Semiconductor Devices II

Part 2

Chapter 3: Contact resistance

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[Outline] Chapter 3: Contact resistance

Resistance scaling - general

- Contact resistance
- Quantum limit of resistance
- How to measure contact resistance

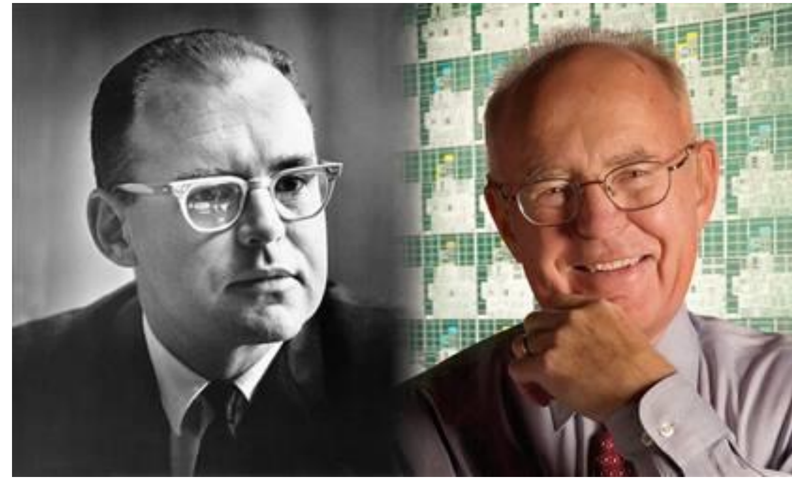
Contacts to 2D materials

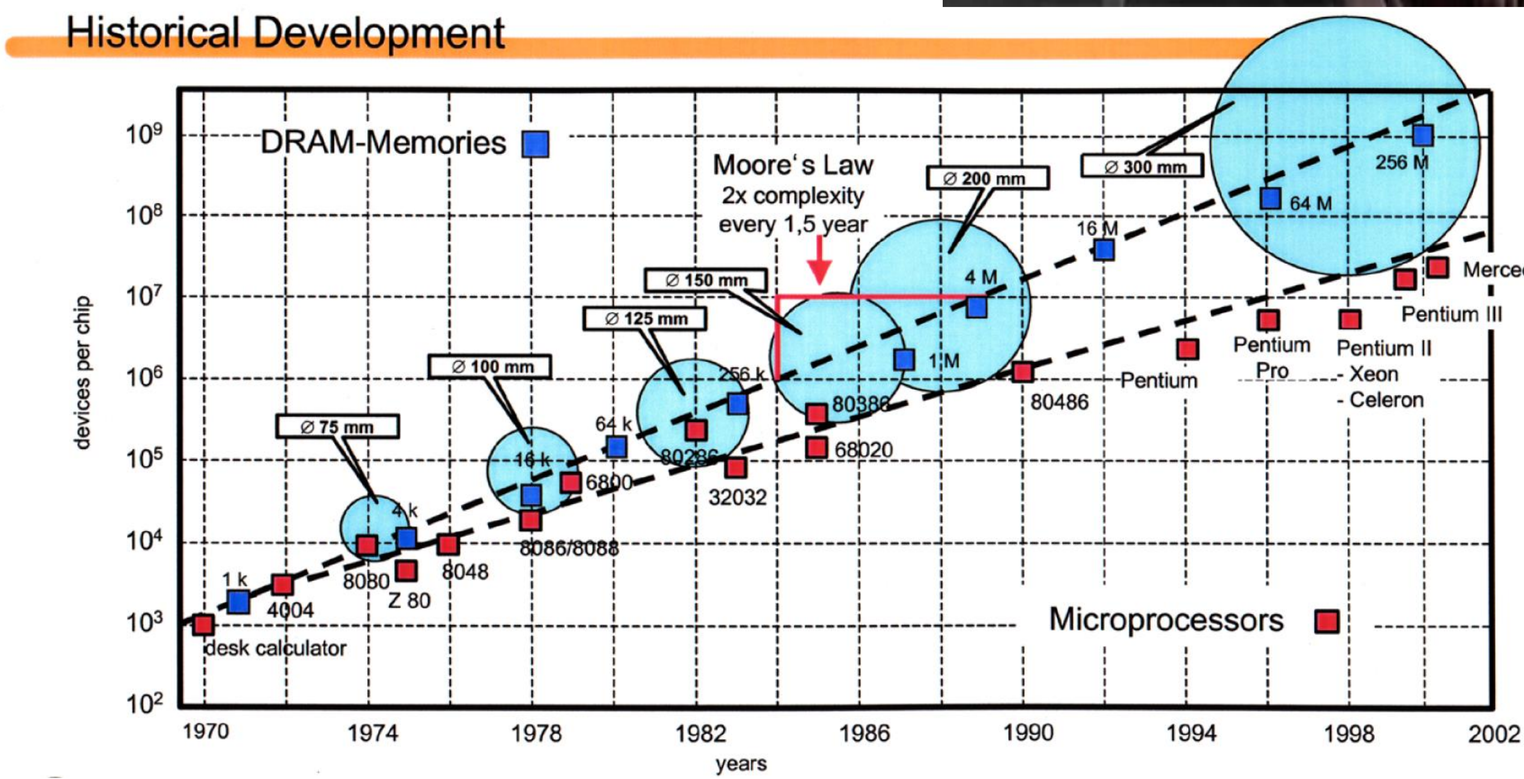
- Contact geometries
- Contact resistance scaling
- Strategies for reducing the contact resistance

Moore's Law

Gordon Moore, co-founder of Intel stated in 1965:

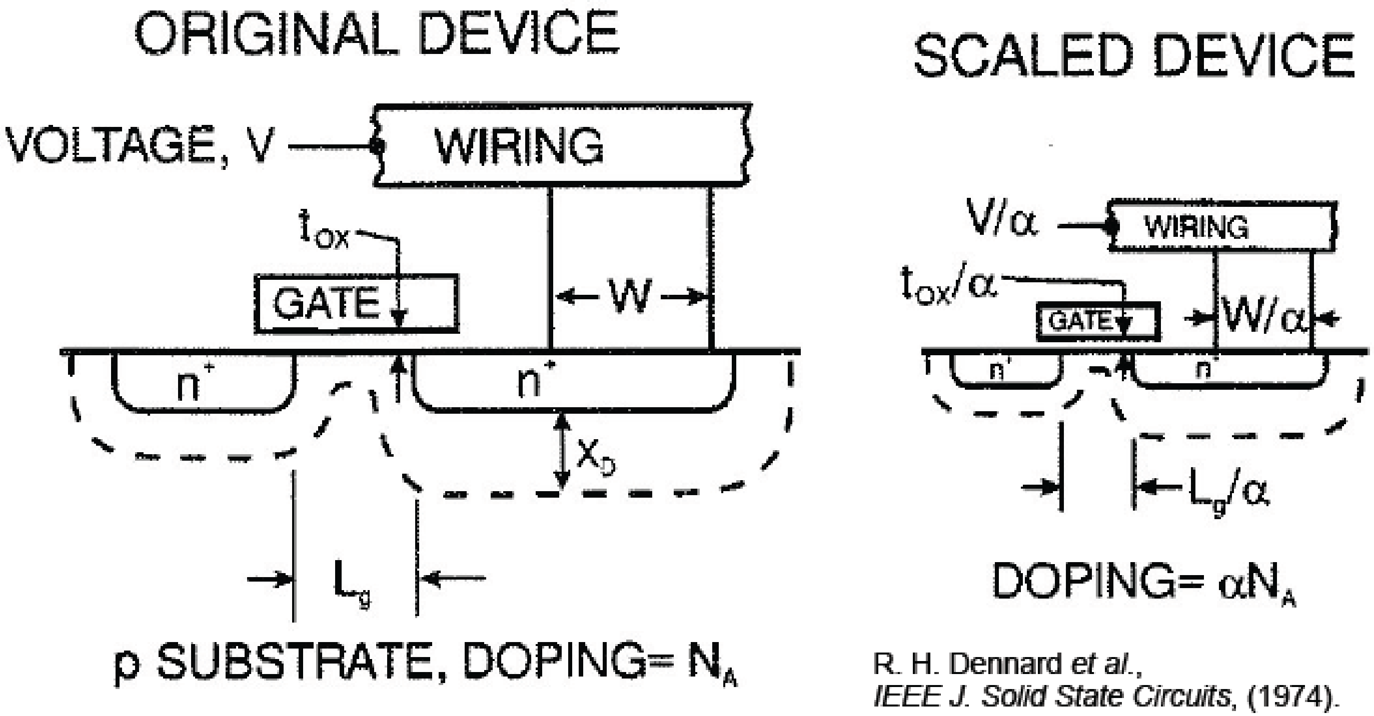
"The number of transistors that can be inexpensively placed on an integrated circuit is increasing exponentially, doubling approximately every two years"





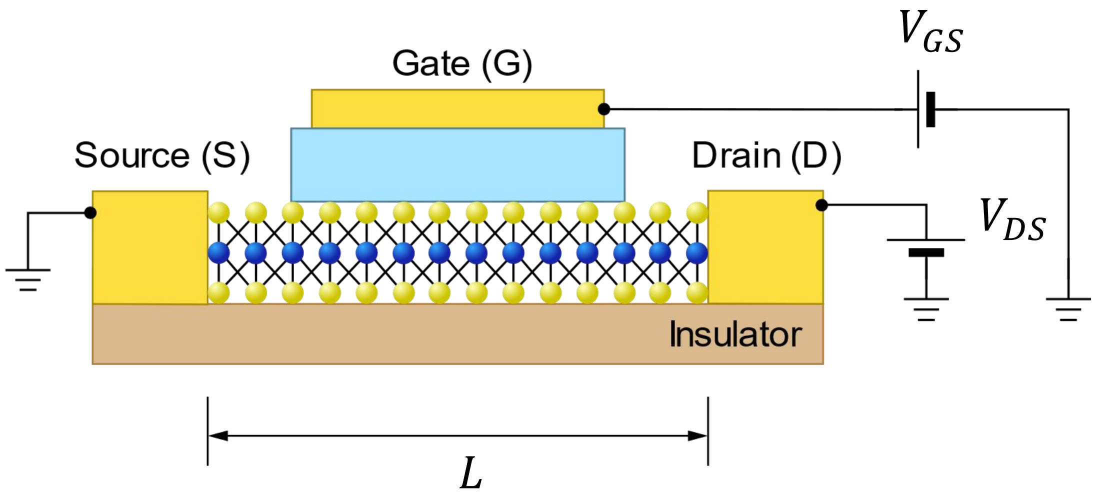
http://nobelprize.org/nobel_prizes/physics/laureates/2000/phyadv.pdf

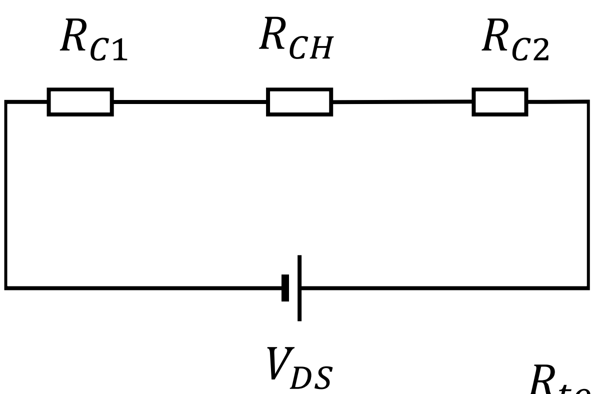
CMOS Scaling: Dennard Scaling (IBM)



If the **dimensions**, **dopant concentrations** and **voltages** are scaled as shown, according to simple electrostatics the **electric field configuration** will be exactly the same

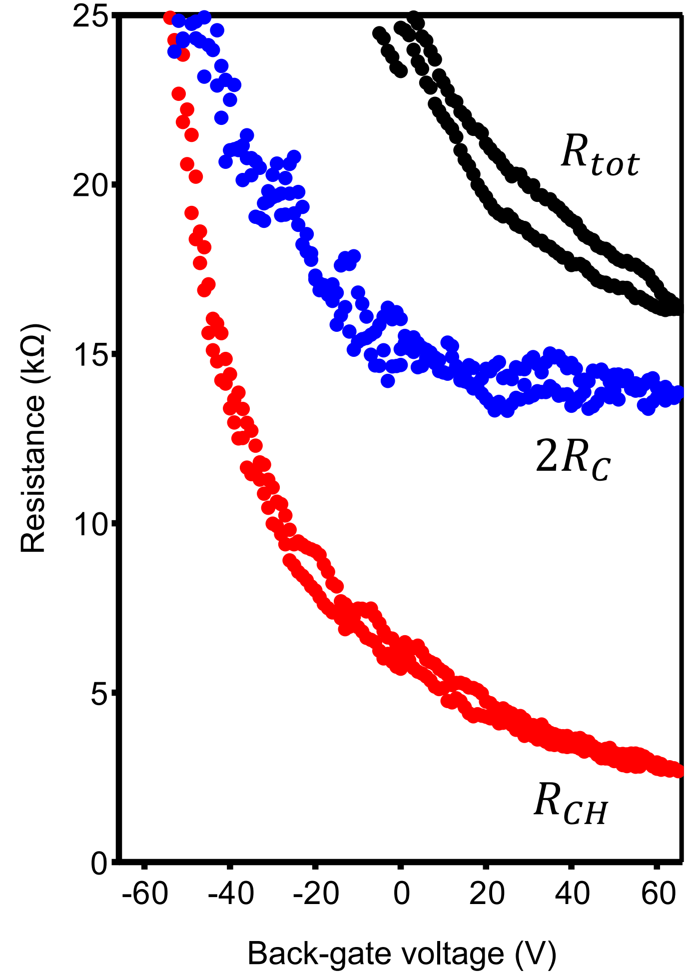
Contact resistance in practice





$$R_{tot} = R_{CH} + R_{C1} + R_{C2}$$
$$R_{tot} = R_{CH} + 2R_C$$

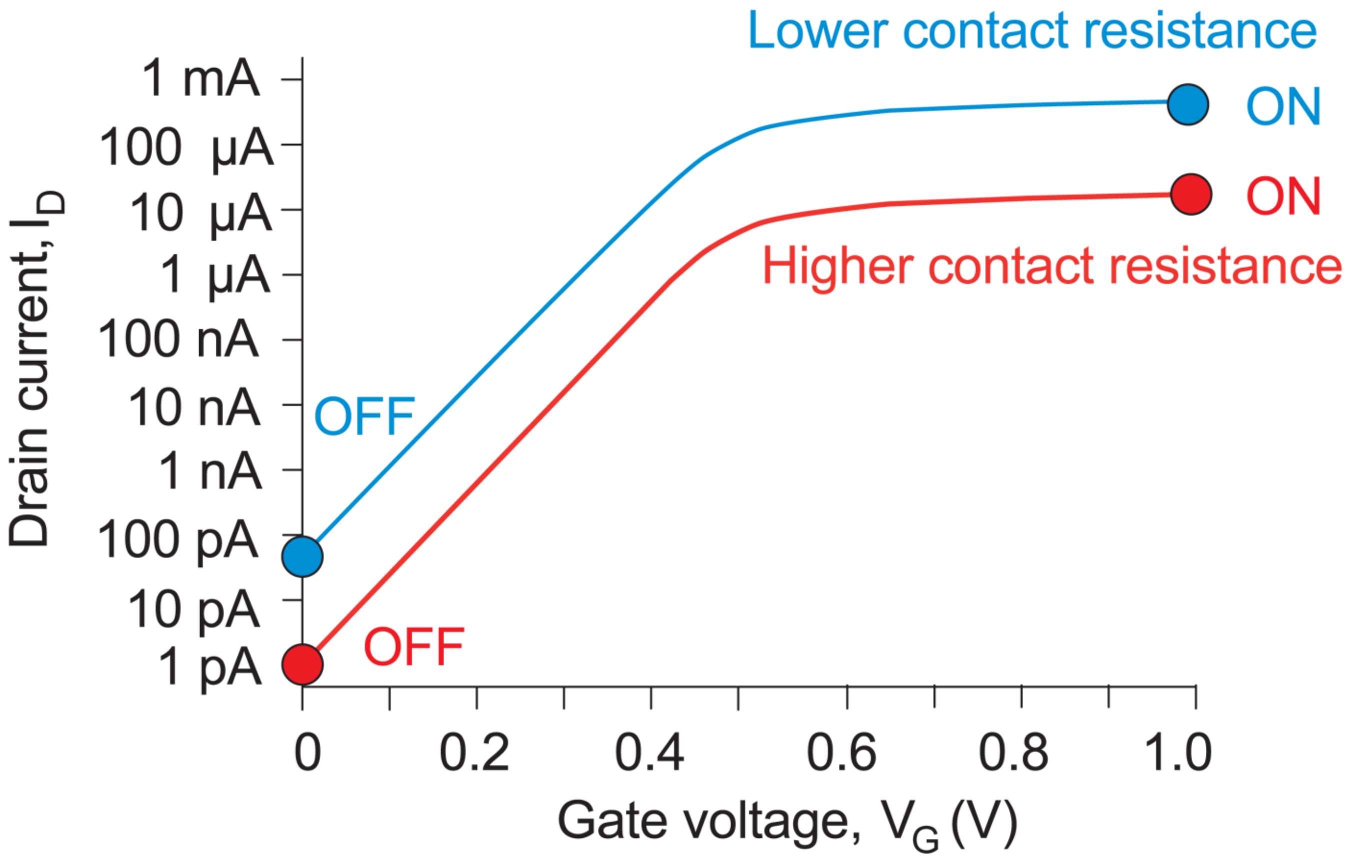
Scales with L



Allain et al., ACS Nano (2014)

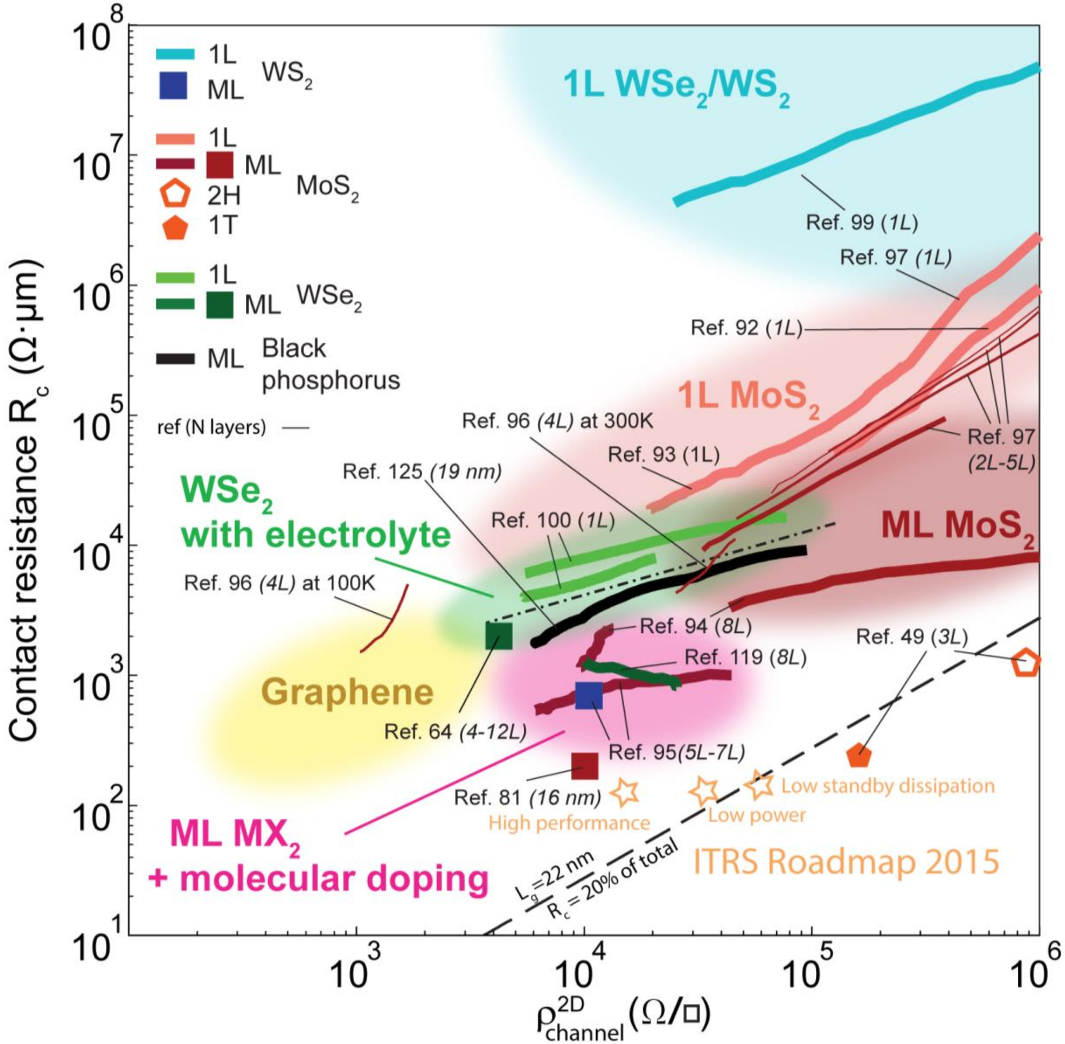
R_{CH}	channel resistance
R_{C1}, R_{C2}	individual contact resistances
R_{tot}	total resistance

Influence on FET characteristics



How much contact resistance can we tolerate?

$2R_C < 20\%$ of R_{tot} ITRS 2012 requirement for low-standby-power SOI FETs



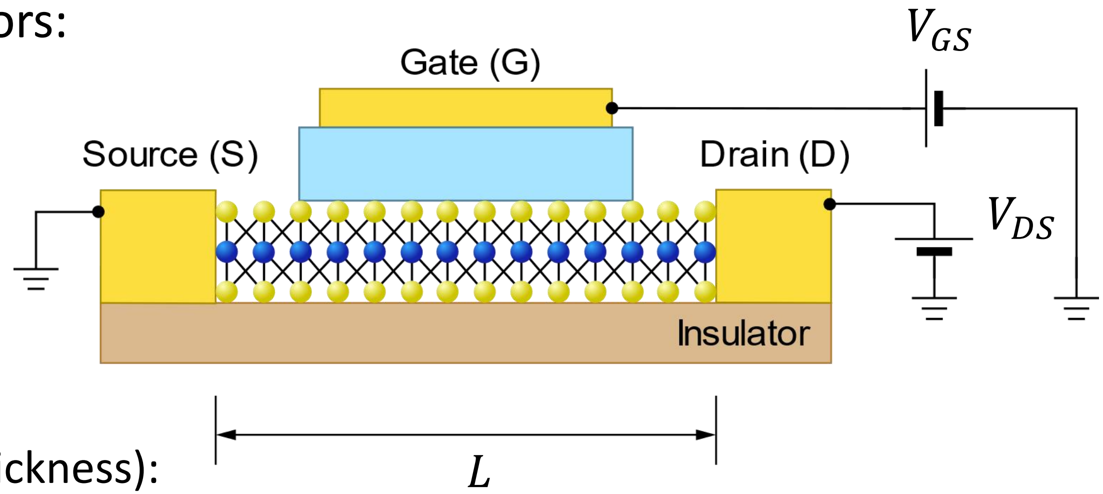
Allain…Bannerjee, Kis; Nature Materials (2015)

How far can we go: quantum limit of resistance

For macroscopic ($L \gg l_m$) conductors:

Ohm's law $I_{DS} = \frac{V_{DS}}{R}$

Resistance $R = \rho \frac{L}{S}$



Resistance for a 2D material (no thickness):

$$R = \rho_{2D} \frac{L}{W}$$

Resistance scaling $L \to 0$ $(L < l_m)$:

$\lim_{L \to 0} R = 0$ Mathematics

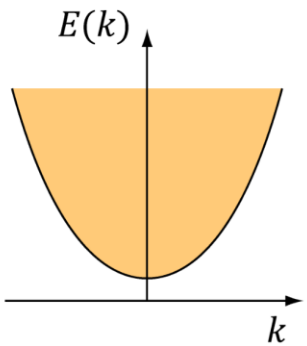
$\lim_{L \to 0} R = R_C$ Reality

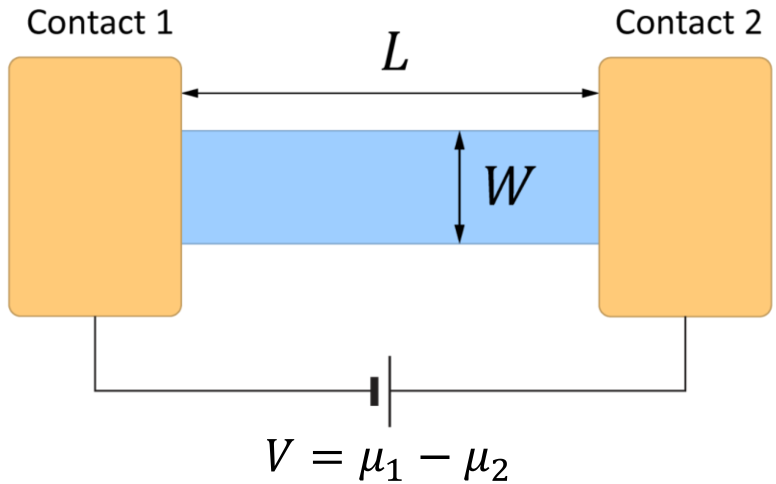
l_m	elastic mean free path (1-10 nm for 2D semiconductors)
ρ	resistivity
ρ_{2D}	2D resistivity
L	length
S	cross-sectional area
W	width
R_C	contact resistance (on the order of kΩ)

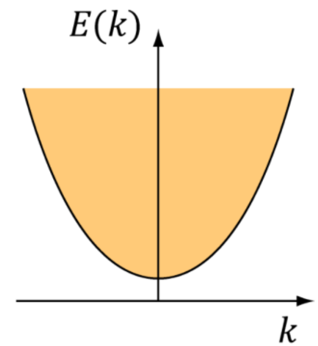
There is a fundamental, quantum limit on how far the resistance can scale!

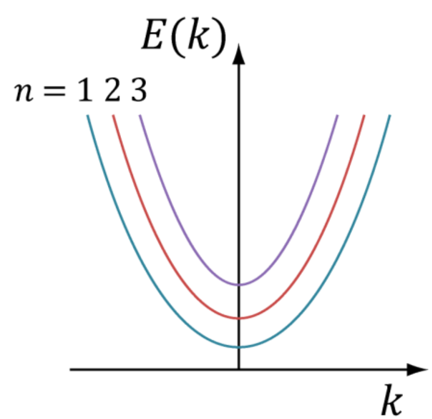
Quantum resistance

As the dimensions decrease, resistance approaches a limiting value R_C









Spin degeneracy

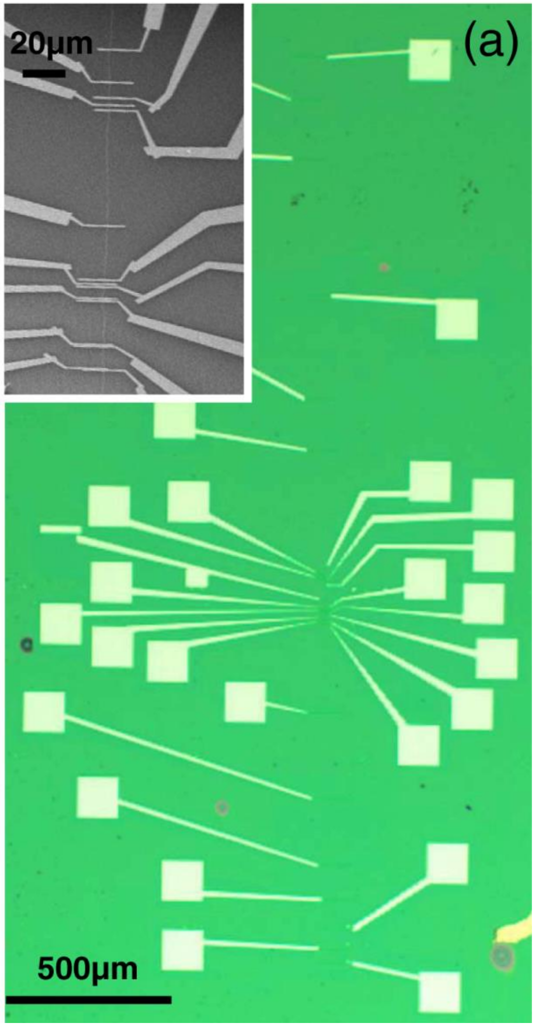
$$G_0 = \frac{2e^2}{h} = 7.75 \times 10^{-5} S = (12.9\ k\Omega)^{-1}$$

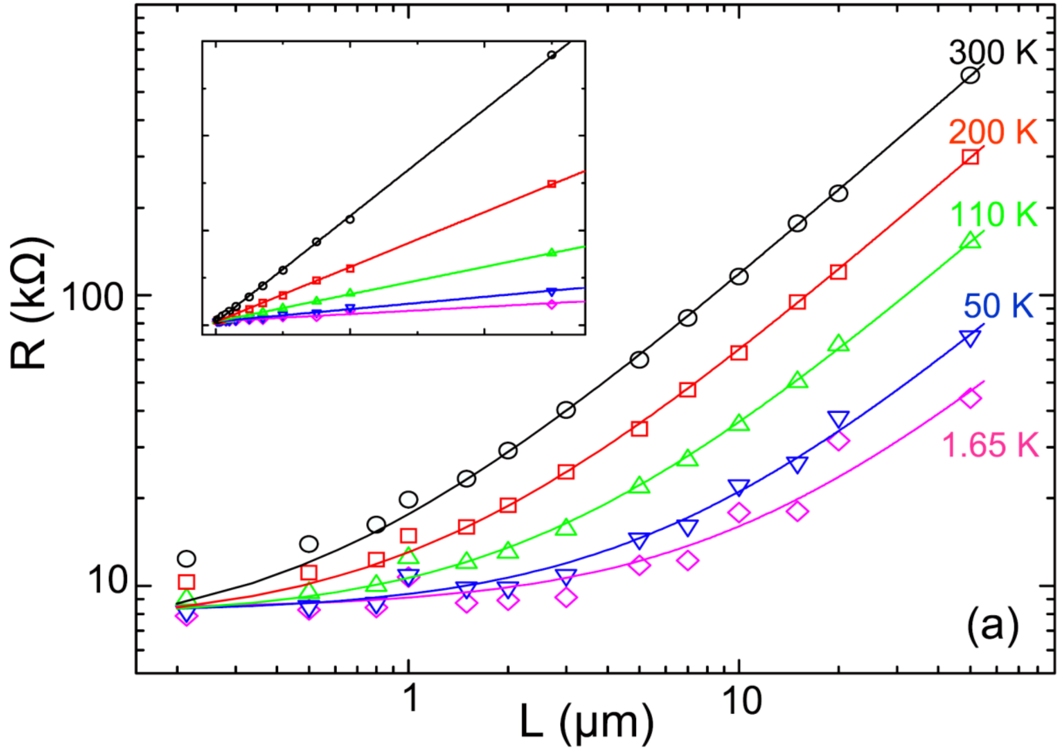
G_0	conductance quantum
e	elementary charge
h	Planck constant

Origin: conductor and contact pads are dissimilar materials (with and without quantum confinement)

Example: carbon nanotube

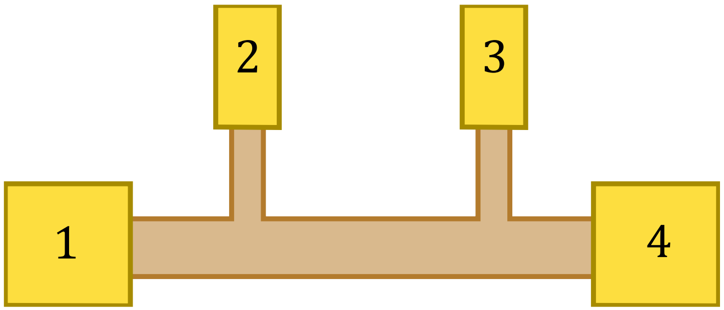
Several milimeters long carbon nanotube, with multiple contacts

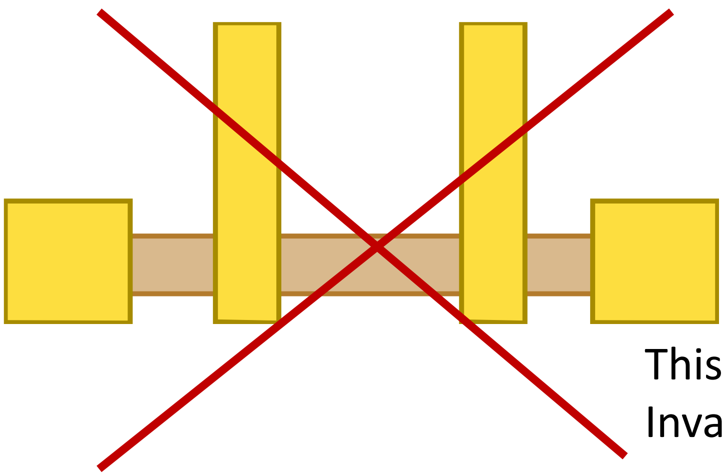




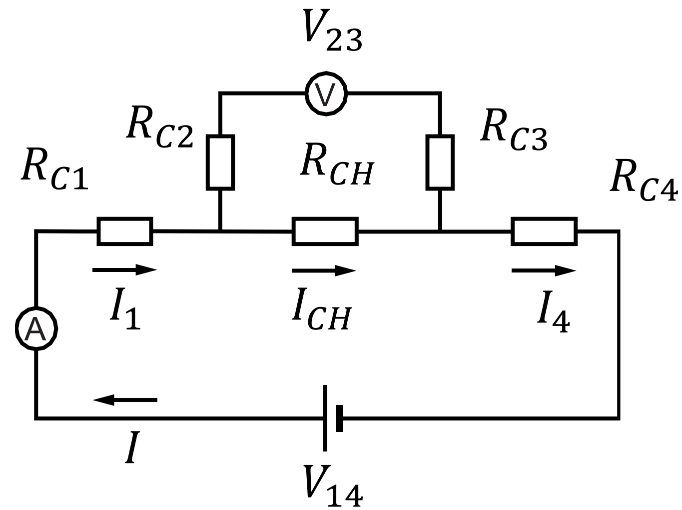
Purewal et al., PRL 98, 186808 (2007)

Contact resistance measurements - 4 probe technique





This is not a 4C device!
Invasive contacts!



$$R_{CH} = \frac{V_{23}}{I} \qquad R_{tot} = \frac{V_{14}}{I}$$

$$2R_C = \frac{V_{14} - V_{23}}{I}$$

Internal resistance of the voltmeter must be high so there is no current flowing through it:

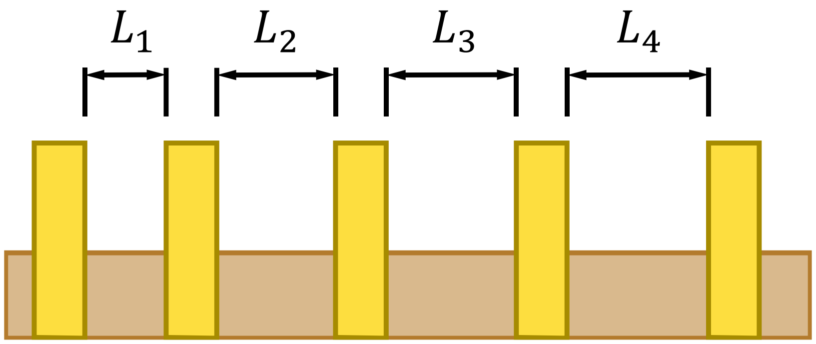
$$I_1 = I_{CH} = I_4 = I$$

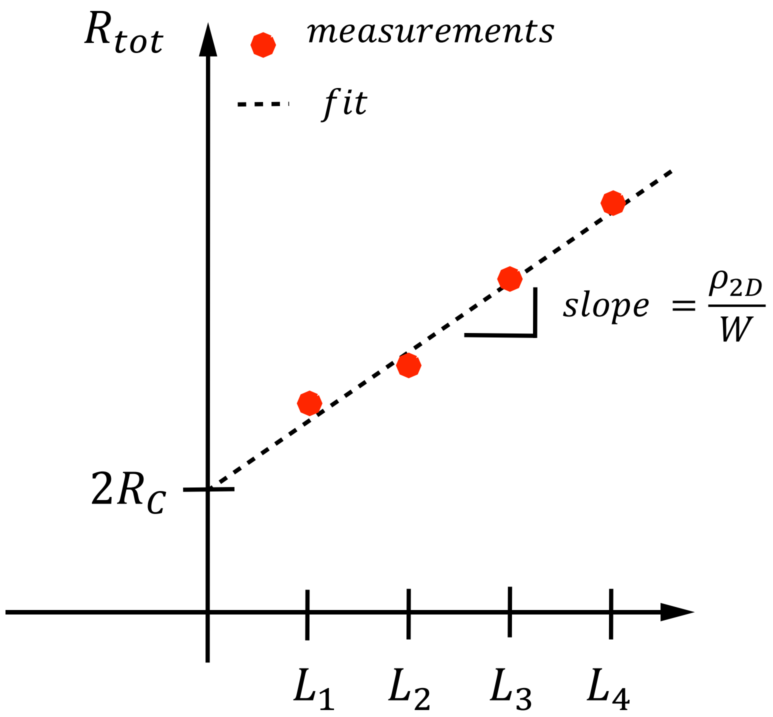
Contact resistance measurements – TLM

Transmission line measurements;
transfer length method

Resistance for a 2D material w contacts:

$$R_{tot} = \rho_{2D}\frac{L}{W} + 2R_C$$





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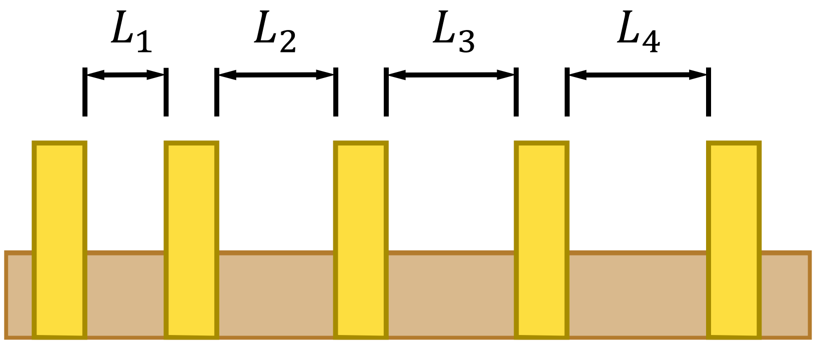
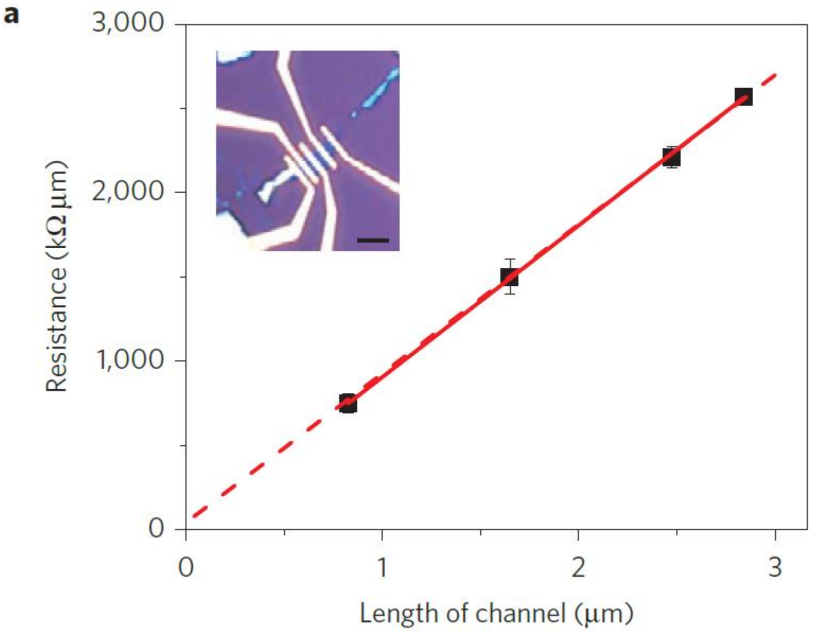
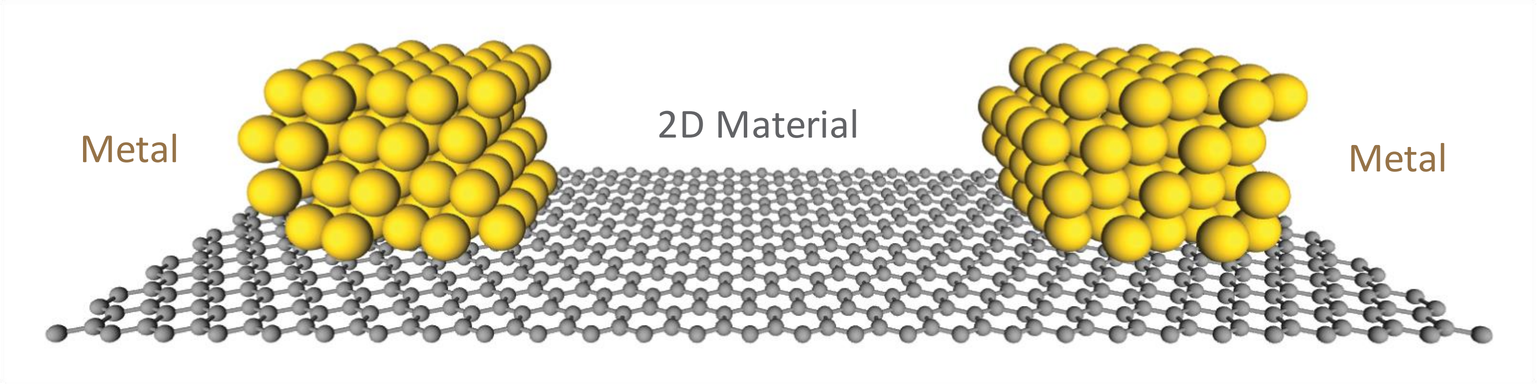




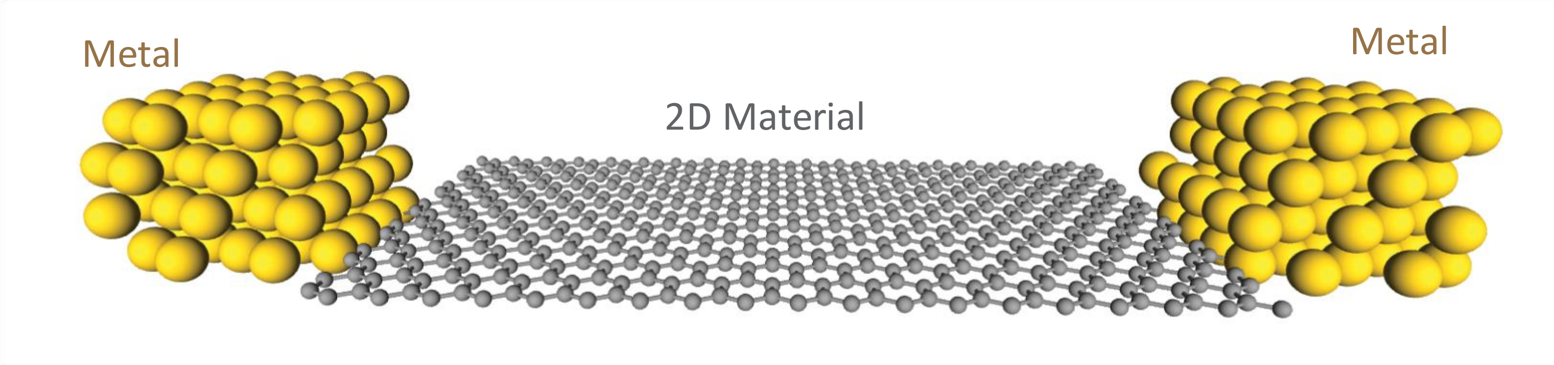
Kappera et al., Nature Materials (2014)

Contact geometry

Top-Contact

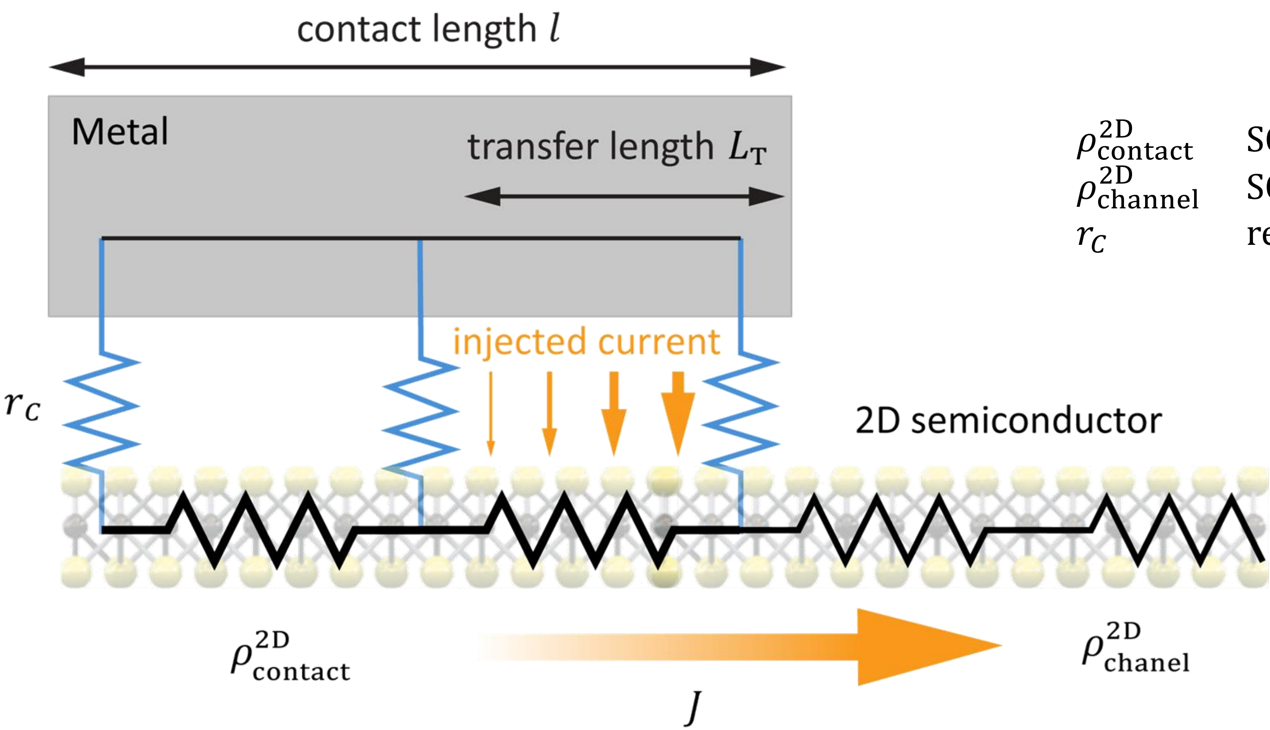


Edge-Contact



Contact resistance scaling

Transmission line model, current crowding:



$\rho^{2D}_{contact}$ SC resistivity under the contact
$\rho^{2D}_{channel}$ SC resistivity in the channel
r_C resistivity of the SC/metal interface

Common assumption: $\rho^{2D}_{contact} = \rho^{2D}_{channel}$

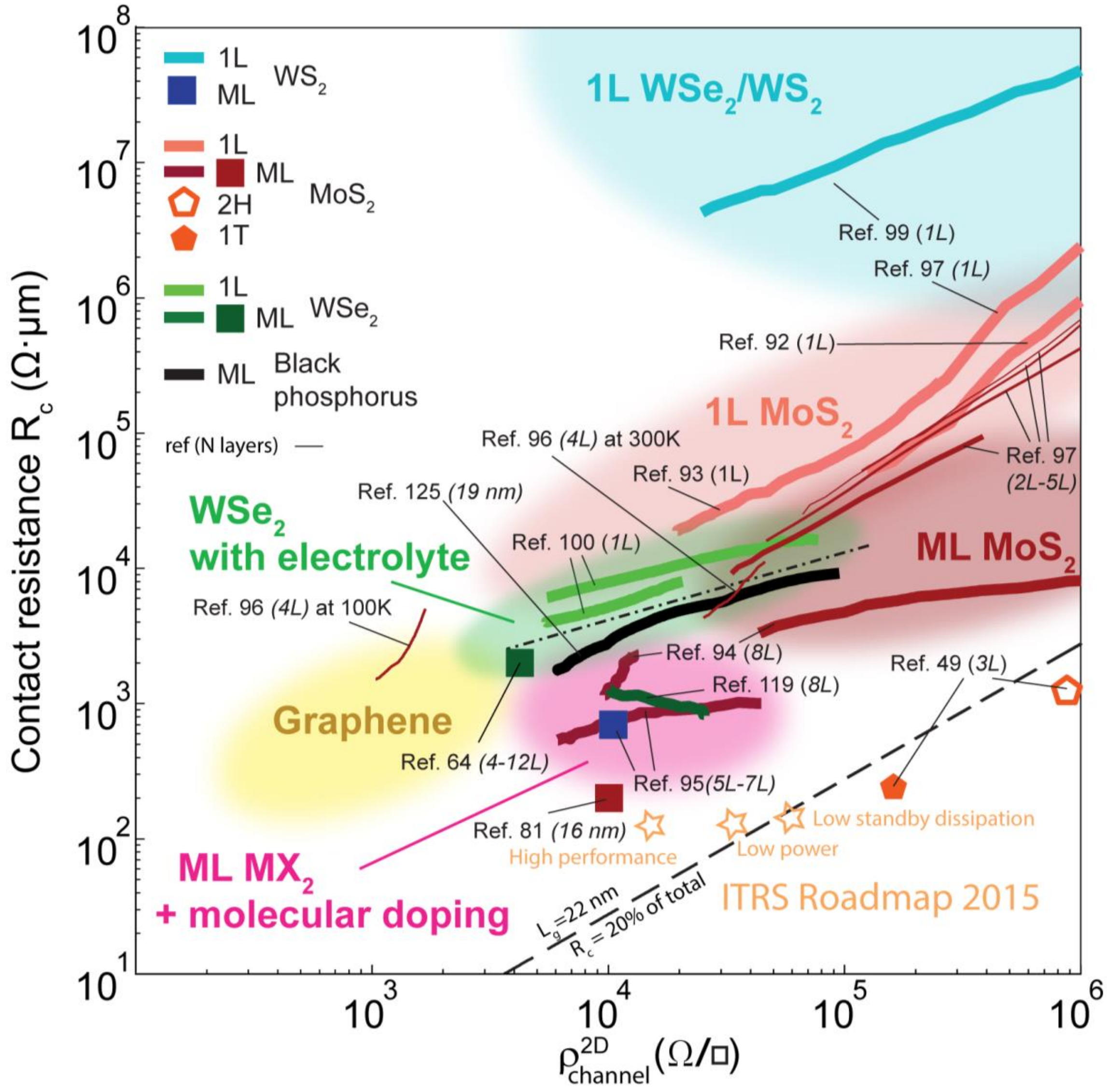
$$R_C = \sqrt{\rho^{2D} r_C} coth\left(l\sqrt{\rho^{2D}/r_C}\right) \qquad for\ l \gg L_T = \sqrt{r_C/\rho^{2D}} \quad : \quad R_C = \sqrt{\rho^{2D} r_C}$$

$$L_T = 20 - 600 \text{ nm}$$

Independent of l!

Allain…Bannerjee, Kis; Nature Materials (2015)

Experimental review



State of the art

$R_C = 200 - 300\ \Omega \cdot \mu\mathrm{m}$

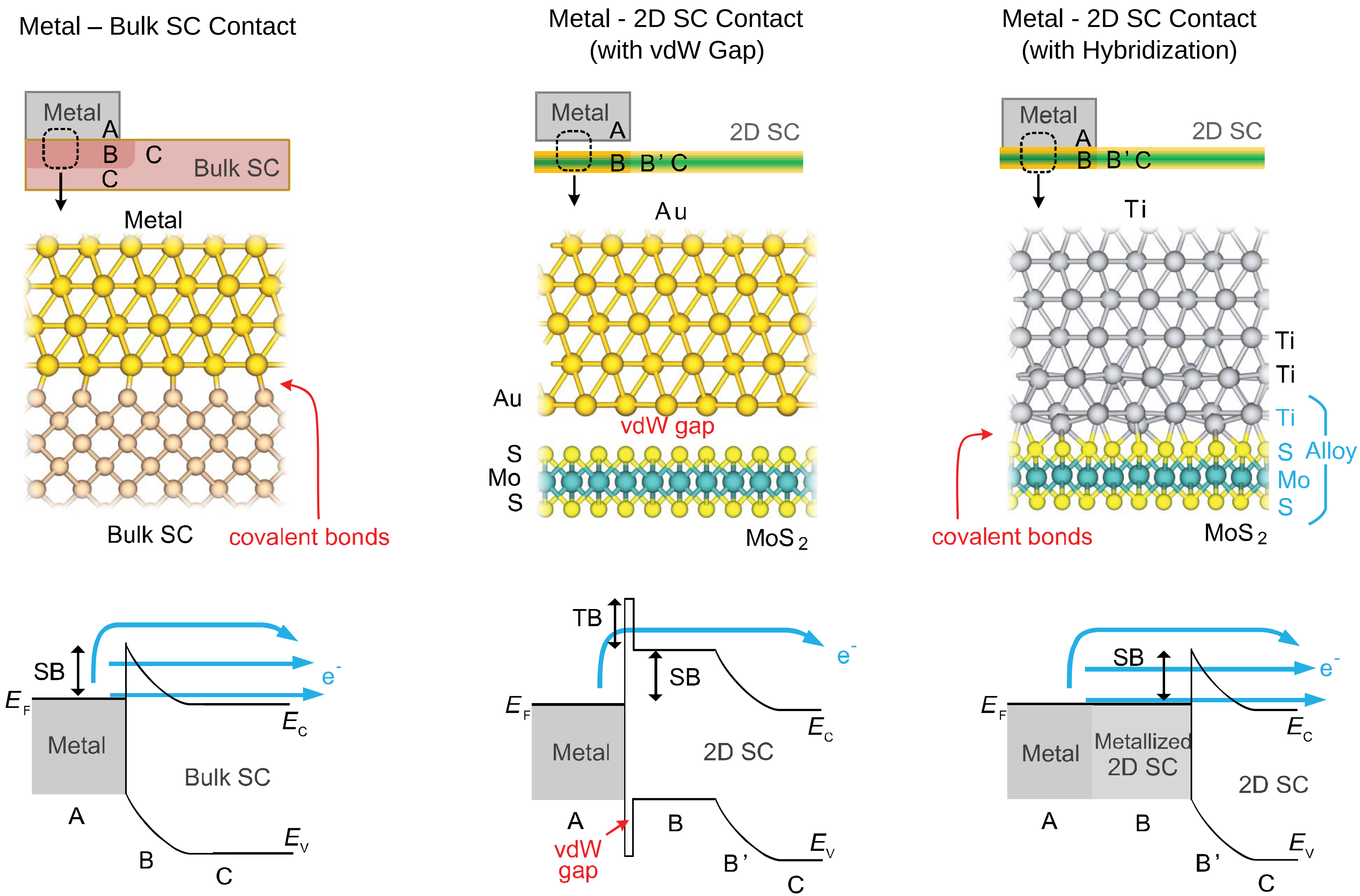
Theoretical limit

$R_C = 30\ \Omega \cdot \mu\mathrm{m}$ for

$n_{2D} = 10^{13}\ cm^{-2}$

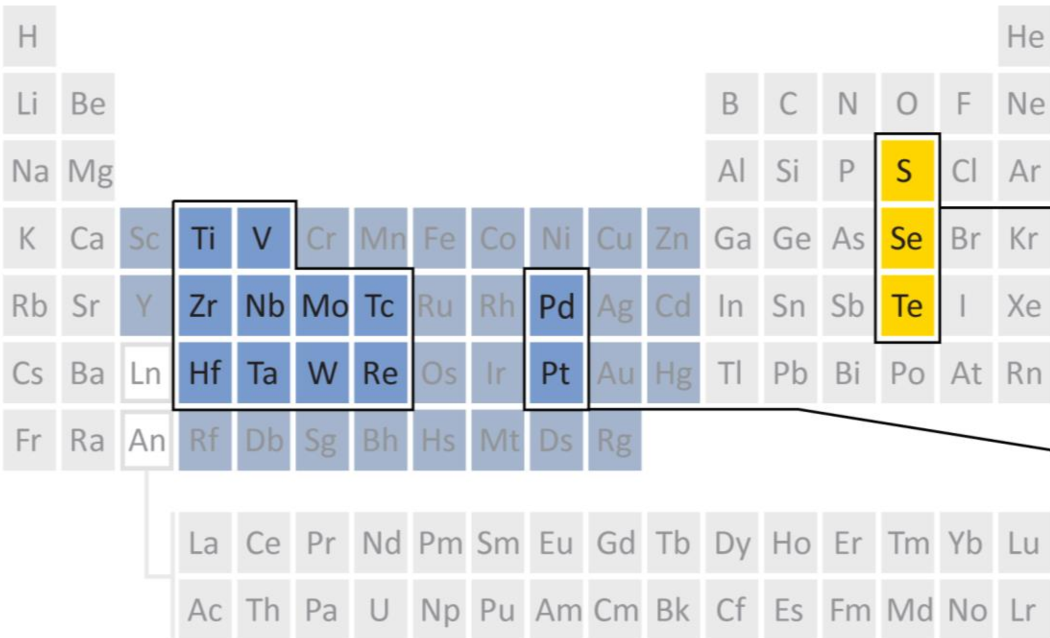
Allain…Bannerjee, Kis; Nature Materials (2015)

Electrical contacts to 2D materials

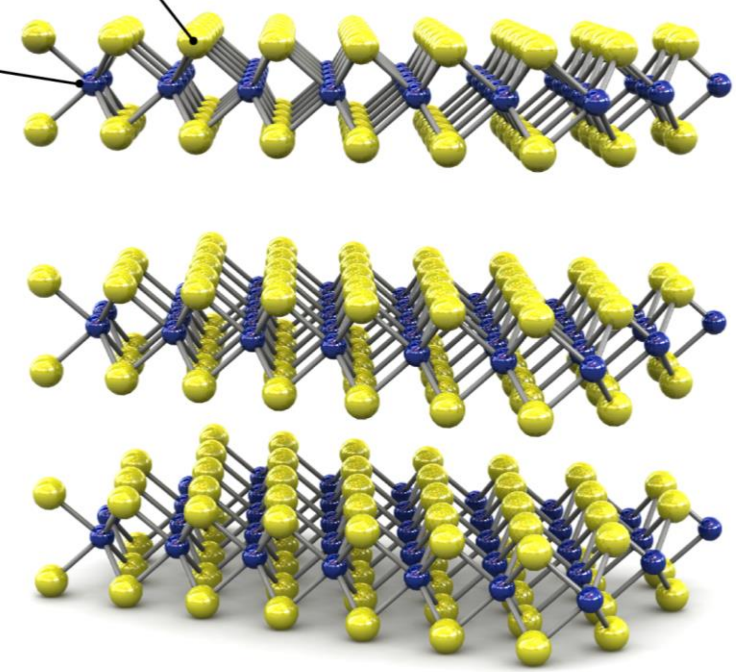


Allain…Bannerjee, Kis; Nature Materials (2015)

2D Transition Metal Dichalcogenides (TMDCs)



- Common formula: MX_2
- 40 stable materials

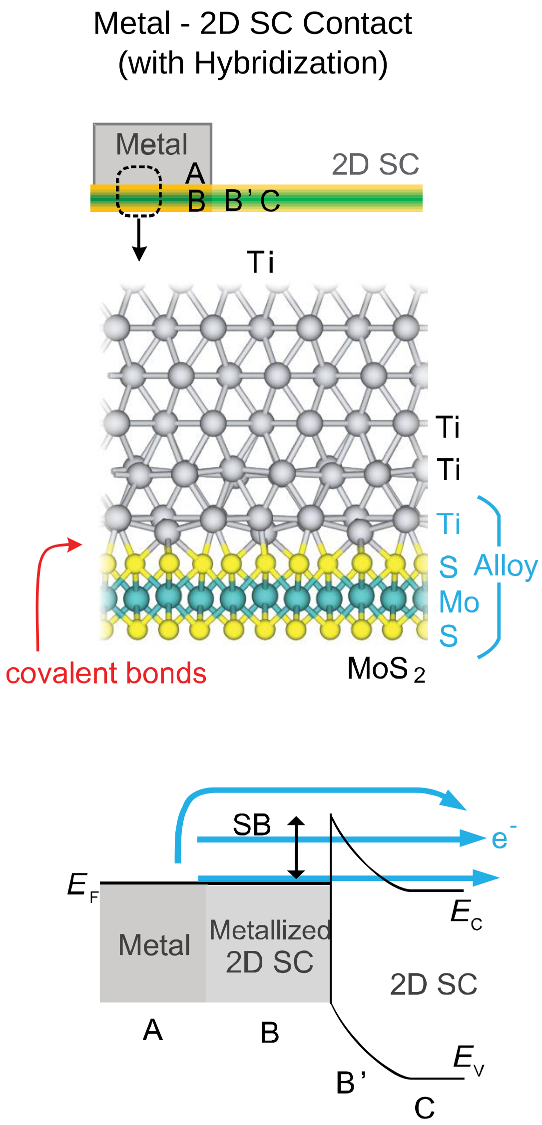


Semiconductors:	MoS_2 $MoSe_2$ WS_2 WSe_2 $MoTe_2$ WTe_2
Semimetals:	TiS_2 $TiSe_2$
Metals, CDW, superconductors:	$NbSe_2$ NbS_2 $NbTe_2$ TaS_2 $TaSe_2$ $TaTe_2$

Charge-injection mechanisms

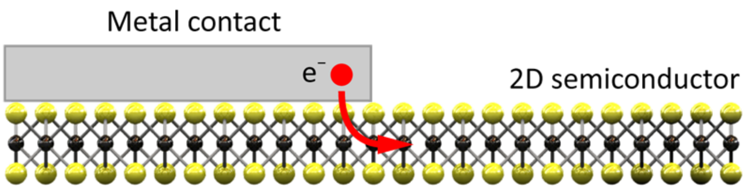
Two mechanisms:

- Thermionic emission **over** the Schottky barrier
- Field emission (tunneling) **through** the Schottky barrier



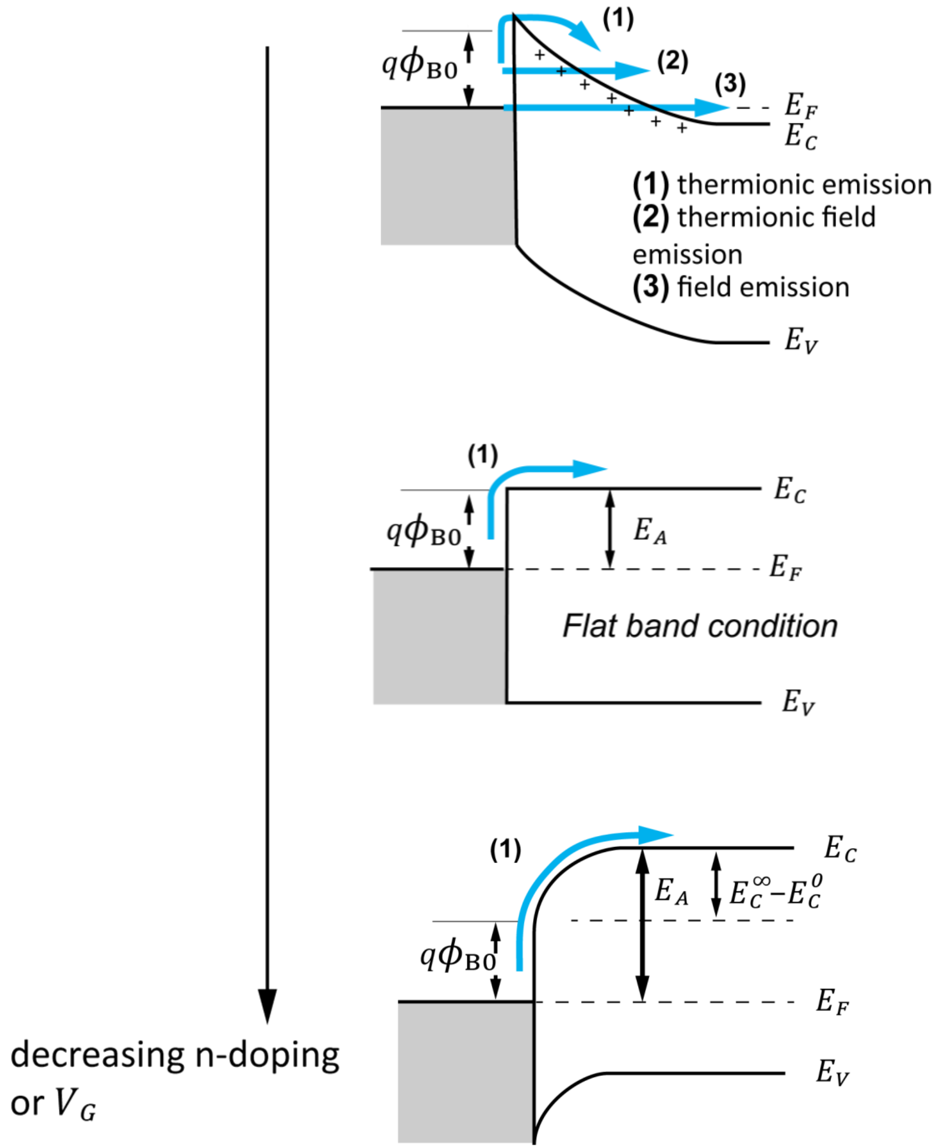
Allain…Bannerjee, Kis; Nature Materials (2015)

Charge-injection mechanisms



Two mechanisms:

- Thermionic emission over the Schottky barrier
- Field emission (tunneling) over the Schottky barrier



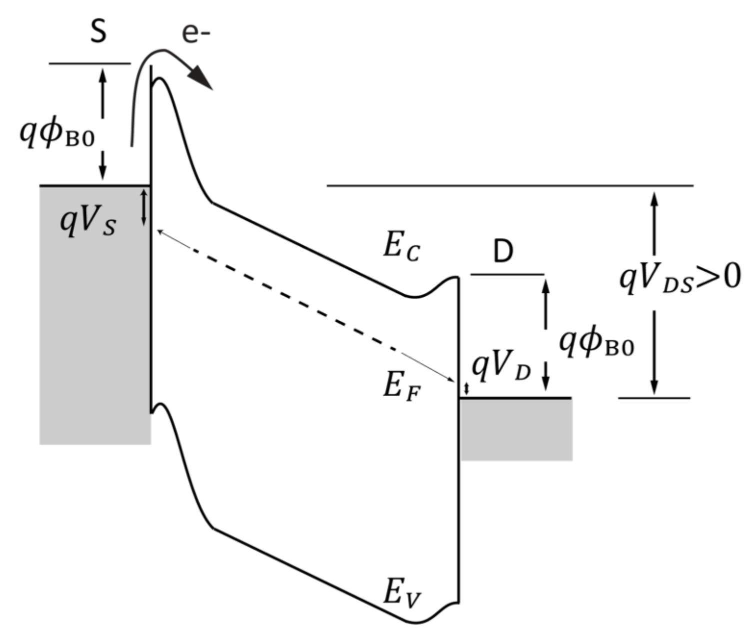
Simpler extraction of the Shottky barrier height $q\phi_{B0}$

Allain…Bannerjee, Kis; Nature Materials (2015)

Schottky barrier height extraction

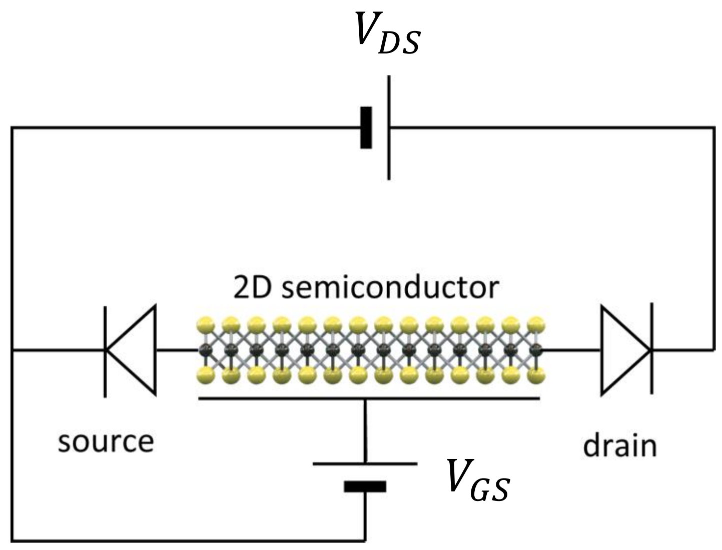
Procedure follows these points:

1. Identify contact with dominant barrier
2. Measure current, extract barrier height
3. Modify barrier height with gate voltage, extract Schottky barrier



One barrier each at source and drain:

- Back-to-back connected diodes
- Biasing curve can be linear

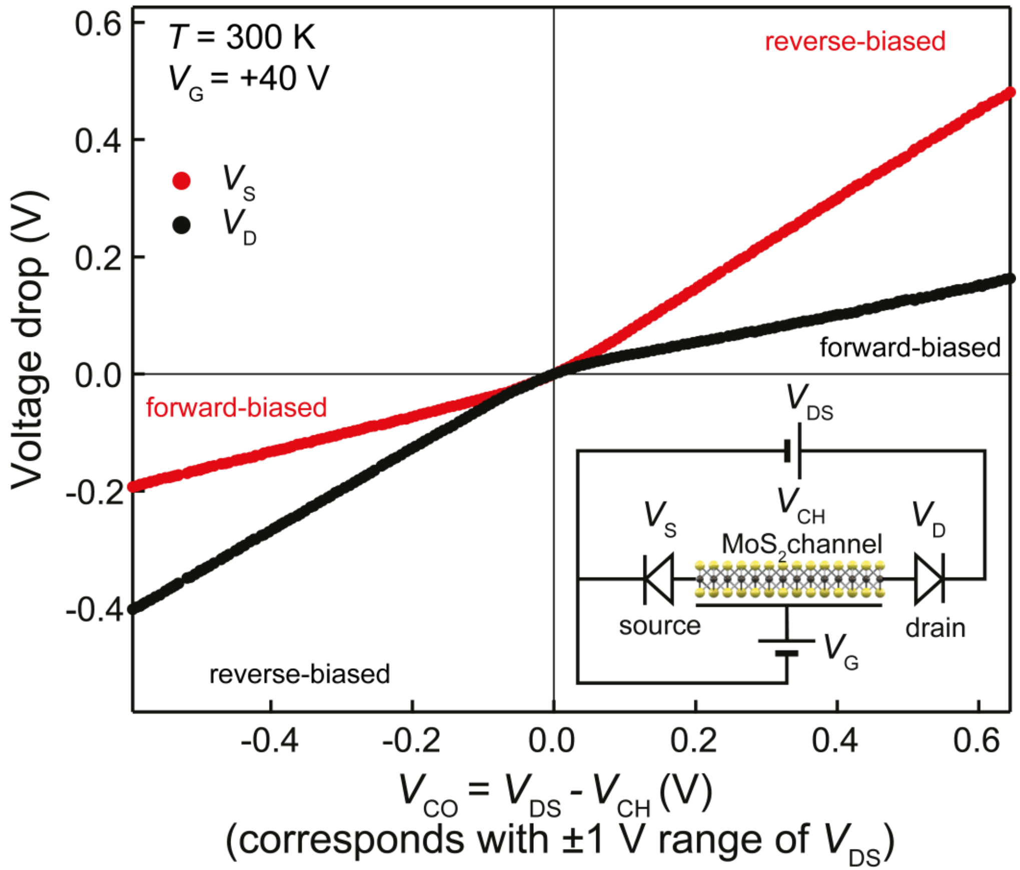


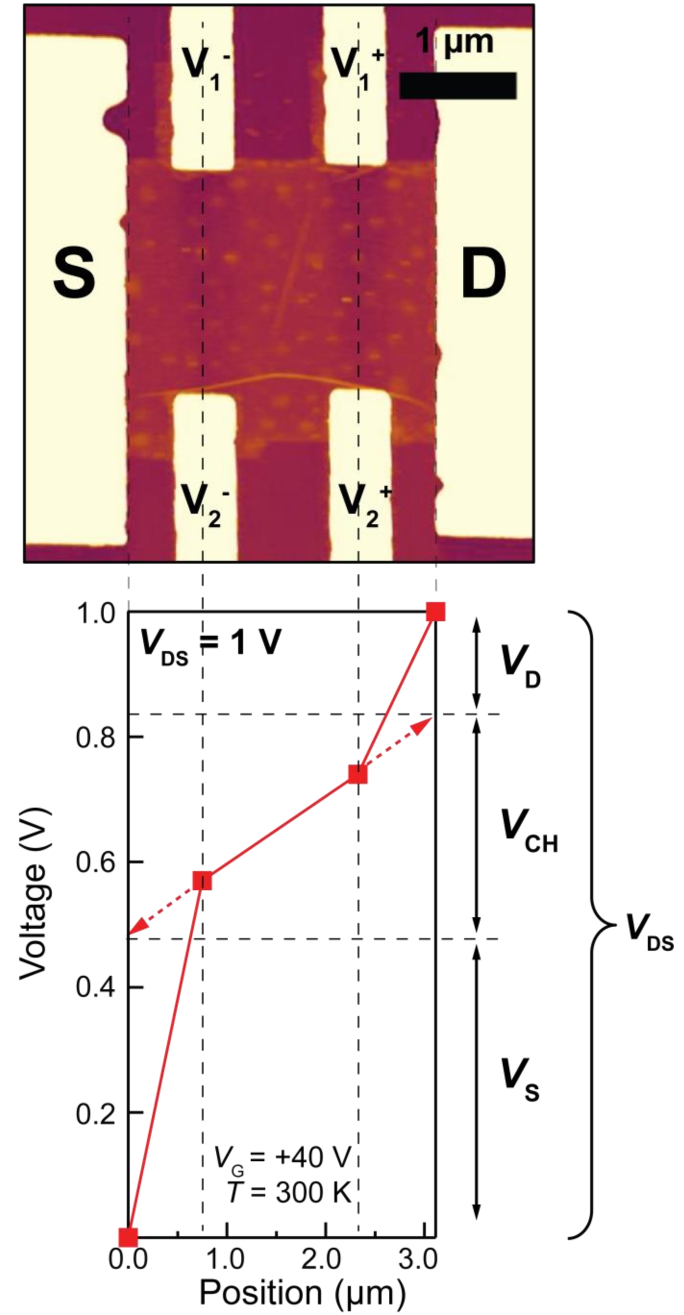
D. Lembke, PhD thesis (2015, EPFL)

Schottky barrier height extraction

One barrier each at source and drain:

- Back-to-back connected diodes
- Biasing curve can be linear
- Most of the voltage drop occurs on the negatively biased diode (Point 1)





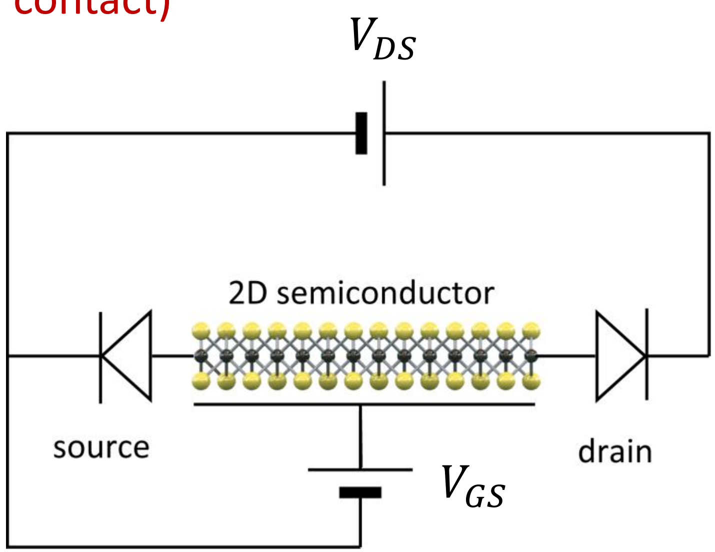
D. Lembke, PhD thesis (2015, EPFL)

Point 1: Schottky barrier height extraction

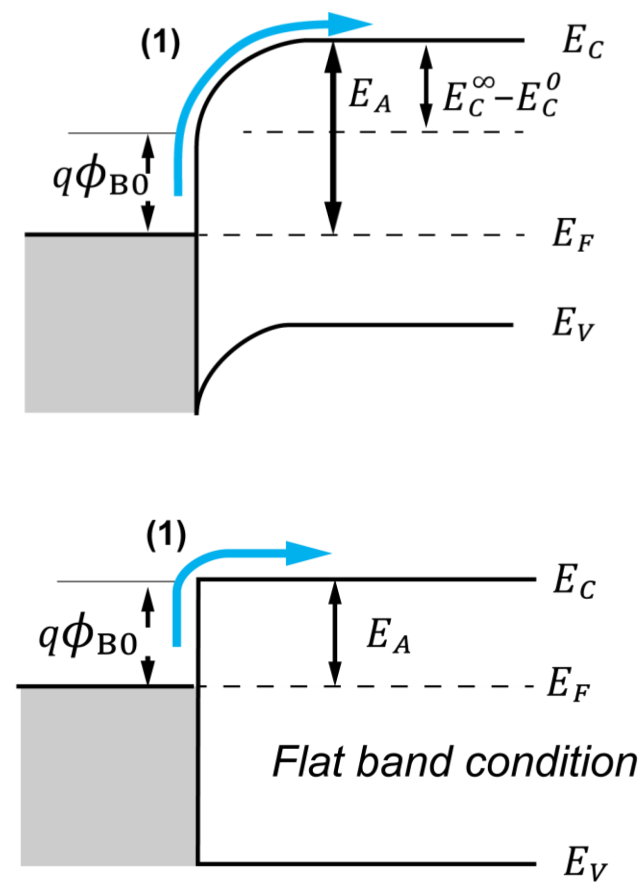
From the activation energy E_A in the thermionic emission regime

One barrier each at source and drain:

- Back-to-back connected diodes
- Biasing curve can be linear
- most of the drop occurs at the reverse-biased diode (source for n-type FET) (Point 1: identify dominant contact)



$$E_A = q\phi_{B0} + E_C^{\infty} - E_C^{0}$$

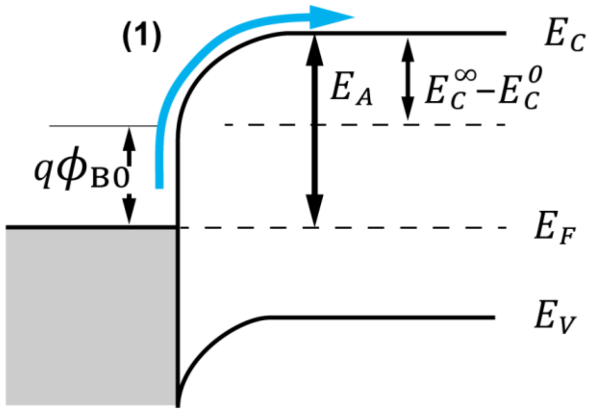


Allain…Bannerjee, Kis; Nature Materials (2015)

Point 2: Schottky barrier height extraction

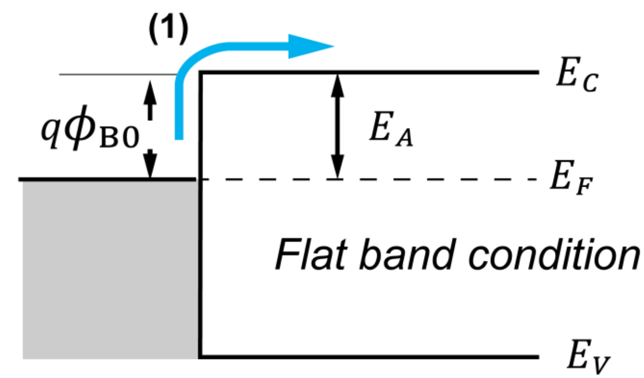
Point 2: Assuming that most of the drop occurs at the reverse-biased diode (source for n-type FET), the injected current density is:

$$J = A^* T^\alpha \exp\left[-\frac{q\phi_{B0}}{k_B T}\right]\left[1 - \exp\left(-\frac{qV_{DS}}{k_B T}\right)\right]$$



For $qV \gg k_B T$ ($k_B T \approx 20$ mV; OK until ~1000 K):

$$J = A^* T^\alpha \exp\left[-\frac{q\phi_{B0}}{k_B T}\right]$$



In the sub-threshold regime (low V_G):

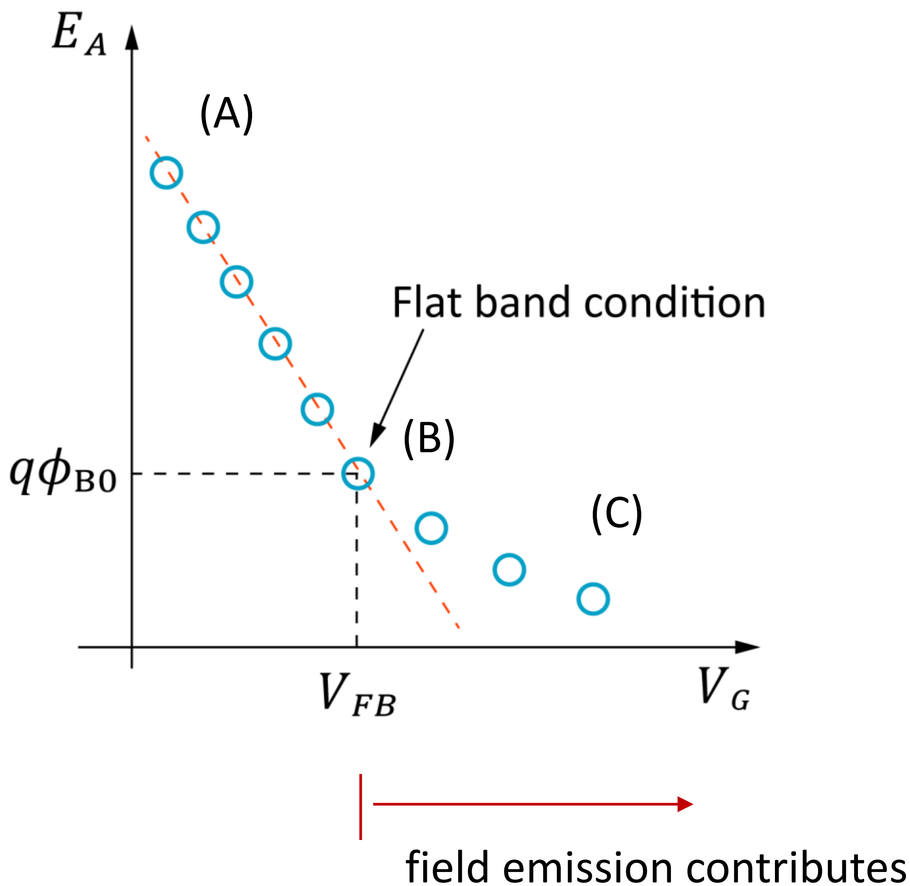
$$J = A * T^\alpha \exp\left[-\frac{E_A}{k_B T}\right] \qquad E_A = q\phi_{B0} + \underbrace{E_C^\infty - E_C^0}$$

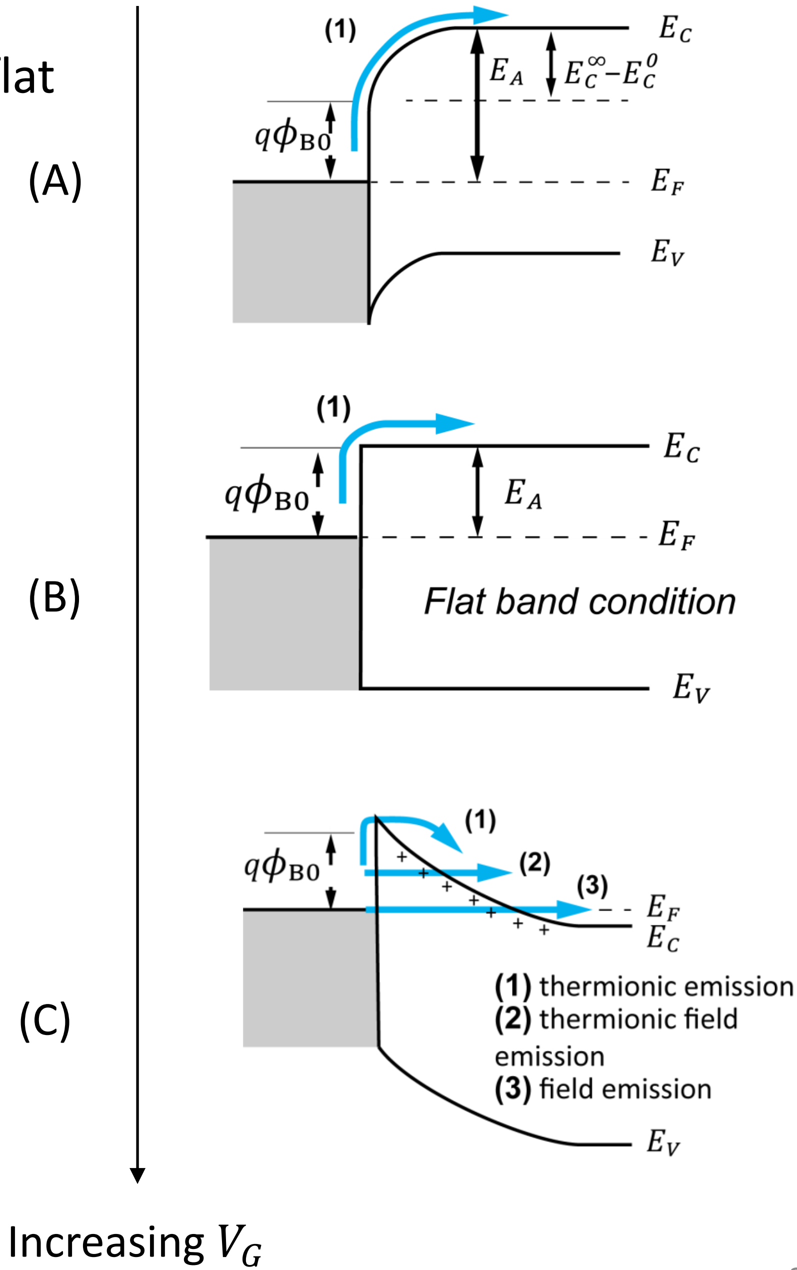
Difference between the conduction bands in the bulk (∞, far from the contact) and at the interface (0)

A^*	Richardson constant
ϕ_{B0}	Schottky barrier height
α	2 for bulk SC, 3/2 for 2D

Point 3: Schottky barrier height extraction

Point 3: Extract E_A as a function of V_G, identify flat band voltage V_{FB}:

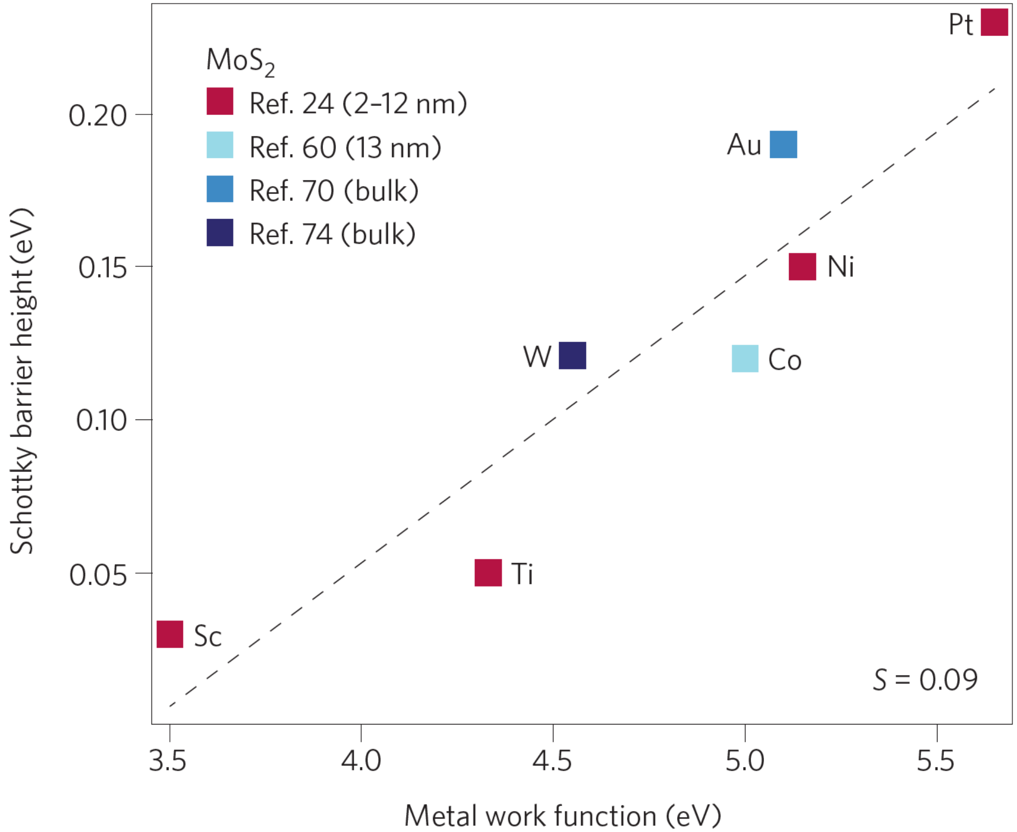




Schottky barrier height

Fermi level pinning

- Metal – 2D SC alloy
- Gap states because of weaker S - Mo bonding
- Choice of metals for contacts alone not the most suitable strategy for reducing R_C



Allain…Bannerjee, Kis; Nature Materials (2015)

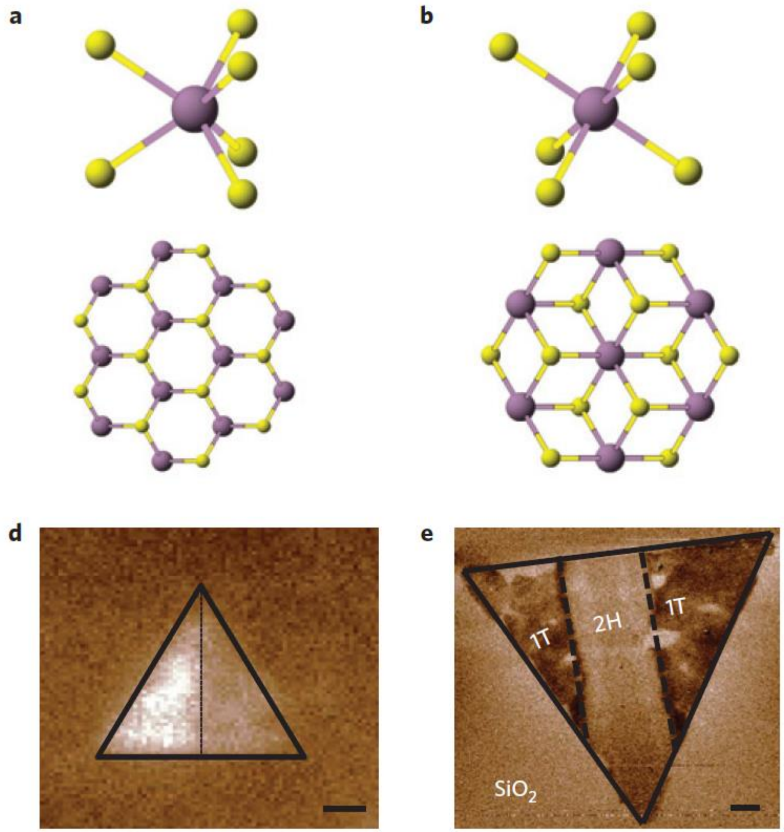
Strategies for reducing contact resistance

Several strategies appear promising:

- Phase engineering
- Doping
- Edge contacts
- Direct transfer

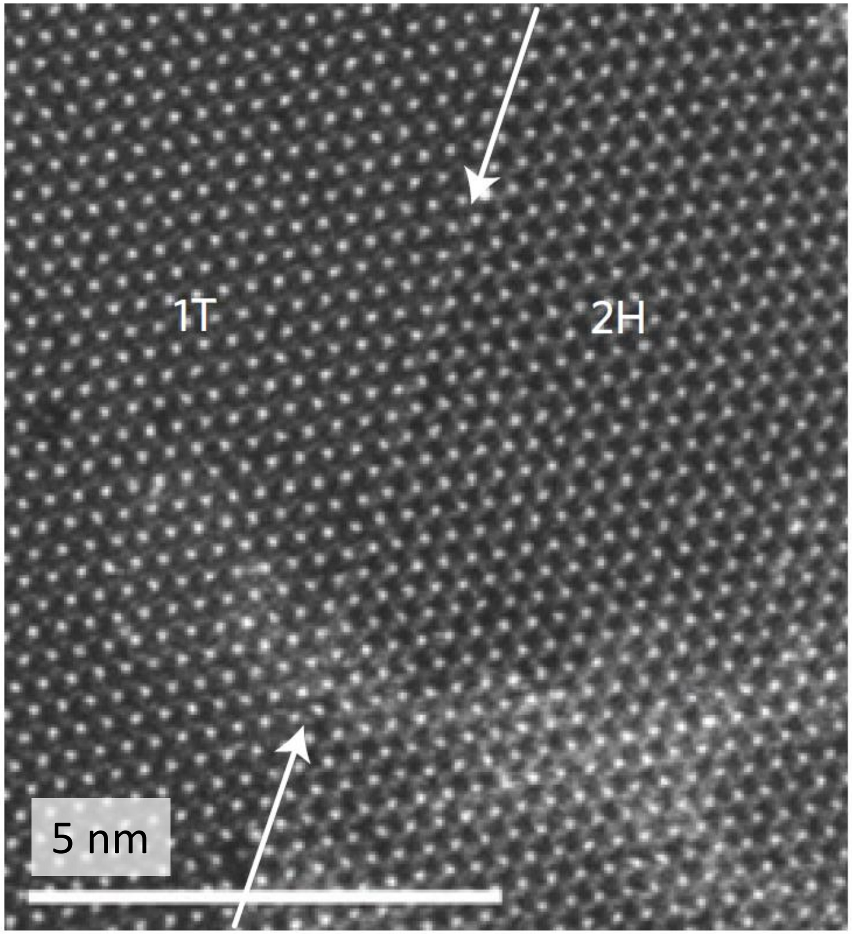
Phase engineering

Heavy doping by Lithium can trigger a phase transition into a metallic phase



2H phase of MoS_2 semiconductor

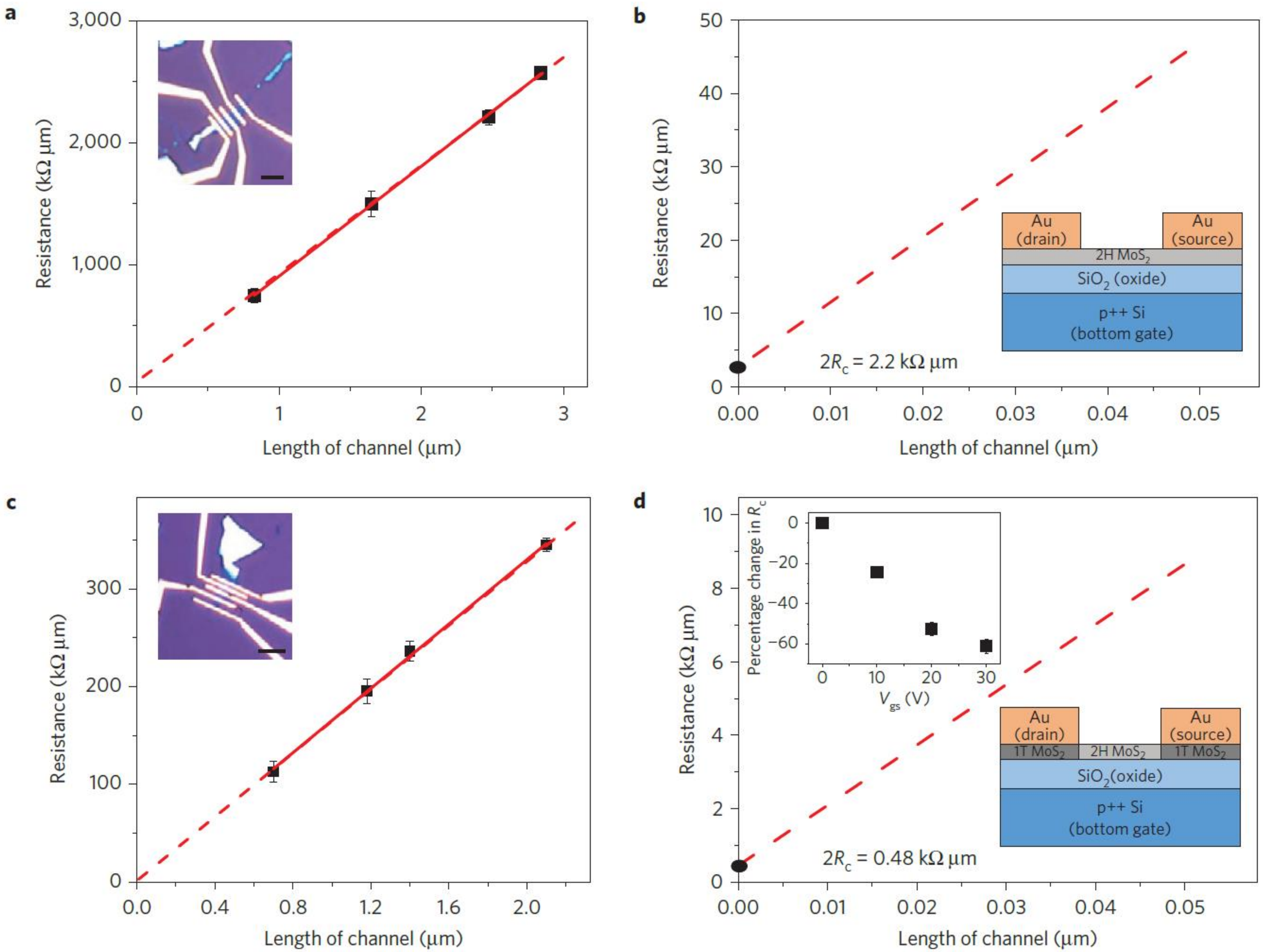
1T phase metallic



Kappera et al. Nature Materials (2014)

Phase engineering

$R_C = 200 - 300\ \Omega \cdot \mu m$

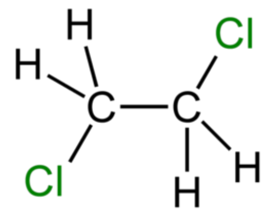


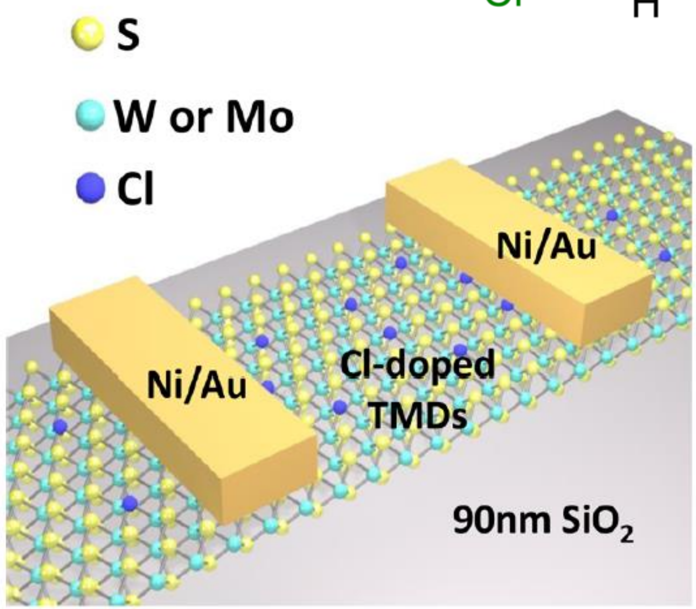
Kappera et al. Nature Materials (2014)

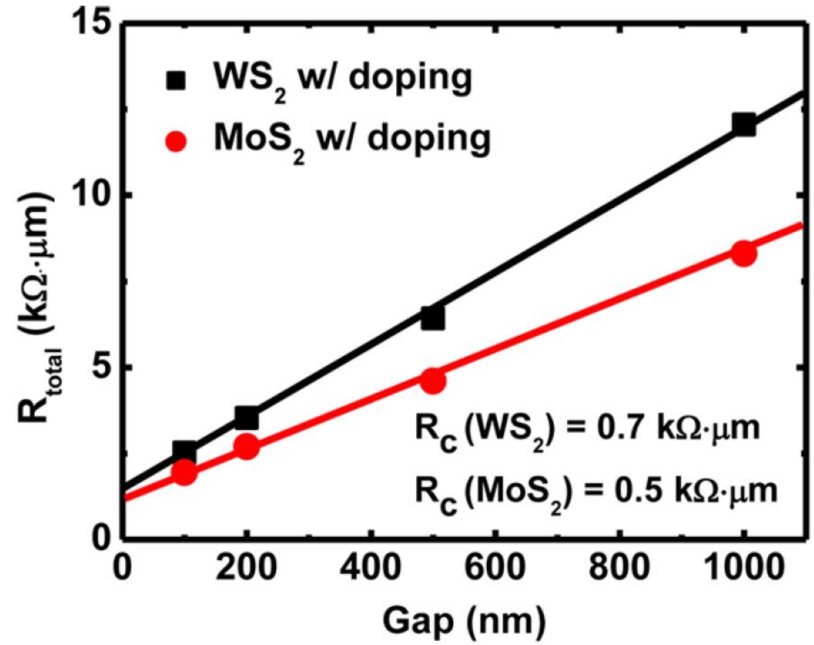
Doping

$R_C \approx 500\ \Omega \cdot \mu m$

Cl doping by soaking the flakes in dichloroethane

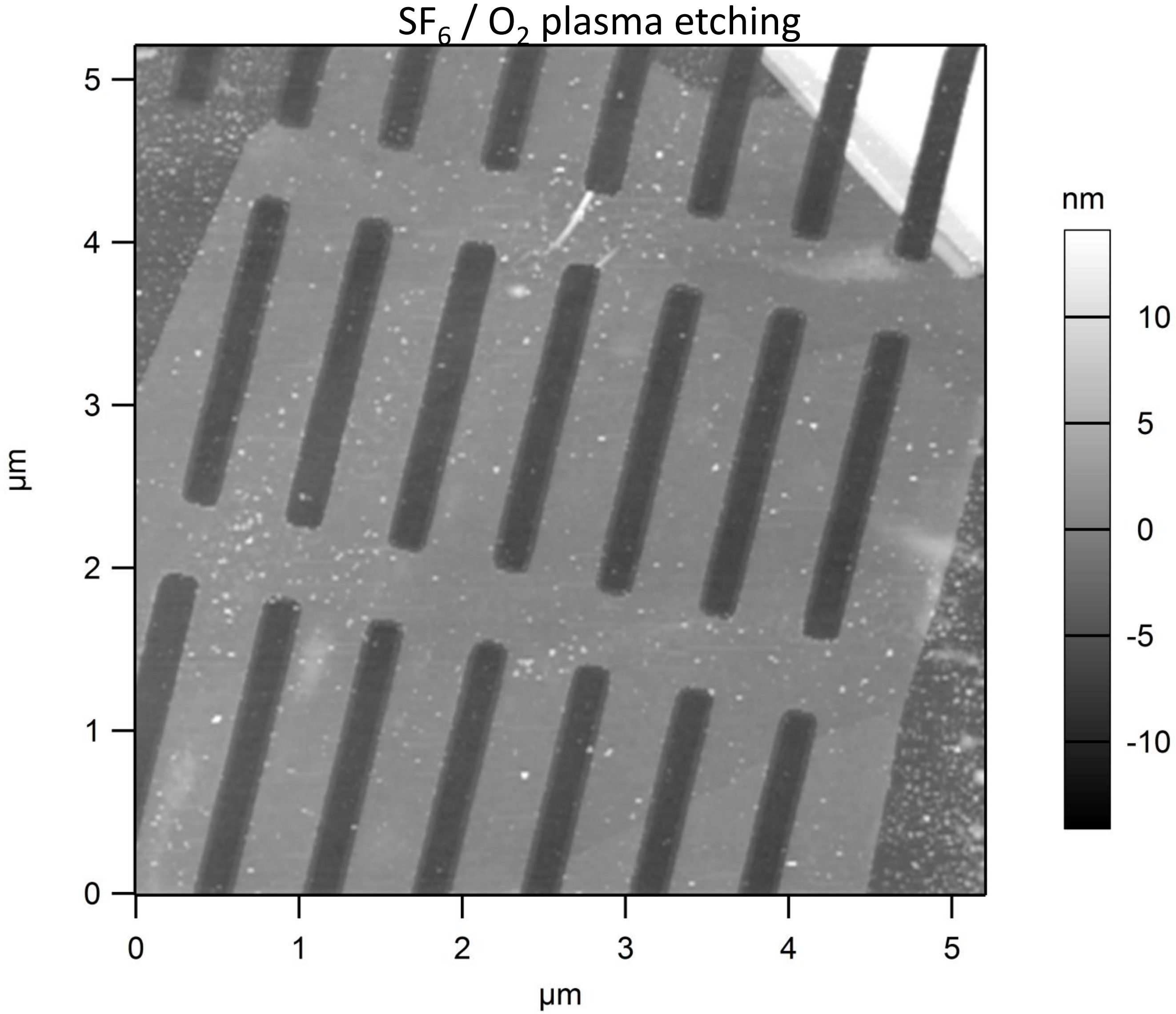






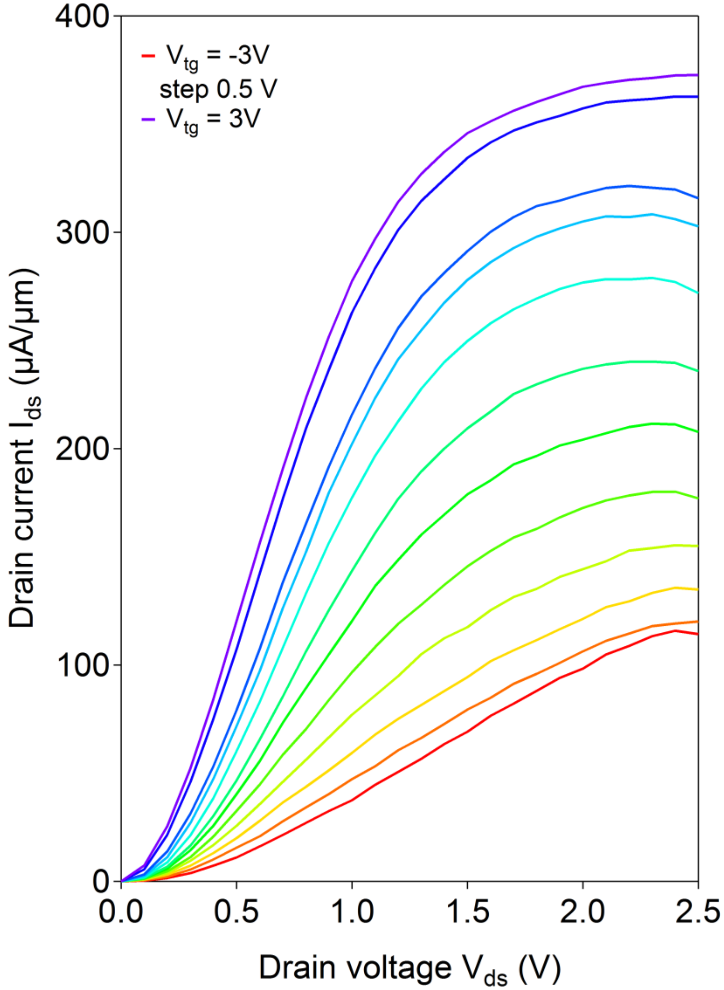
Yang et al. Nano Letters (2014)

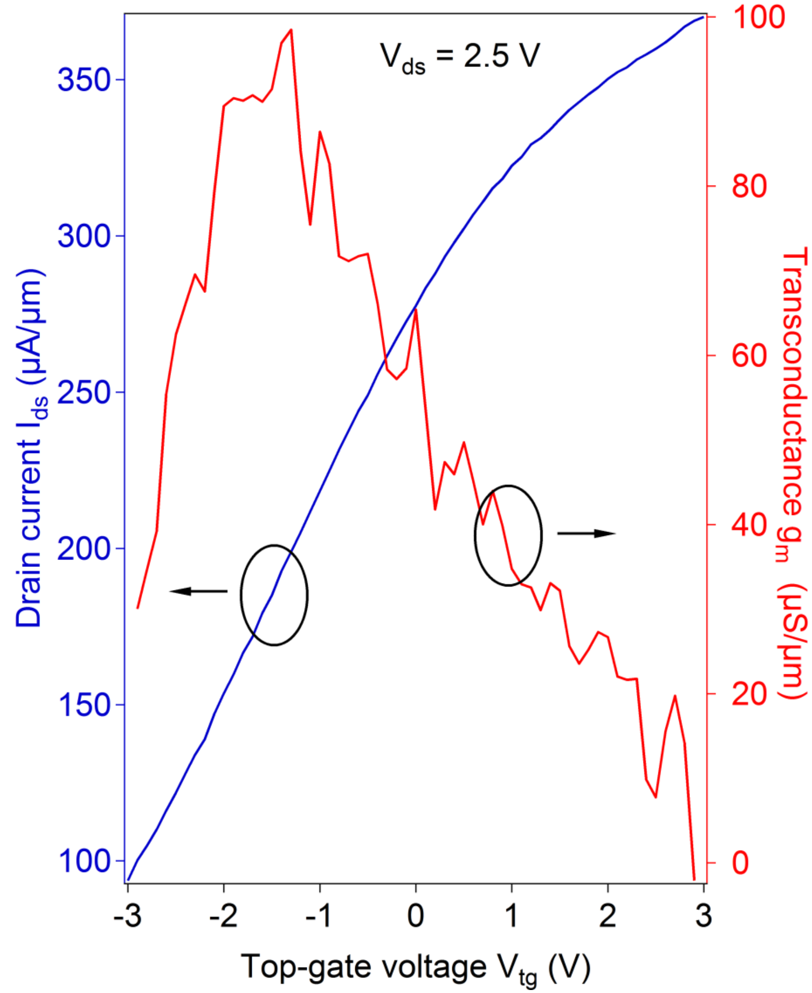
Edge contacts



Krasnozhon et al. IEDM (2015)

Edge contacts



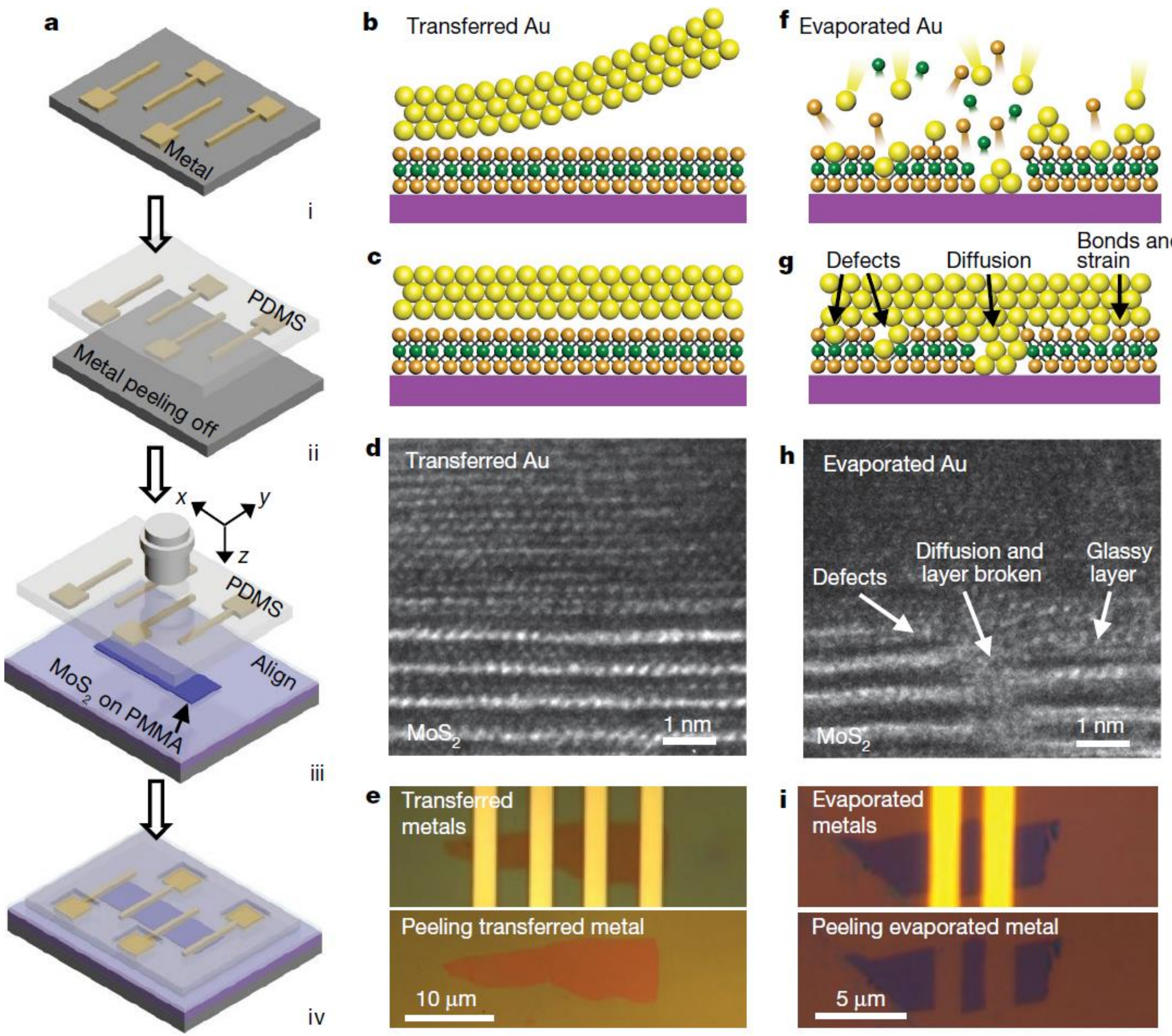


I_{max} = 370 μA/μm

$g_{m,max}$ = 98 μS/μm

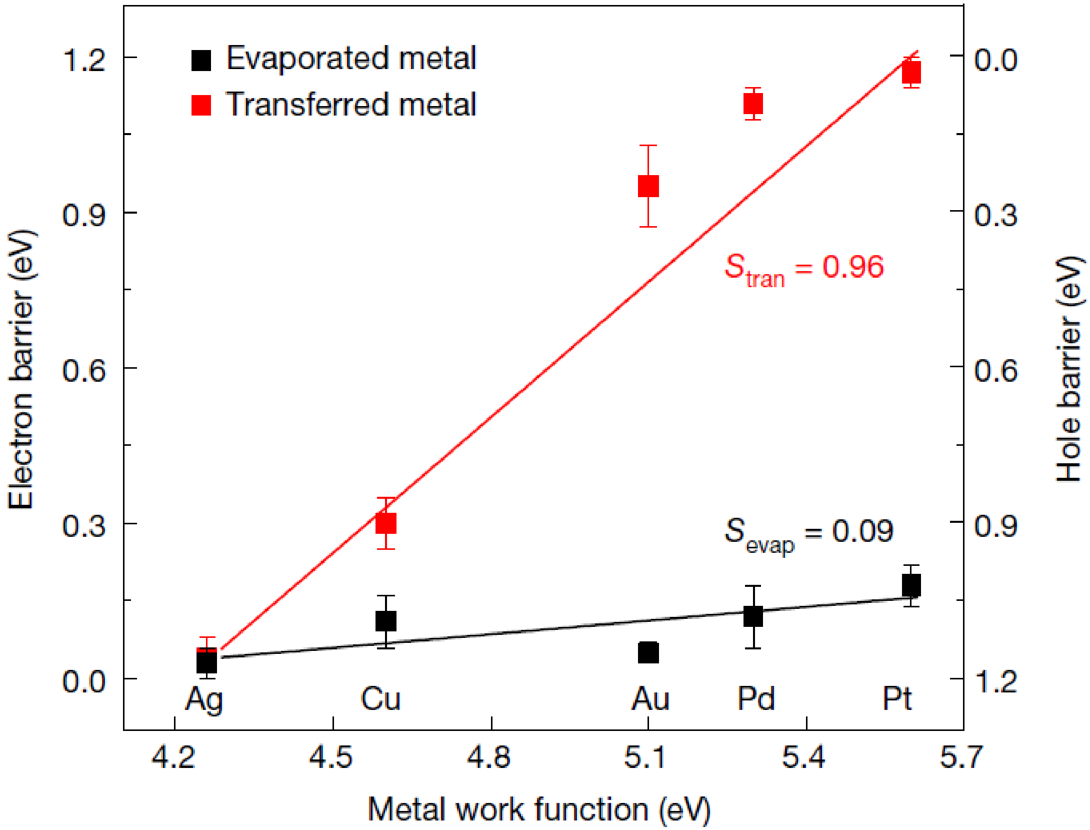
Pristine: 170 μA/μm 45 μS/μm

Direct transfer of contacts onto 2D materials



Liu et al. Nature (2018)

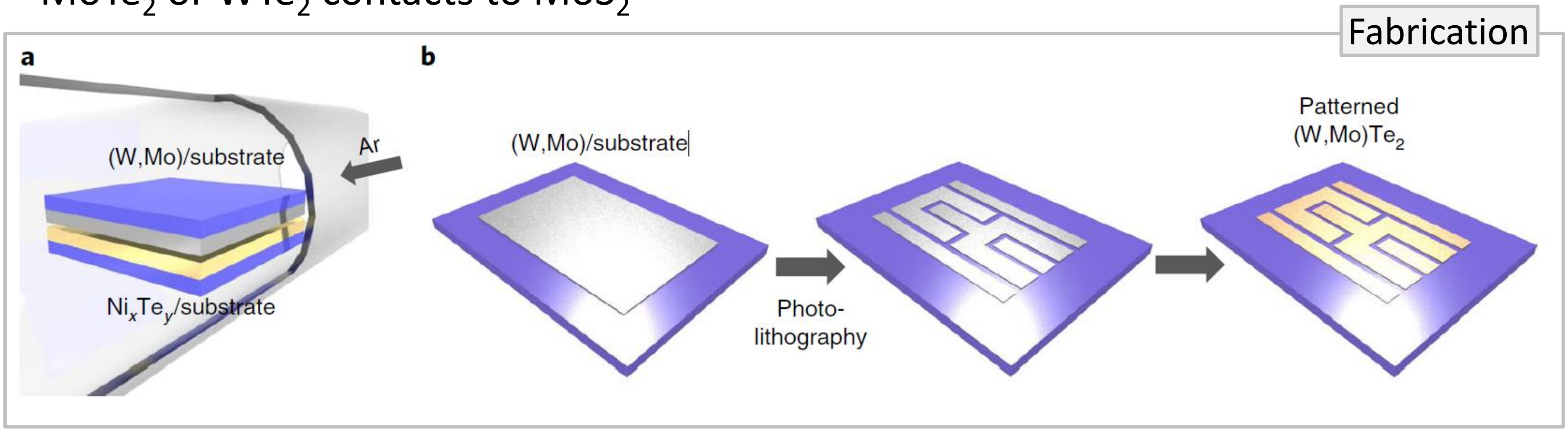
Direct transfer of contacts onto 2D materials

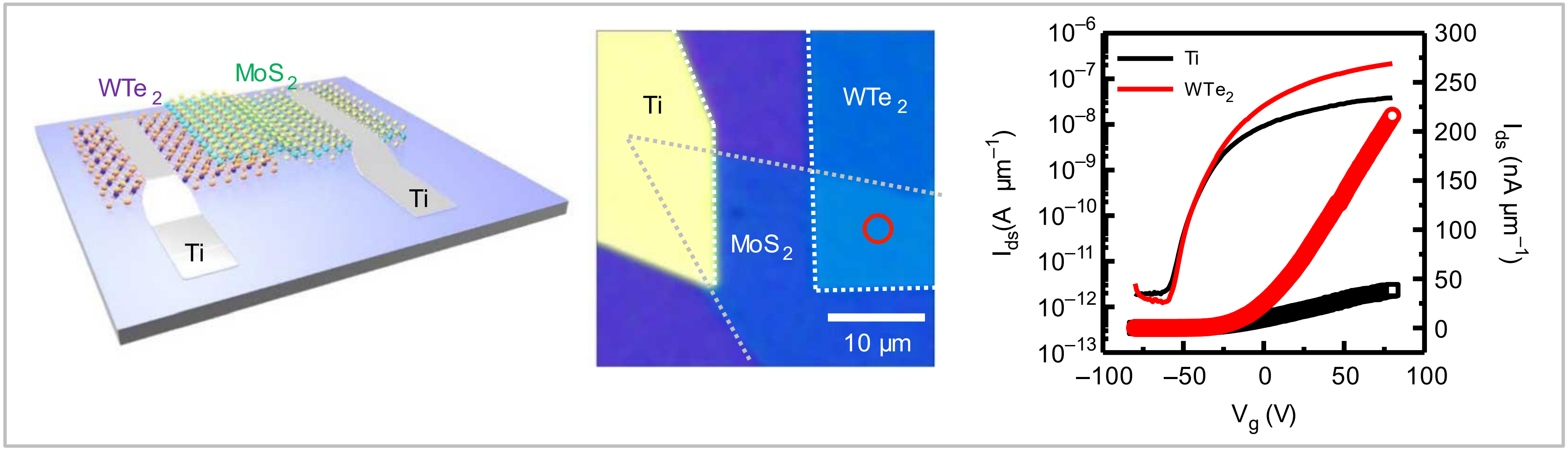


Liu et al. Nature (2018)

Direct transfer of 2D materials onto 2D contacts

- $MoTe_2$ or WTe_2 contacts to MoS_2

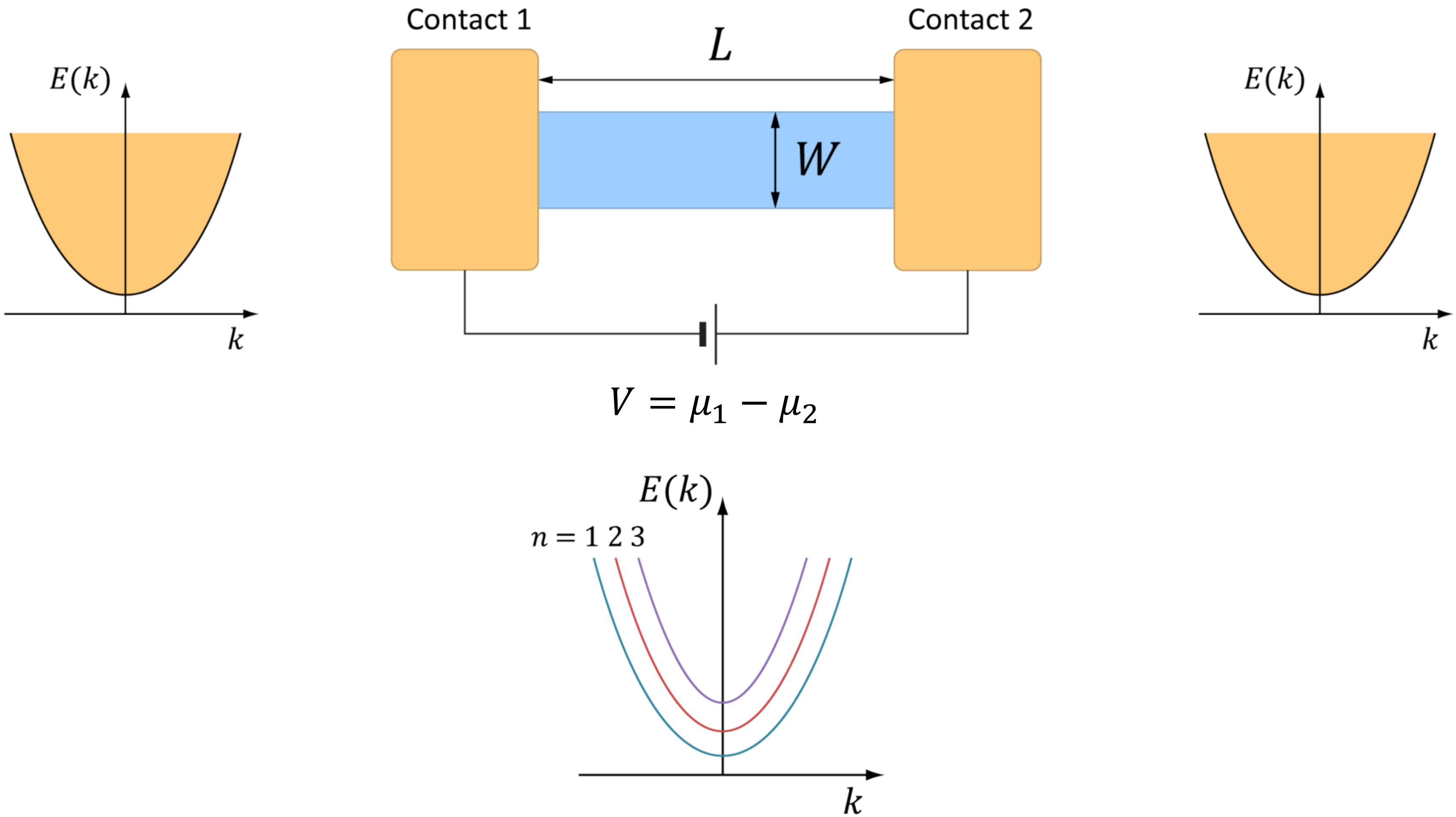




Song et al. Nature Electronics (2020)

Quantum resistance

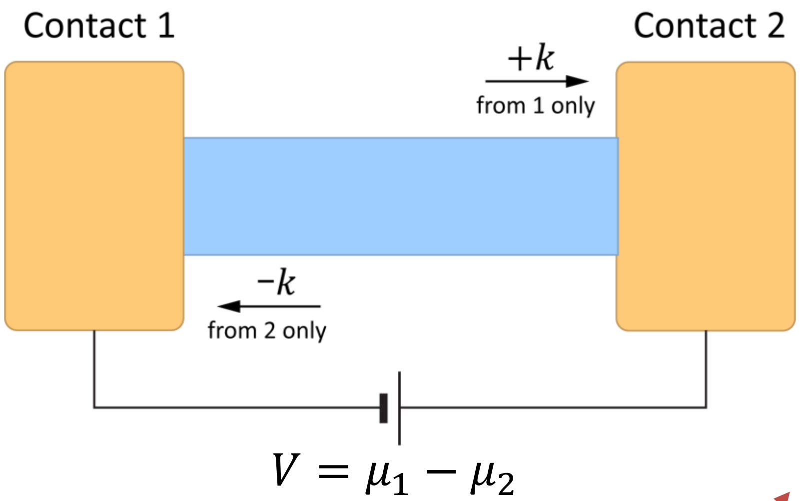
As the dimensions decrease, resistance approaches a limiting value R_C



Origin: conductor and contact pads are dissimilar materials (with and without confinement)

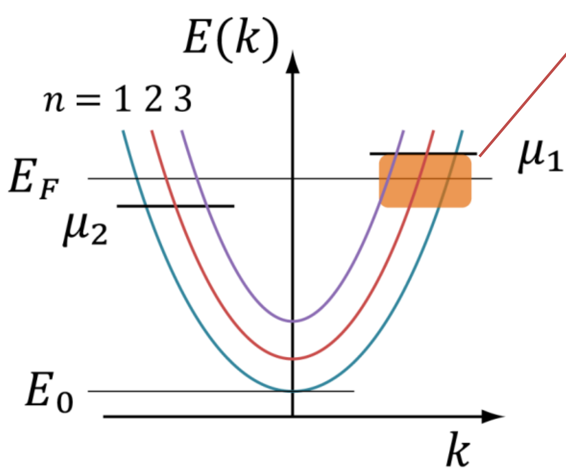
Quantum resistance for a ballistic conductor

No scattering in the channel



$+k$ states: occupied only by electrons from contact 1

$-k$ states: occupied only by electrons from contact 2



Total current is carried by $+k$ states between μ_1 and μ_2

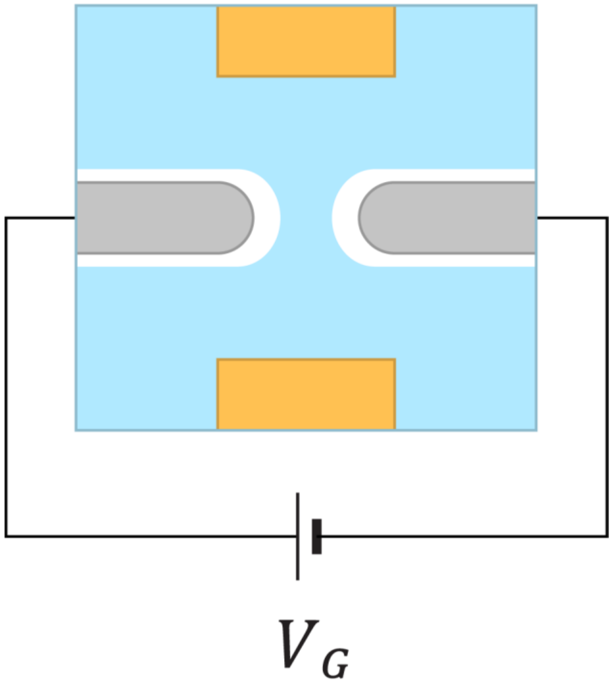
$$I = \frac{2e^2}{h} M \frac{\mu_1 - \mu_2}{e} = G_C V$$

$$G_C = \frac{2e^2}{h} M$$ 2 from spin degeneracy

$$\frac{1}{G_C} = R_C = \frac{12.9\ k\Omega}{M}$$

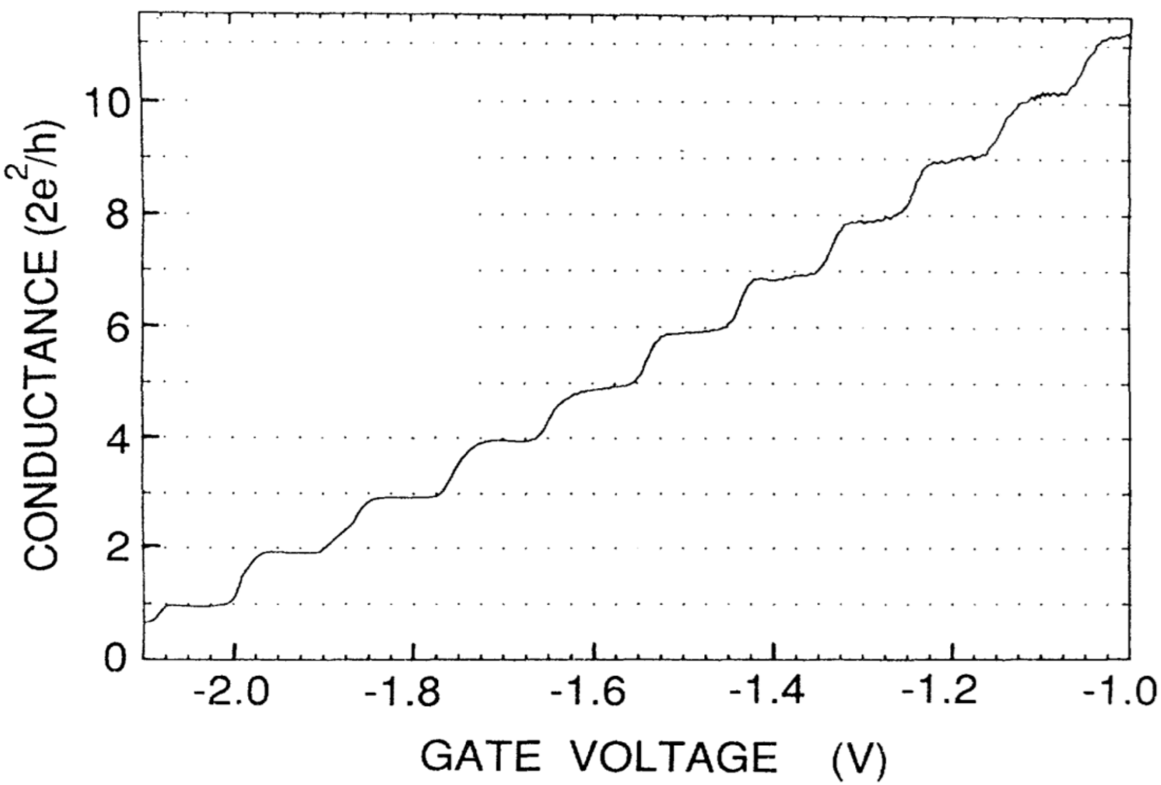
M number of modes (subbands)

Quantized conductance: GaAs



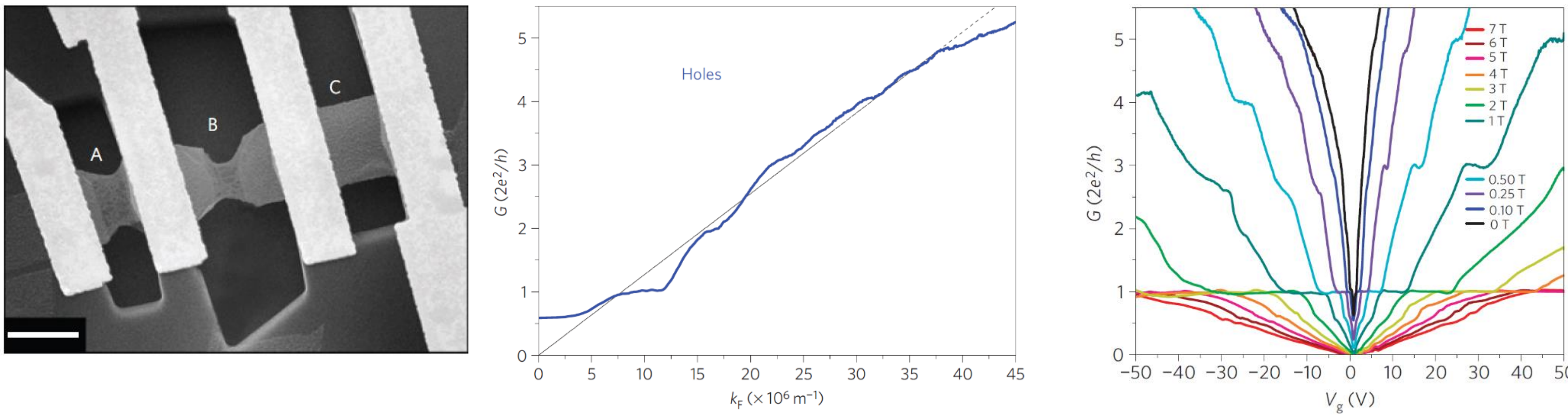
$$G_C = \frac{2e^2}{h} M$$

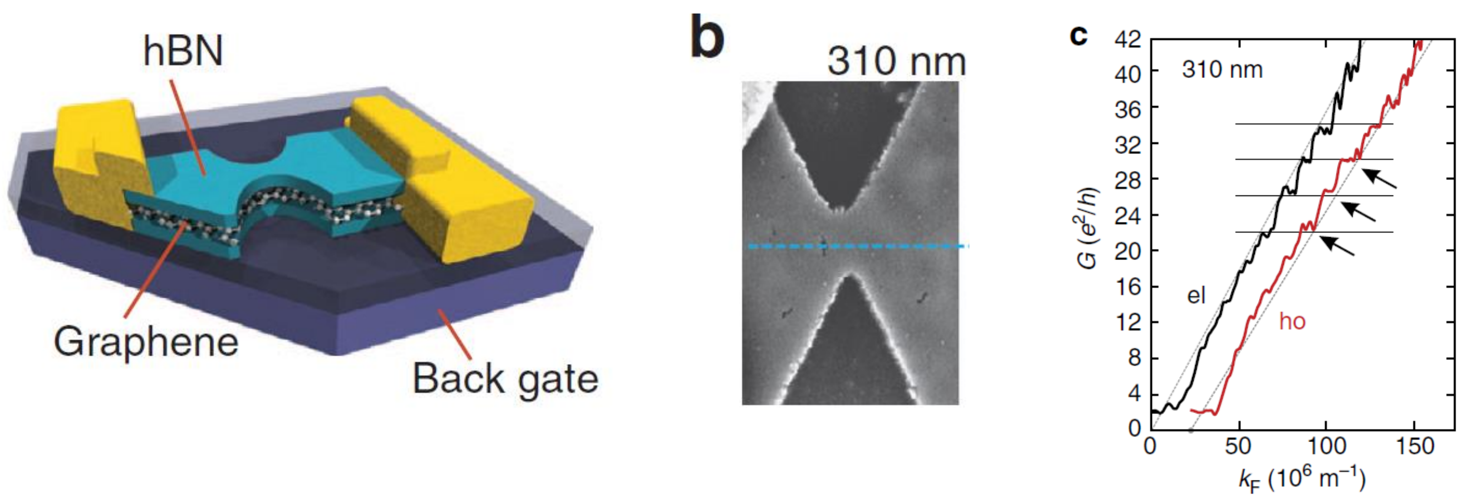
$$\lambda_F = 100 \text{ nm}$$



Van Wees et al., PRL 60, 848 (1988)
Van Wees et al., PRB 43, 12431 (1991)

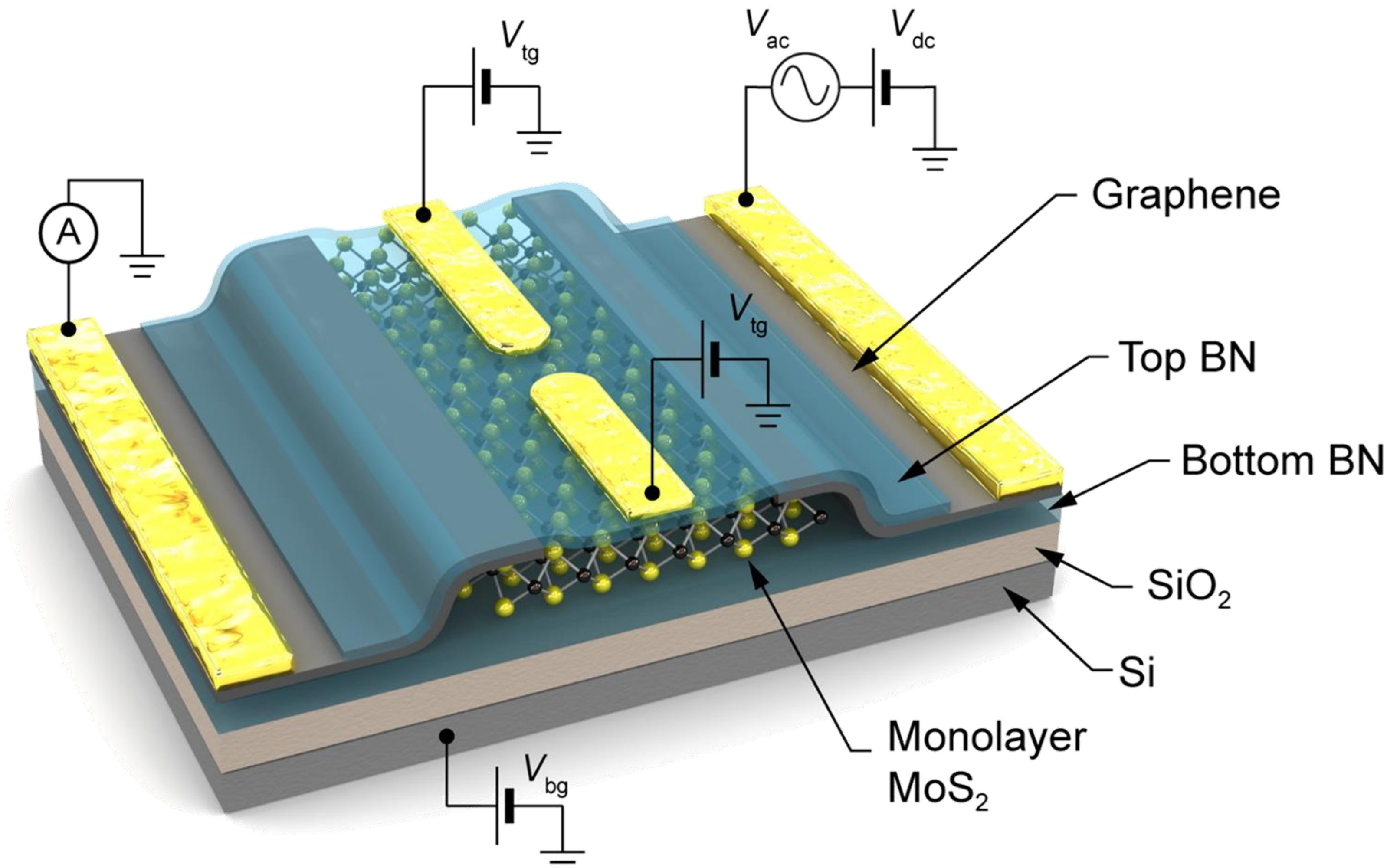
Quantized conductance: graphene





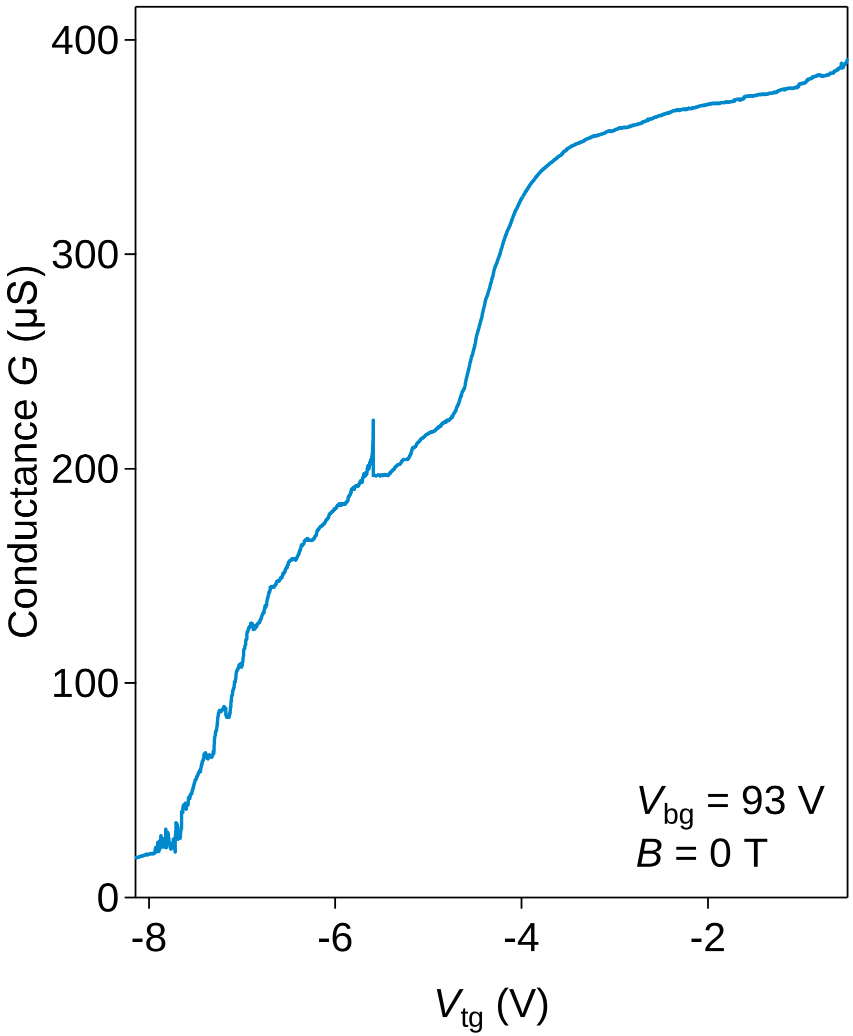
Tombros, Wees, et al. Nat. Phys. (2011)
Terrés, Stampfer, et al. Nat. Comm. (2016)

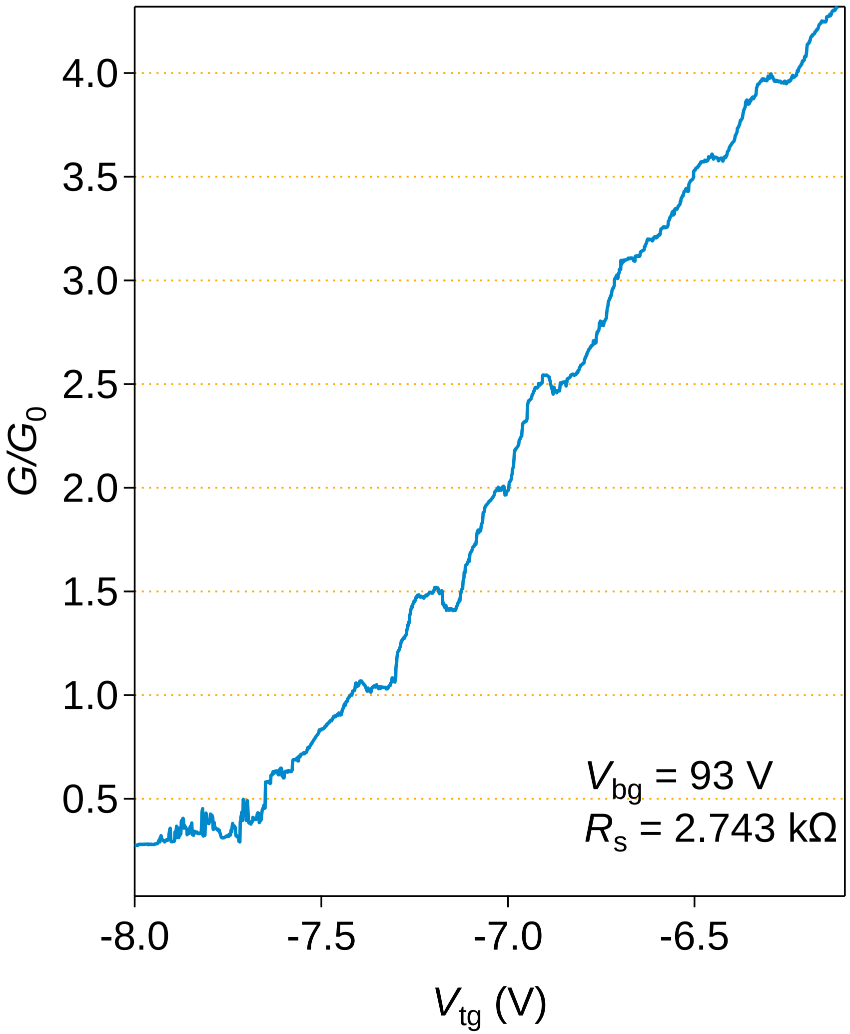
Quantized conductance: MoS_2



Marinov…Kis; Nature Comms. (2017)

Quantized conductance: MoS_2

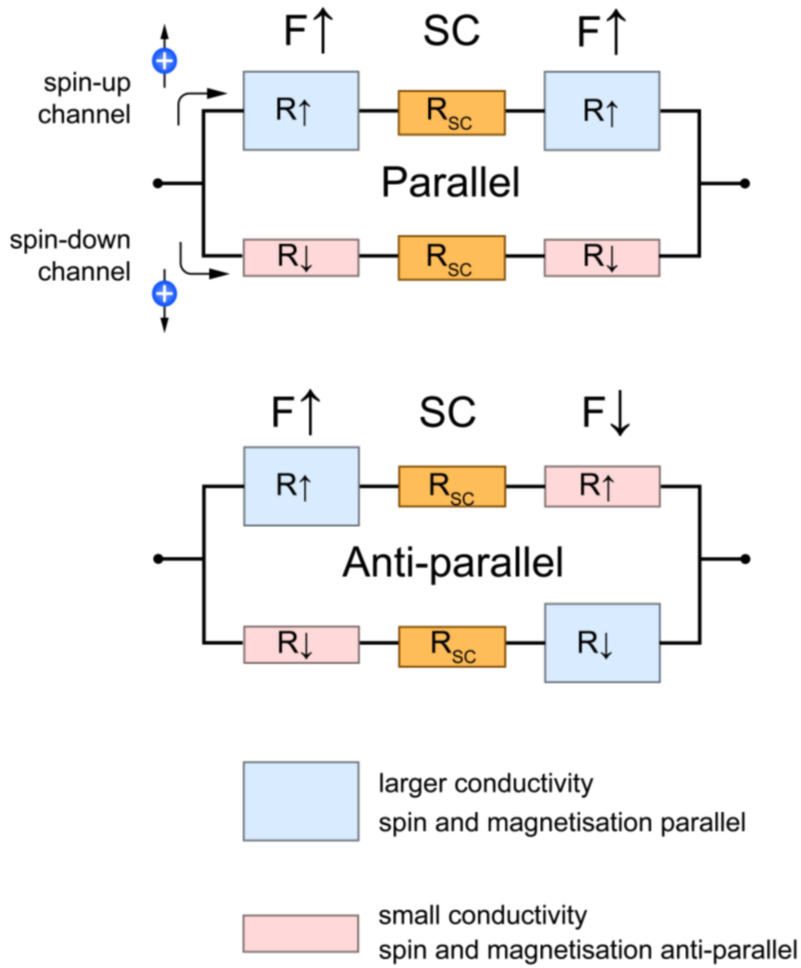


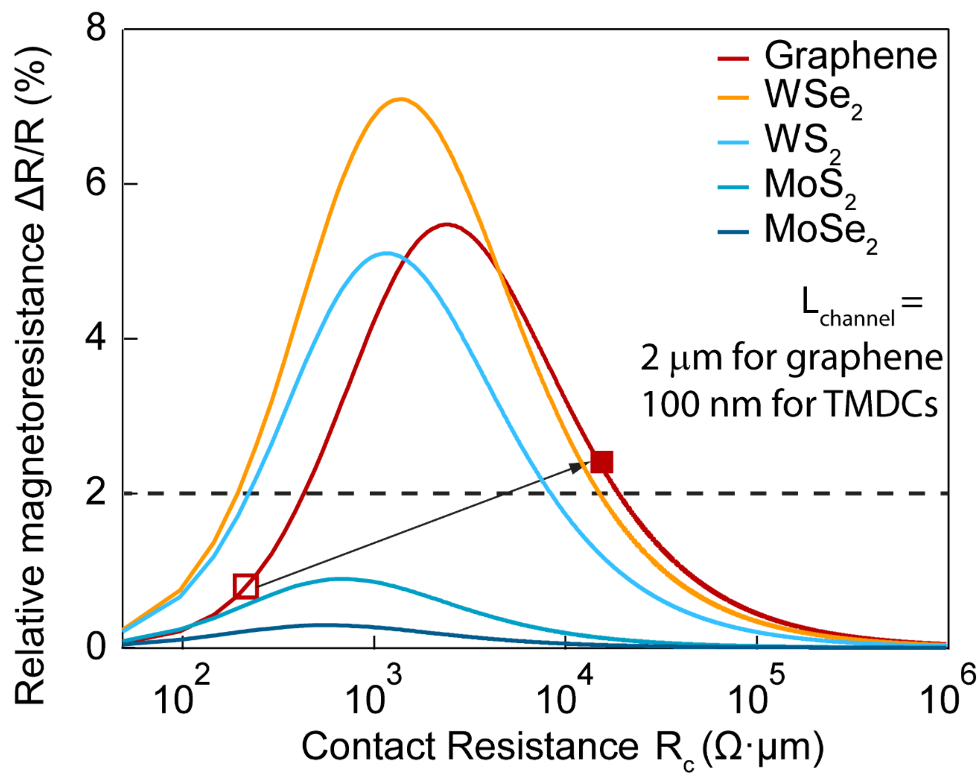


Steps of e^2/h : degeneracies lifted

When low R_C is not good: spin injection

Conductivity mismatch problem

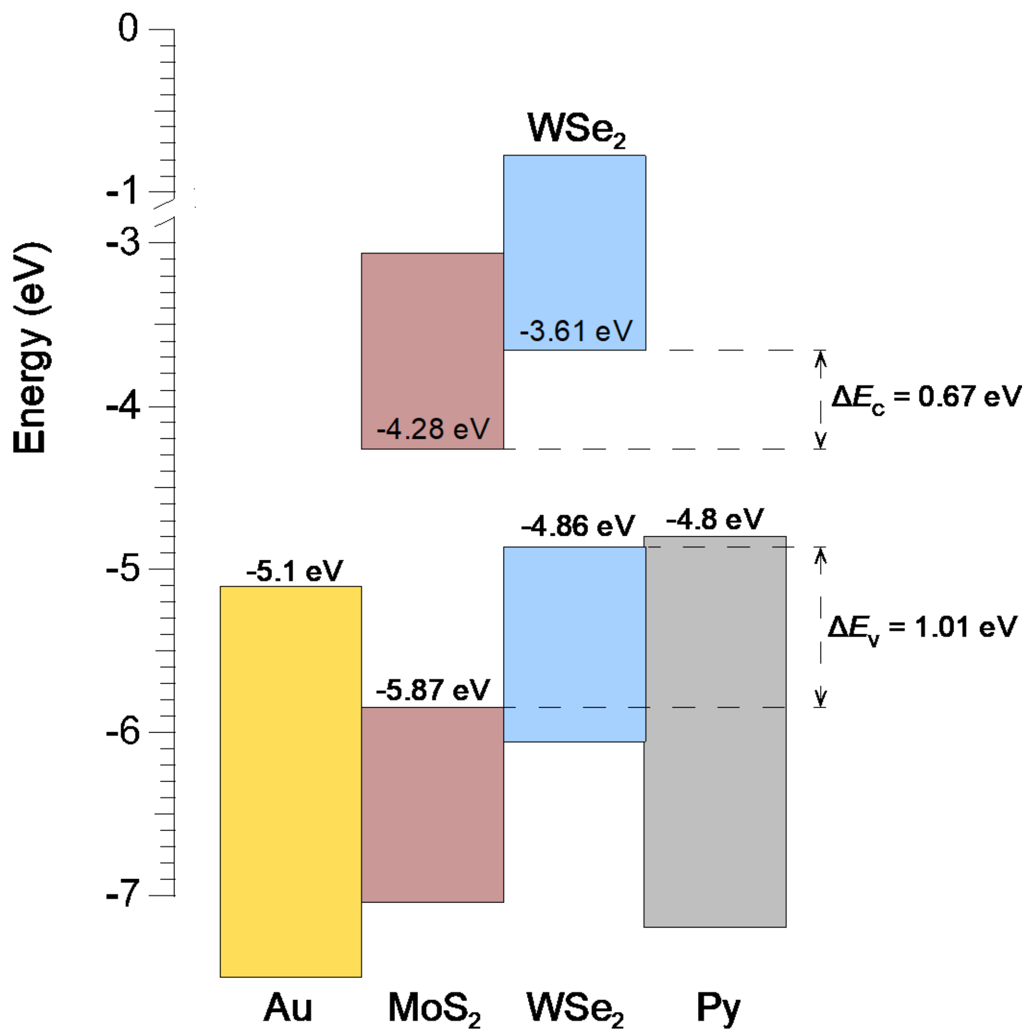




Allain…Kis; Nat. Materials (2015)

Schmidt, van Wees et al. PRB (2000)

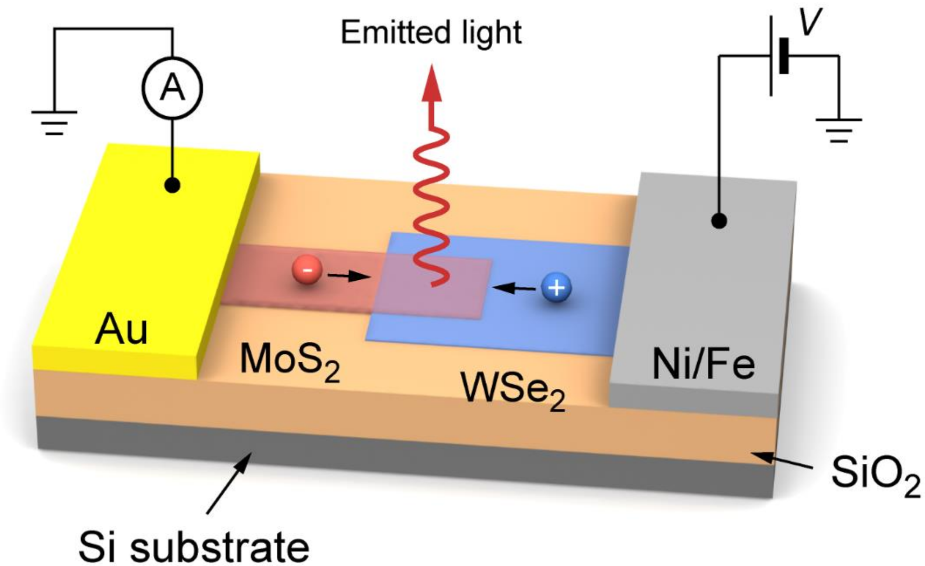
Permalloy Electrodes

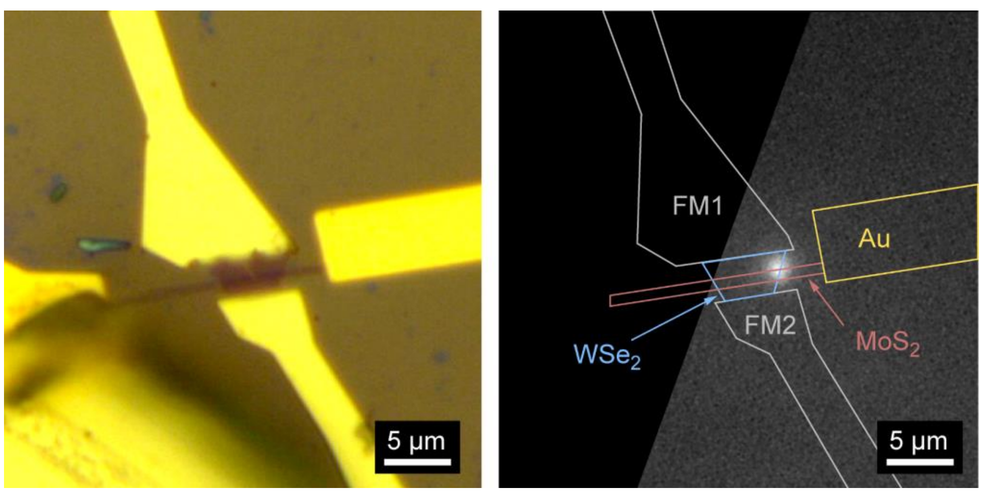


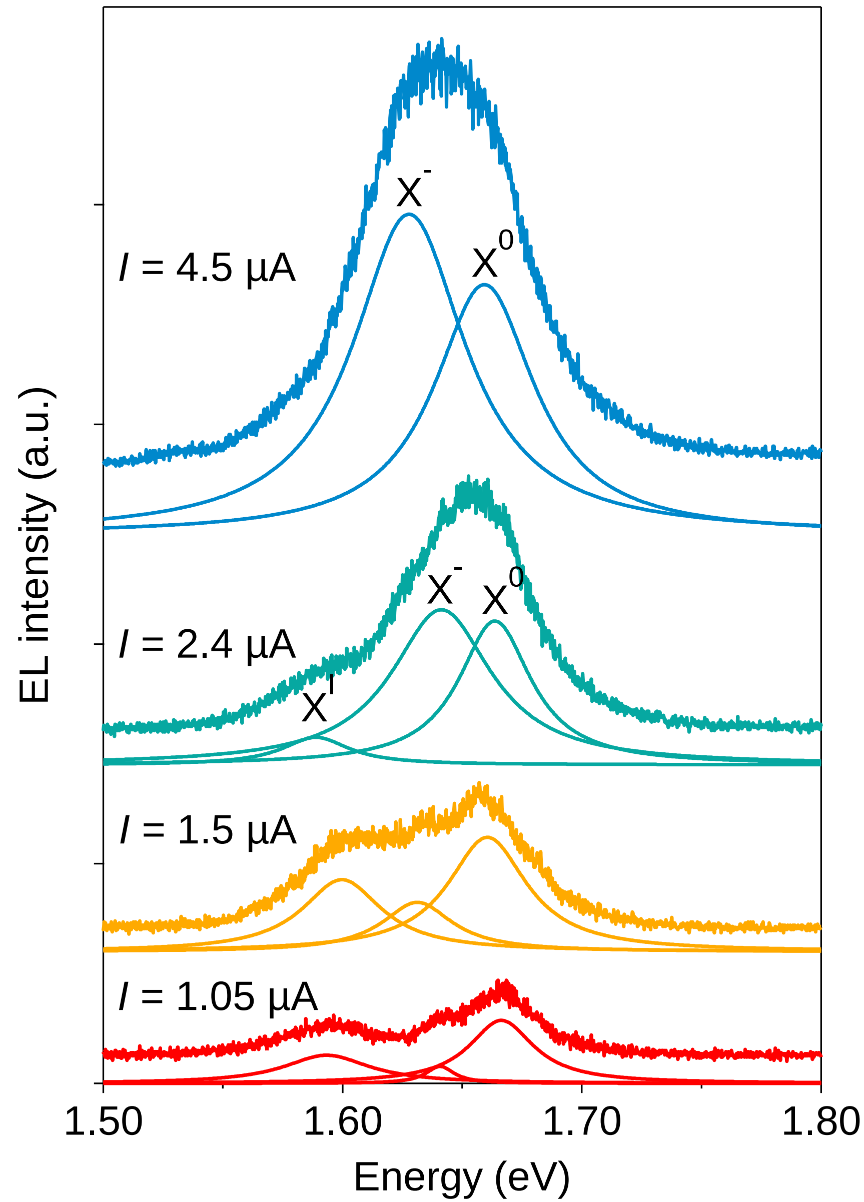
Band alignement: Kang…Wu; Applied Physics Letters (2013)

PY work function: Wang…Xiu; Sci. Rep. (2014)

Heterostructure LED with a Lateral FM Contact

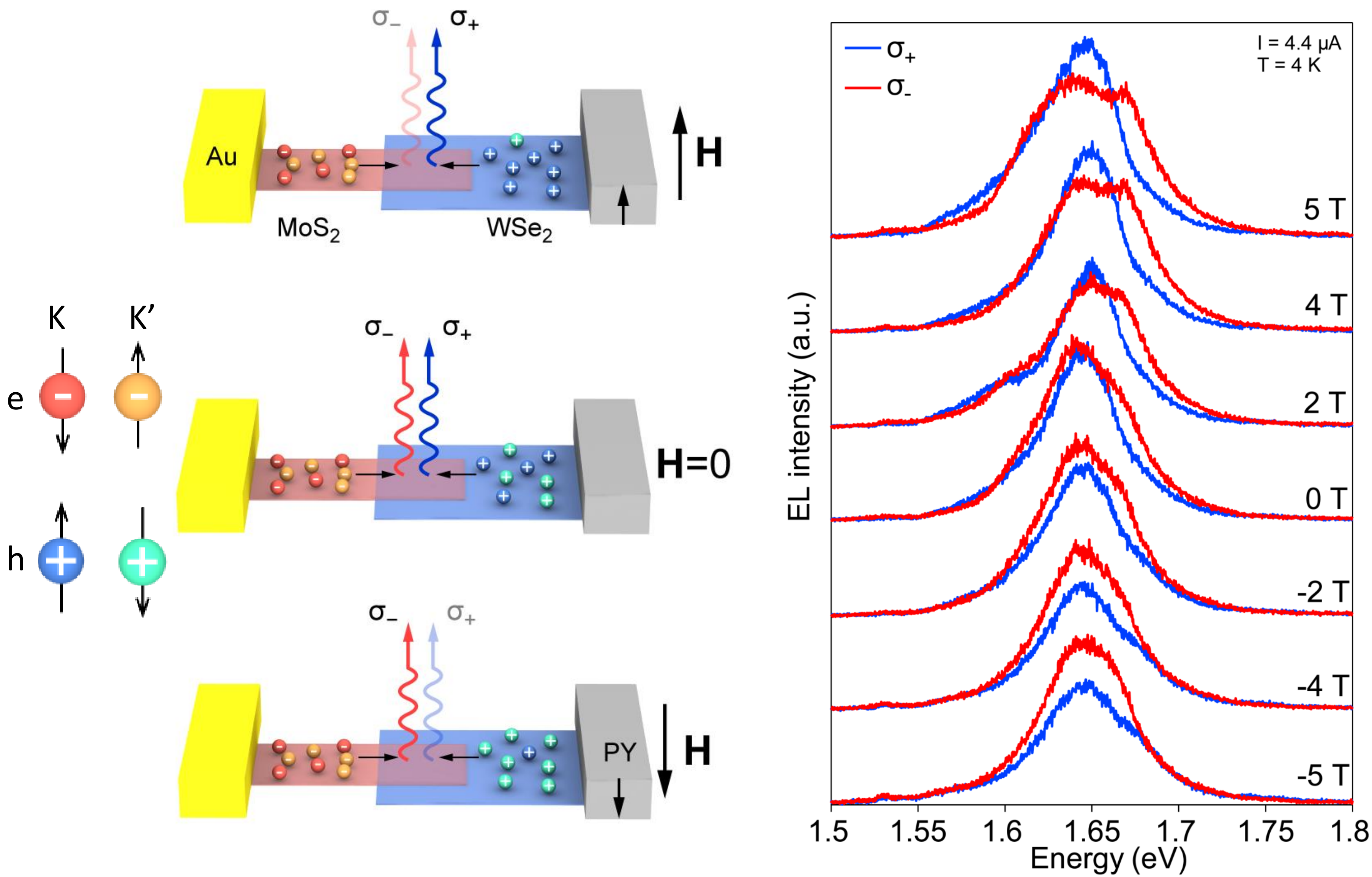






Lopez Sanchez…Kis; Nano Lett. (2016)

Valley Polarization by Spin Injection



Lopez Sanchez…Kis; Nano Lett. (2016)

Recapitulation

Resistance scaling - general

- Devices limited by contact resistance
- Quantum limit of resistance
- Contact resistance can be measured using 4-probe and TLM

Contacts to 2D materials

- Contact geometries – edge, top and combination
- Contact resistance scaling – transmission line model
- Almost all current examples in the literature fall short of ITRS requirements
- Schottky barrier extraction from the flat band condition
- Fermi level pinning
- Strategies for reducing contact resistance: phase engineering, doping, etching contacts, transfer of contacts

Origins of the quantum limit

- Ballistic charge injection

Spin injection into 2D materials

- Conductivity mismatch problem

Thank you for your attention!