Iontronics

Principal investigators

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Electric field control of materials properties is one of the longstanding issues in solid-state science. In conventional field-effect gating technique using solid gate dielectric (SiO_2 or high-k dielectric), the charge carrier density accumulated is rather small, of the order of ~ 10^{13} cm^{-2}. In this project, we employ a different route for carrier doping which relies on an electrochemical concept to control materials properties with an electric field. By applying a voltage to an electrolyte, we accumulate ions at the solid/liquid interface which produce a huge electric field of the order of 10 MV/cm. Owing to this extremely high electric field, we are able to open ambipolar conducting channels at the surface of semiconductors with the capability to push the charge density accumulation as high as few 10^{15} cm^{-2}. We report here on our recent work on ambipolar ionic liquid-gated transistor of WS_2 multiwall nanotubes.

Description

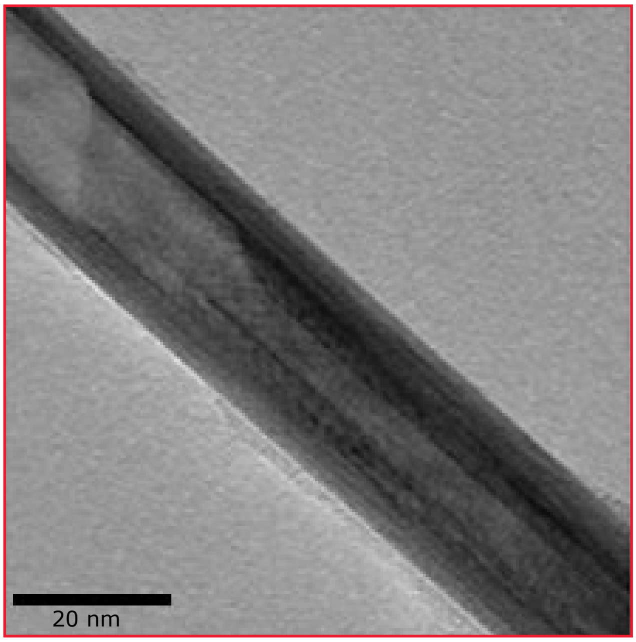
Following the success of graphene with its wealth of new fundamental physics and device applications, a new stream of work is now focusing on inorganic layered materials that can be exfoliated from bulk crystals to make one or several layers-based two-dimensional devices. In particular transition-metal-dicalcogenides (TMDs) of the form of TX2, where T stands for transition metal (Mo, W, Rh...) and X for a chalcogen atom (Se, Te, S...) have gained great attention recently as these layered systems show remarkable properties for applications in nano- and opto-electronics.

In contrast to the zero band-gap of graphene, transition-metal-dicalcogenides are semiconducting with an indirect band gap of order ~2 eV that enables to engineer one or few atomic layers thick field effect transistors. MoS_2-based transistors have recently shown remarkable performance with high I_{on}/I_{off} ~ 10^8 and mobility of order 10^2 $cm^2/V/S$. For opto-electronic applications the cornerstone relies on the transition in monolayer transition-metal-dicalcogenides to a direct band gap located at the K and K' corners of the Brillouin zone (forming two nonequivalent valleys with selective optical inter-band selection rules).

Furthermore, under ionic liquid gating and the ensuing high electron density, MoS_2 and WS_2 materials turn superconducting below a gate-tunable critical temperature that reaches a maximum of 10 and 2 K respectively.

In this context we conducted a study of an allotrope of the 2D transition-metal-dicalcogenides, that is, multi-wall nanotubes (MWNT) of WS_2. Contrary to the carbon nanotubes, these inorganic nanotubes retain their semiconducting band gap whatever the chirality, which enables to tailor nanoscale field effect transistors. They inherit the layered structure of the bulk phase comprising weakly coupled WS_2 layers, and can be grown in mono- or multi-layer walls tubes (Fig. a).

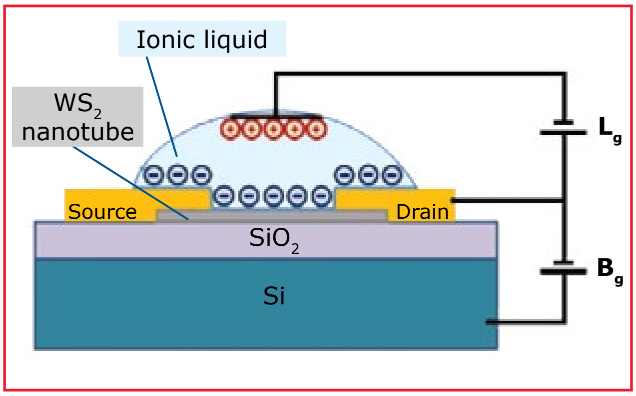
Although WS_2 and MoS_2 nanotubes have been discovered in 1992 soon after carbon nanotubes, their electronic properties and their potential for nano-electronic devices have been little addressed compared to their carbon counterparts. In this work we have studied WS_2 multi-wall nanotube transistors gated with ionic liquid. We demonstrate the opening of a conducting electron or hole channel depending on the gate voltage.



(a) Transmission electron microscopy picture of the extremity of a WS_2 multiwall nanotube.

WS_2 multi-wall nanotubes were contacted with two metallic electrodes forming the drain and source of the transistor. A counter-electrode immersed in the ionic liquid allows to accumulate the ions on it and to accumulate the counter-ion at the surface of the tube (Fig. b).

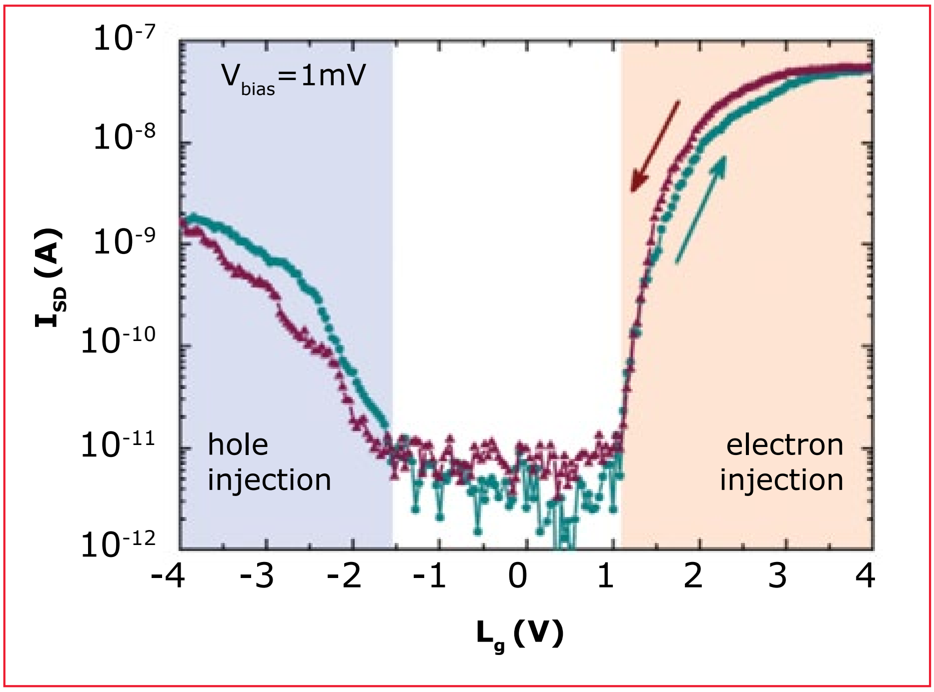
As a result the large electric field generated by the ions at the surface of the tube is strong enough to overcome the band gap and open a conducting channel.



(b) Schematic of the liquid ionic gating measurement configuration.

Fig. c shows the drain-source current as a function of liquid gate voltage L_g. No current is flowing in a gate-voltage window of 2V which is close to the expected bandgap of WS_2. For $L_g > 1$ V, an n-type characteristic is obtained with electron doping of the conduction band. For $L_g < 1$ V, holes are accumulated in the valence band. The device performance shows an $I_{on}/I_{off} \sim 10^4$ and a mobility reaching 10 $cm^2/V/S$, which is mainly limited by the contact resistance.

We have therefore demonstrated the first ambipolar liquid-gated field effect transistor in WS_2 multi-wall nanotubes. The next course of actions consists in improving the contact resistance to reach the intrinsic mobility of the material, and chasing superconductivity that have been already observed in flakes of WS_2 below 2 K.
In addition, this work opens the way for similar study of other wide bandgap semiconductors for which conventional solid dielectric gating as proven inefficient.



(c) Field effect characteristic of a WS_2 MWNT transistor showing ambipolar transport. Beyond the band gap of the material, electron (hole) channel opens for positive (negative) liquid gate values.

Outcomes: Electric-field assisted depinning and nucleation of magnetic domain walls in FePt/Al_2O_3/liquid gate structures,
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Hosting of the 1st French and Japanese joint workshop on electric field effect, with 5 invited Japanese speakers - Grenoble, 18-19 June 2015.

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