International Conference on Multi-Condensate Superconductivity and Superfluidity in Solids and Ultra-Cold Gases, 14 - 18 May 2018 (Trieste, Italy)

Erik PIATTI
Superductivity and Magnetism in Innovative Materials
Dept. of Applied Science and Technology, Politecnico di Torino, Italy

SUPERCONDUCTIVITY AND MAGNETISM IN INNOVATIVE MATERIALS (SMIM)
Laboratory of Theoretical and Experimental Superconductive Tunneling (LaTEST)

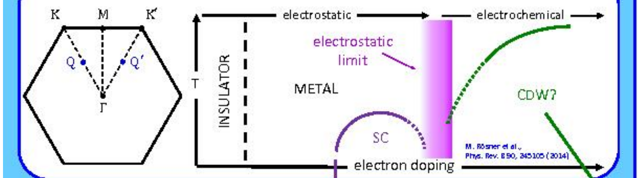
Evidence for multi-valley superconductivity and possible charge density waves in ion-gated few-layer molybdenum disulphide

E. Piatti[1], **D. De Fazio**[2], **D. Daghero**[1], **Q. Chen**[3], **S. R. Tamalampudi**[2], **D. Yoon**[2], **J. T. Ye**[3], **A. C. Ferrari**[2], **and R. S. Gonnelli**[1]
1 *Department of Applied Science and Technology, Politecnico di Torino, 10129 Torino, Italy*
2 *Cambridge Graphene Center, University of Cambridge, CB3 OFA Cambridge, United Kingdom*
3 *Device Physics of Complex Materials, University of Groningen, 9747 AG Groningen, The Netherlands*

OUTLINE

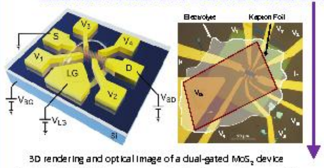
We employ **ionic gating** to control the electric transport properties of **few-layer MoS_2** field-effect devices as a function of electron doping, both in the electrostatic and electrochemical (intercalation) regimes. In the **electrostatic regime**, we observe the expected insulator-to-metal and metal-to-superconductor phase transitions for increasing doping levels. We also observe **two minima in the residual conductance**, corresponding to the Fermi level crossing the spin-orbit split sub-bands in **the Q/Q' valleys**. SC appears and is optimized only close to the **crossing of the second sub-band**, highlighting the essential role of a **multi-valley Fermi surface** and the related Lifshitz transitions **in the SC state at the surface of gated TMDs**.
Upon **field-driven Li intercalation**, electron doping is further enhanced and **SC is suppressed**. We observe **anomalous metallic behavior** as "hump" structures in the T dependence of the resistivity, which can be interpreted as the formation of a **charge density wave** and/or **structural transition** at high doping. These may be in **competition with the SC** phase observed at lower doping levels.

PHASE DIAGRAM OF ELECTRON-DOPED MOLYBDENUM DISULPHIDE



M. Rösner et al., Phys. Rev. B 90, 245105 (2014)

ELECTRIC TRANSPORT IN DUAL-GATED DEVICES: THE ELECTROSTATIC REGIME



3D rendering and optical image of a dual-gated MoS_2 device

- Ionic-liquid **top gate** (LG) to access a **wide range** of the phase diagram
- Solid **back-gate** (BG) to **fine-tune** the doping
- **Longitudinal** resistance R_s probes the **insulator-to-metal** and **metal-to-SC** phase transitions
- **Transverse** resistance R_H probes the **carrier density** via Hall effect

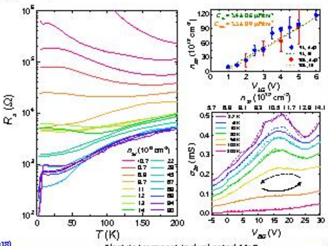
For T > 100 K, R_s is **monotonically decreasing** with increasing carrier density n_{2d}

For T < 100 K, we observe **two kinks** in the carrier density dependence of R_s

The first kink appears for doping levels corresponding to the **metallic phase:** $n_{2d} \sim 1 \div 2 \cdot 10^{13}$ cm^{-2}

The second kink appears for doping levels corresponding to the **SC phase:** $n_{2d} \sim 7 \div 10 \cdot 10^{13}$ cm^{-2}

The first kink can be **continuously tuned** by means of the solid back-gate



E. Piatti et al., submitted (2018)

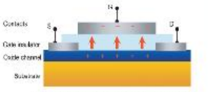
Electric transport in dual-gated MoS_2

IONIC GATING: WHY AND HOW

The field effect is the **modulation of the surface electrical properties of a material induced by the application of an intense electrostatic field.** Field-effect transistors are very common in today's electronics. A field-effect transistor works by **inducing an additional charge** in a surface layer by means of an intense electric field (as in a parallel-plate capacitor). The additional charge is normally supposed to be confined in a surface layer whose thickness is of the order of the electrostatic screening length.

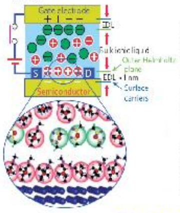
In **conventional** field-effect devices, the gate electrode and the material under study are separated by a **solid dielectric (insulator)** as in a conventional parallel-plate capacitor.

In this configuration, the maximum field that can be applied before the dielectric breaks is of the order of 10^9 V/m and the **maximum density of induced charge is some units in 10^{13} charges /cm^2**.



Typical "top gate" geometry for FE experiments in oxides

C. H. Ahn et al. Nature 424, 1015 (2003)



Much higher fields can be applied by using the **ionic gating technique** that exploits the formation of an **electric double layer** at the interface between an electrolyte (such as an ionic liquid, or a polymer electrolyte system, PES) and the material.

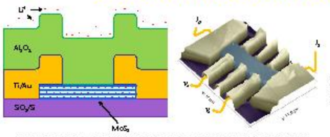
The EDL acts as a capacitor with inter-plate distance of about 1 nm and thus a huge **capacitance.** EDL devices can support very high field-induced charge density, up to **10^{14}-10^{15} charges / cm^2**

Additionally, the ultrahigh electric field can be exploited to **drive ions in the van der Waals gap** between the atomic layers. Field-induced **intercalation** can be exploited enhance the doping level **beyond** the **electrostatic** limit.

K. Ueno et al., Nat. Mater. 7, 855 (2008)
J. T. Ye et al., Nat. Mater. 9, 125 (2010)
J. T. Ye et al., Science 338, 1193 (2012)
Y. Yu et al., Nat. Nanotechnol. 10, 270 (2015)

Ionic gating can thus be used to explore new regions of the phase diagram of a given material and even **induce phase transitions** (i.e. from insulator to superconductor)!

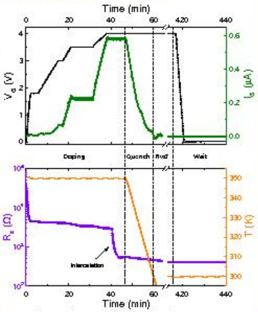
FIELD-DRIVEN INTERCALATION IN ENCAPSULATED DEVICES



Sketch and AFM 3D rendering of an Al_2O_3-encapsulated MoS_2 device

To reach **beyond the SC** dome**: intercalation**

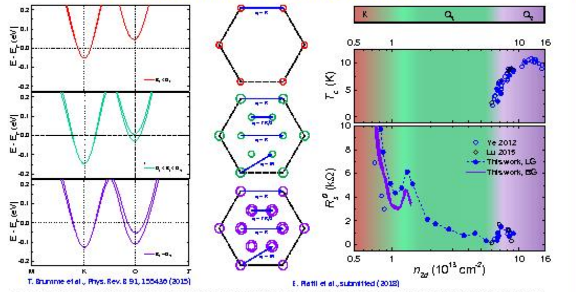
- Employ **Li-based** PES to leave **lattice undamaged**
- Devices are encapsulated in Al_2O_3 to **suppress** contributions from the **surface**
- Li doping can only occur **from the sides** of the device
- Intercalation is achieved at **high V_G** and **high T ≳ 320 K**
- **Quenching** at room T **stabilizes the Li content**



E. Piatti et al., Appl. Surf. Sci. (accepted)

Li doping dynamics detected by electric transport

THE MULTI-VALLEY SUPERCONDUCTING STATE

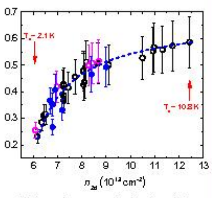


T. Brumme et al., Phys. Rev. B 91, 155436 (2015)

E. Piatti et al., submitted (2018)

Band filling in MoS_2 for increasing field-effect doping. Bandstructure, Fermi surfaces, T_c, and normal-state residual resistance.

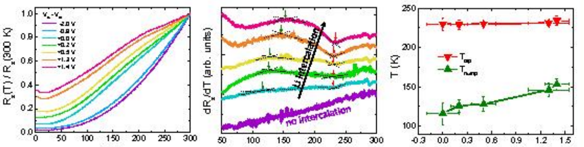
- The conduction band of **gated MoS_2** features two **low-energy valleys at K/K'** and six **high-energy valleys at Q/Q'**, with stronger **electron-phonon** and **spin-orbit** couplings
- **Sub-band crossing** results in **conductance kinks** at low-T: these can be used to **directly probe band filling** (and strain)
- **First sub-band** at Q/Q' is filled already in the **metallic** state
- **Second sub-band** at Q/Q' is filled immediately after **SC** appears
- Abrupt **change in Fermi surface** topology: **Lifshitz** transition(s), resulting in a **critical boost** to the **electron-phonon coupling**
- Enhanced Fermi surface connectivity is **critical** in explaining the relatively **high T_c ~ 10 K**.



Electron-phonon coupling boost vs. doping

E. Piatti et al., submitted (2018)

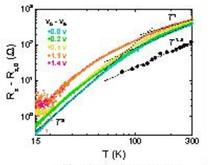
ANOMALOUS METALLIC BEHAVIOR AND POSSIBLE CHARGE DENSITY WAVES



T-dependent electric transport in Li_xMoS_2: sheet resistance R_s, first derivative dR_s/dT, and hump-dip structures doping dependence

Li intercalation triggers the development of **anomalous metallic transport** in the encapsulated devices

- V_{th} is the V_G value where **stable intercalation is achieved**
- **SC is suppressed** below the minimum accessible temperature (3 K)
- Li ions introduce disorder (RRR is strongly reduced for $V_G - V_{th} > 0$)
- **Hump anomalies** emerge in the T-dependence of R_s
- **Hump-dip** structures are observed in dR_s/dT, which evolve differently with increasing Li doping
- These could be associated either to **CDW phase(s)** and/or to **structural transitions** (2H/1T/1T'): need for **SPECTROSCOPY**
- R_s(T) scaling is **compatible with CDWs**



E. Piatti et al., Appl. Surf. Sci. (accepted)

R_s(T) scaling with increasing T

PERSPECTIVES

Extend band-filling mapping to the **closure of the SC dome**: possibly associated to **emptying of K/K' valleys**

Optical spectroscopy measurements as «smoking gun» of CDWs and/or structural transitions

Quantum critical behavior in the intermediate regime between SC and CDWs?

What about **other semiconducting TMDs**, such as WS_2?