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Transistors on Nano-sheets Beyond Graphene

Jianting Ye[1], Yijin Zhang[1], Masaro Yoshida[1], Yu Saito[1], and Yoshihiro Iwasa[1,2]

[1] Quantum-Phase Electronics Center and Department of Applied Physics, The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone: +81-3-5841-6871 E-mail: yejianting@ap.t.u-tokyo.ac.jp
[2] CERG, RIKEN, Hirosawa 2-1, Wako 351-0198, Japan

Abstract

Future transistor technologies would benefit from the development of techniques in making atomically thin nano-sheets pioneered in graphene researches. Integrating these interesting thin films with an efficient field-effect gating mediated by movement of ions has formed a fast growing research field for creating exotic states at the surface of these nano-sheets. By making a new-type of transistor called electric-double layer transistors (EDLTs), which can be electrostatically doped to a high carrier density of ~10^{14} cm^{-2}, the unique system combining these two advantages enabled observations of novel transport phenomena with quantum phase transition including gate-induced metal-insulator transition, superconductivity and magnetism, providing emerging opportunities for device sciences.

1. Introduction

Important discovery of ways to prepare ultra-thin single crystals first developed in the research of graphene revolutionized our vision of device science. Formed by a monolayer of carbon [1,2], fabricated using a simple method of cleaving bulk graphite with Scotch tapes, graphene is one of promising new materials for microelectronics. Making graphene is a typical top down method from bulk material down to its ultimate building block of atomic layer of one carbon atom is a natural trend following the research of making devices using nano-materials. The success of graphene immediately raised the possibility of applying similar technique to other layered materials. The early examples include atomic layers of boron nitride, transition-metal dichalcogenides, and complex oxides like layered high T_c cuprate. All nano-sheets prepared appeared to be stable 2D crystals under ambient conditions exhibiting high crystal quality on a macroscopic scale [2]. Many layered materials were well studied with varieties of properties of charge, orbital, and spin in their bulk form. Isolating them into atomically thin nano-sheets provide new materials opportunities to study them in a different paradigm [3].

Apart from the development of making nano-sheets, independently, people have long-time dreams of modulating quantum phase transition using electric field effect. The most well known example is to manipulate the superconducting transition using field effect generated by a transistor. Recently, the introduction of new device structure using electric double layer (EDL) gate dielectrics enabled an effective switching of superconductivity from an insulator [4]. As we will elaborate afterwards, the charge accumulation ability of EDL gated transistor (EDLT) was significantly improved after using ionic liquid, a molten organic salt under room temperature leading to a effective doping up to an order of 10^{14} cm^{-2}.

Combining the advantage of the making ultra-thin flakes and highly efficient ion-gated transistors, new effort was made to accumulate high-density carriers using EDLT device structures on high-quality channel surface found on nano-sheets. From fundamentals of making such a device, we would describe below how this combination had enabled recent success in inducing superconductivity [5–7], creating new transport properties [8,9], and modulating magnetism [10]. These results represented a rapidly growing field with emerging opportunities for future researches.

2. Experiments

Nano-sheet of single crystals were fabricated by exfoliating bulk crystals using an adhesive tape, a process usually referred as Scotch tape method [1]. After the first success of making ultra-thin nano-sheets: graphene, varieties of layered materials were studied using the similar method [2]. Figure 1 shows several nano-sheets isolated from layered material (such as graphene, ZrNCl, MoS_2 *etc*.). Ultra-thin sheets with high accuracy in thickness, namely controlling the thickness and flatness of the sheet in atomic precision, can be easily prepared. Besides being atomically thin, the flatness of the nano-sheet is the crucial point especially for making transistors since it provides the ideally flat channel for high performance transport. Optical micrograph could act as a very effective way to identify even a single atomic step for the flake with a thickness up to 20~30 nm [6,9], which avoids the slow characterization using atomic force microscopy (AFM). These atomically flat surfaces prepared on cleaved layered materials formed the basis of achieving high performance field effect transistors.

To fabricate an EDLT device on nano-sheets, we first cleave with a piece of Scotch tape repeatedly from a bulk single crystal. By pressing against a SiO_2/Si substrate, we are able to transfer the nano-sheet from the tape onto the substrate. Using interference color of 300 nm SiO_2 grown on a highly doped silicon substrate, the thickness of the flakes could be precisely determined by analyzing optical micrographs to extract the intensity shift in the green channel (in RGB composition) in reflection or optical intensity in transmission when the substrate is transparent [5], To confirm the thickness, we also calibrated the thickness with features appeared in Raman spectroscopy, and AFM determination. A flake with a thickness of 20~30nm (estimated optically and confirmed by AFM) was subsequently patterned into a Hall bar configuration using conventional micro-fabrication techniques (electron beam lithography, electron-beam evaporation, and lift-off). The electrodes consisted in a multilayer Ti/Au/SiO2 (10/50/30nm).

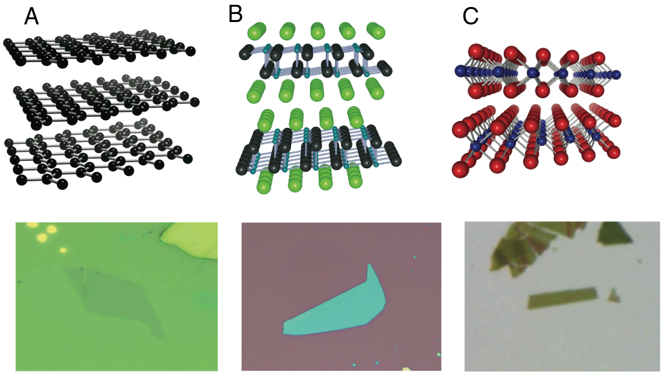

Fig. 1 (A-C) Upper panel, ball-and-stick models of bulk graphite (C: black), ZrNCl (Zr: cyan, N: black, and Cl: green), and 2*H*-MoS_2 (Mo, blue and S, red) single crystals showing layered structure stacked by Van de Waals gap. Lower panel, optical micrograph of nano-sheets prepared using graphene method from corresponding of bulk crystal in reflection (A and B) and transmission mode (C).

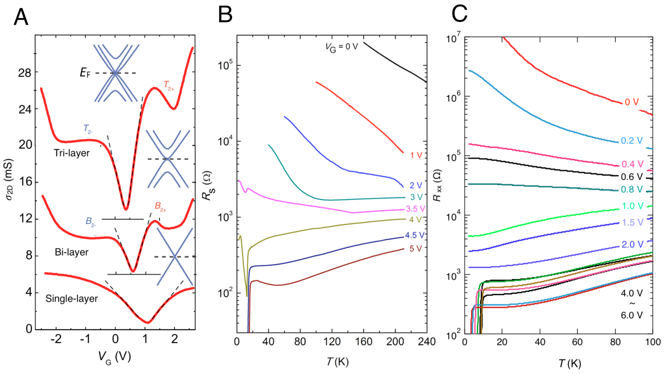

Fig. 1 (A-C) Transport properites of various layered materials under liquid gating. (A) Transfer characteristics of graphene of mono, bi- and tri-layers at room temperature. (B) and (C), temperature dependence of sheet resistivity of liquid gated ZrNCl and MoS_2.

3. Results

As shown in Fig. 2, we measured various layered materials for their transport properties under the liquid gating especially for the highly doped states. At room temperature, the differences in transfer curve for mono, bi-, and tri-layer graphene were clearly seen as monolayer graphene showed only conductivity saturation at high carrier density. While anomalous conductivities in bi- and tri-layer graphene were observed when Fermi levels were raised or lowered to access the upper conduction or valence bands (shown in the band structure of graphene for different thickness from one to three layers) as a function of liquid gate voltage applied [8]. Keeping the gate voltage applied and cooling the devices down to the low temperature, we fixed the induced carriers by freezing the ion movement. As a result, gate-induced metal to insulator transition and gate induced superconductivity as a function of liquid gate voltage could be realized as shown in Fig. 2 (B) and (C). The relatively high transition temperatures in both samples of ZrNCl (15 K) [6] and MoS_2 (10 K) [7] are significant improvements from previous work of inducing superconductivity in $SrTiO_3$ (0.3 K) [4] indicating that the method of liquid gating could be useful in accessing the superconducting properties in various kinds of materials.

4. Conclusions

From the results obtained, ionic liquid gating appears to be an effective and reliable technique to accumulate very large amounts of carriers at liquid/solid interface on layered materials. At the current stage, it appears that all the ingredients necessary for a rapid progress in directions of fundamental and technological interest that combine the unique properties of layered material and ionic liquid dielectrics are already available.

Acknowledgements

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