance of several devices for different measurement configurations at low temperature (0.3K – 2K).

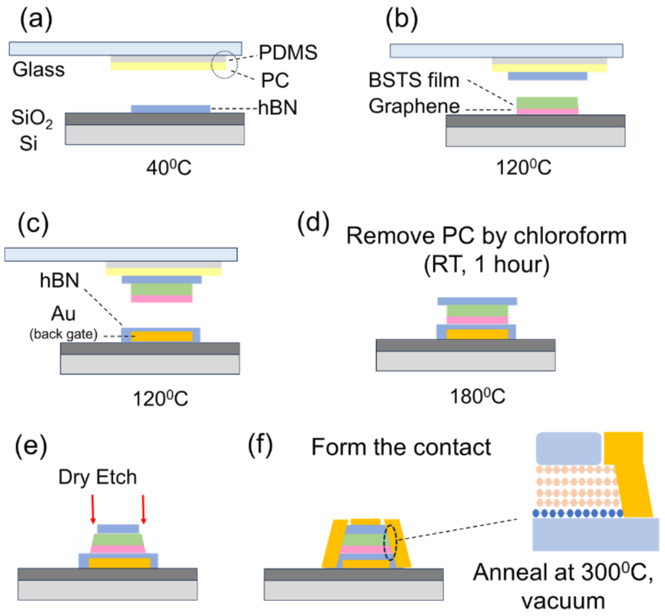

Figure 2. Dry transfer method to make the graphene-BSTS heterostructures.

４．研究成果

Result 1. Fabricate the double-sided epitaxial vdW heterostructures and dual-gate devices for electrical transport measurements.

We grew the BSTS thin films on CVD graphene by vapor-deposition method. The cross-sectional TEM image and XRD data show that graphene serves as a crystalline substrate for the epitaxy growth of BSTS films [6].

A dual gate field effect transistor was fabricated by stacking the graphene/BSTS heterostructure thin film between two layers of h-BN by the dry transfer method. The Hall bar structure was fabricated by dry etching. Finally, the edge contact was formed along the edge of the samples.

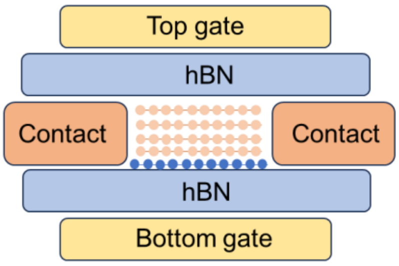

Figure 3. The cross-section of the dual gate devices.

Result 2. Observation of helical edge states with a 9nm BSTS-graphene dual gate devices

We first studied the behavior of a 9nm BSTS-graphene dual gate device in a Hall bar structure (Figure 4a). Figure 4b shows the color map of resistance of device as the function of top and back gate voltages. The resistance saturates at the maximum value ~ 13 kΩ (~ $R_Q/2$), which is consistent with the existence of helical edge states [7]. We also measured other configurations to confirm the existence of helical edge states through non-local transport measurement (Fig. 4b).

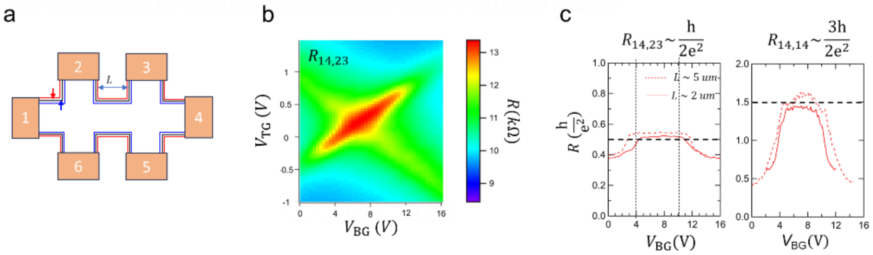

Figure 4. (a) A Hall bar device (b) Color map of device resistance as a function of back and top gate voltages. (c) Device resistance as a function of back gate voltages (top gate voltages V_{TG} was set at 0.2V) with different configuration. $R_{ij,kl}$ is the value of non-local resistance with the current injected from contact *i* → *j* and the voltage was measured between contact *k* → *l*. $R_{ij,kl} = V_{kl}/I_{ij}$

Result 3 Temperature dependence of the vdW graphene-BSTS with different BSTS film thicknesses

In order to clarify in detail the evolution of 2D-TI states in BSTS/graphene heterostructures with different thicknesses, we fabricated BSTS/graphene heterostructures with BSTS thicknesses of 2 nm, 3 nm, 9 nm and 20 nm in the same device structure and measured the temperature dependence of $R_{14,23}$ as shown in Figure 5. We observed the signature of the helical edge states when the BSTS thickness was in the range of 3-9 nm. At 2 nm, the temperature dependence of the resistivity shows the insulator behavior. We expected that the gap of graphene had been opened due to the Keule mechanism [8].

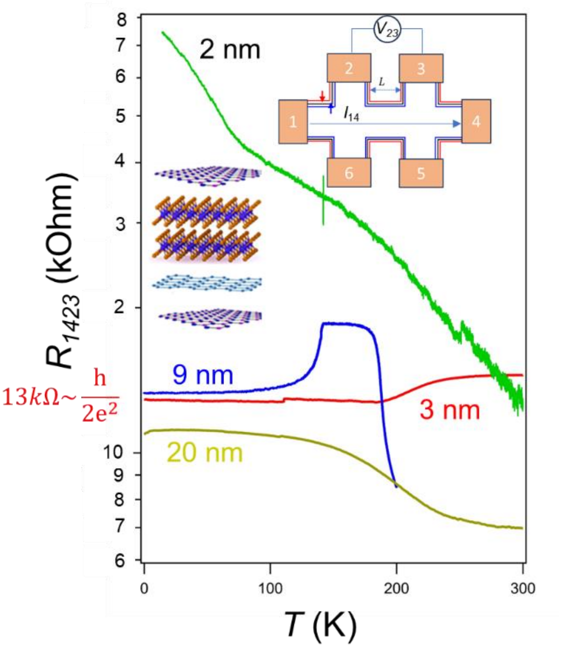

Figure 4. Temperature dependence of the vdW graphene-BSTS with different BSTS film thicknesses. Four probe measurements were performed with the current injected from contact 1 to 4 while the voltage was measured between contact 2 and 3. Signature of the helical edge states was observed when the BSTS film thickness in the range of 3 – 9 nm (R_{1423} ~ 13 kOhm ~ $R_Q/2$).

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５．主な発表論文等

〔雑誌論文〕　計0件

〔学会発表〕　計0件

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

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