Ohmic contact engineering in few-layer Black Phosphorus

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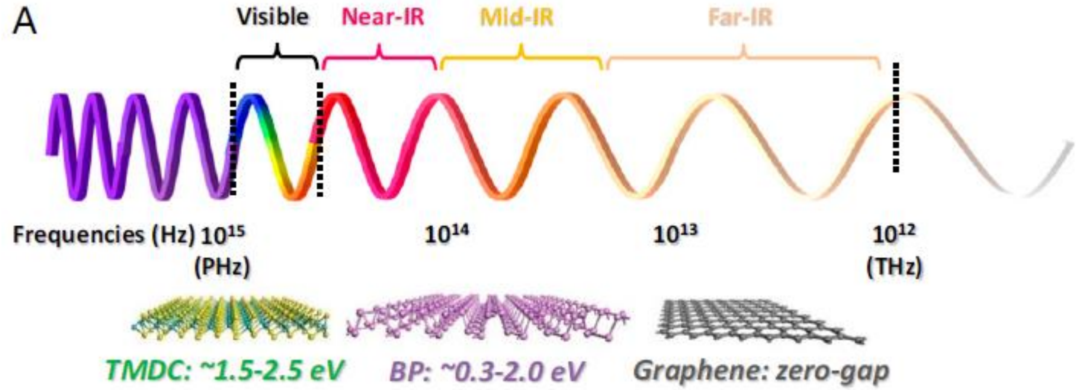
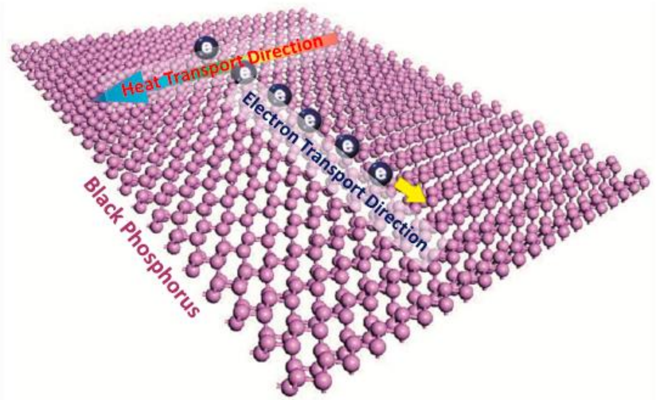
Context

- New materials for different applications than silicon-based electronics

- 2D semiconducting materials for multifunctional devices





X. Ling et al., PNAS 112 (2015) 4253

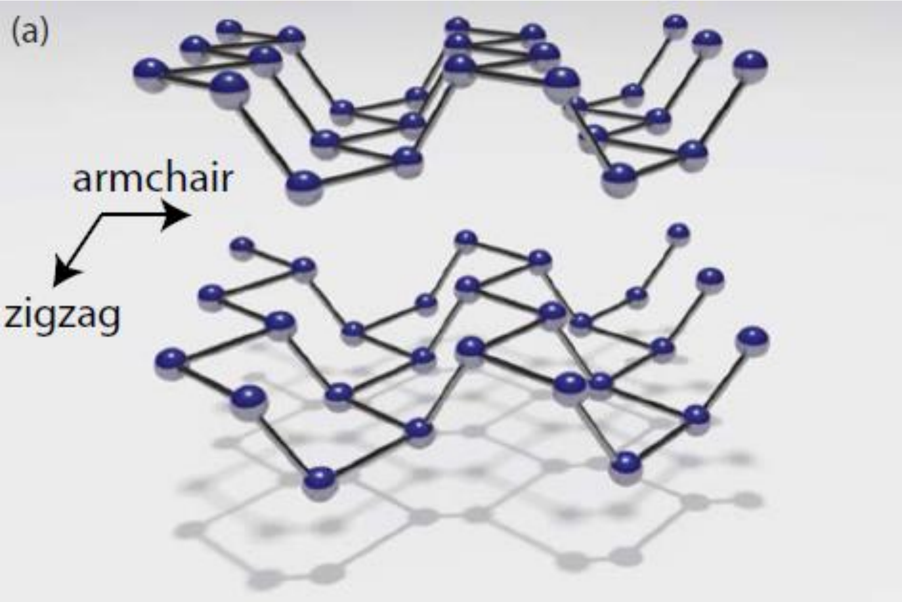
- Perspective of black phosphorus field-effect transistors

- What is the best contacting metal to black phosphorus ?

Outline

- Black Phosphorus presentation
- Metal-Semiconductor contact
- Electrical contact engineering
- Field-Effect transistors
- Field-effect transport measurements
- Summary and discussion

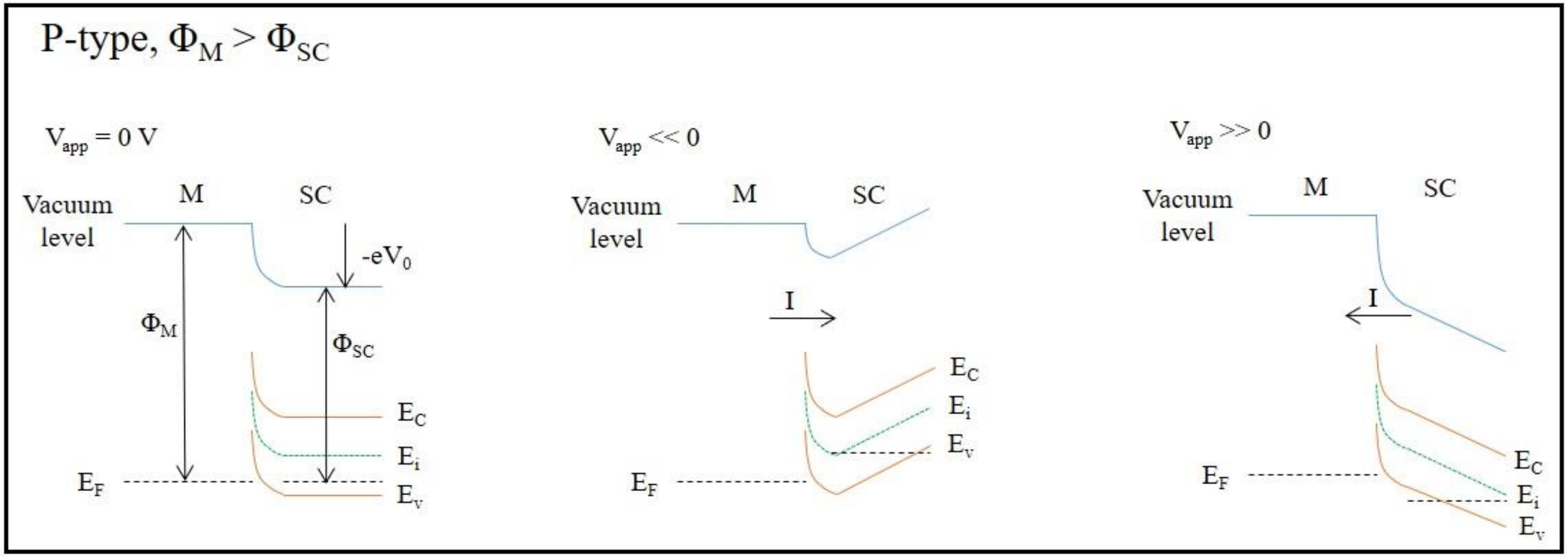
Black Phosphorus Presentation



N. Hemsworth et al., Phys. Rev. B 94 (2016) 245404

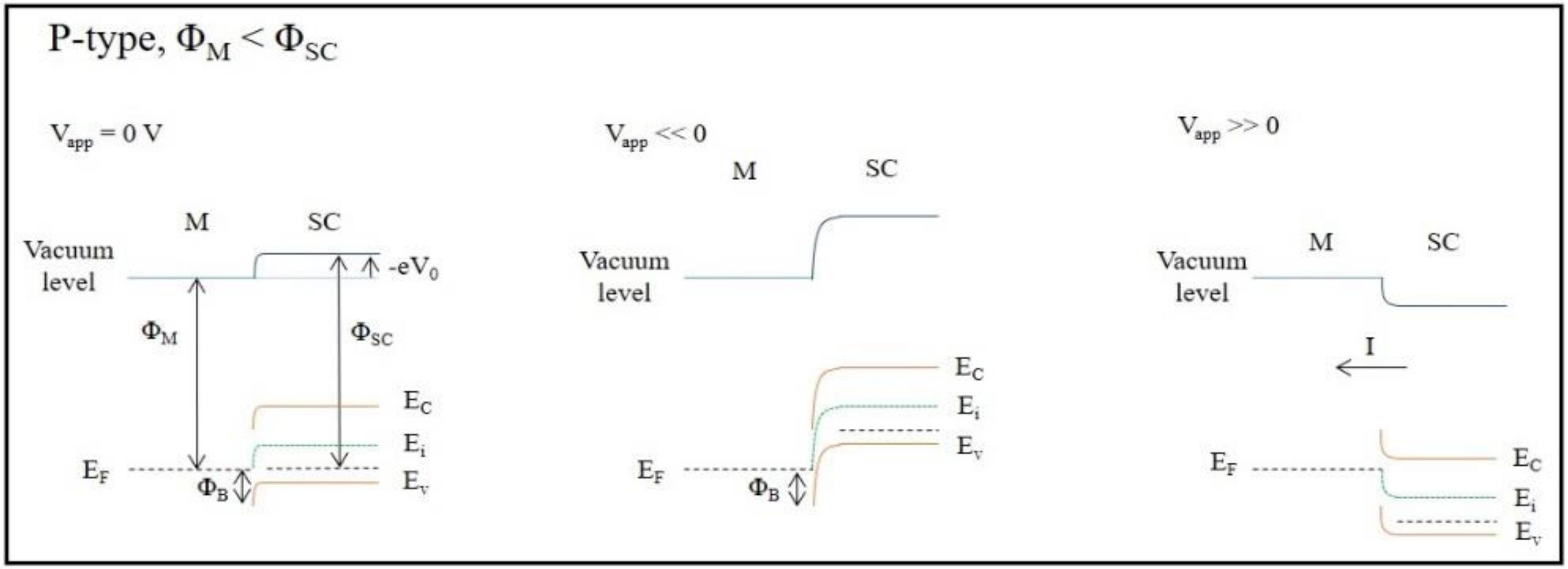
- Layered & puckered structure
- Intrinsic P-doped semiconductor
- Direct band gap from 0,3 eV to 1-2 eV, tunable with strain and layer number
- High hole mobility : 64000 cm²/(V.s) at 30K (A. Morita, Appl. Phys. A 39 (1986) 227)
- Highly anisotropic & reactive material

Metal-Semiconductor Contact



- Holes accumulation at the interface
- Ohmic contact
- Drift-Diffusion current

Metal-Semiconductor Contact



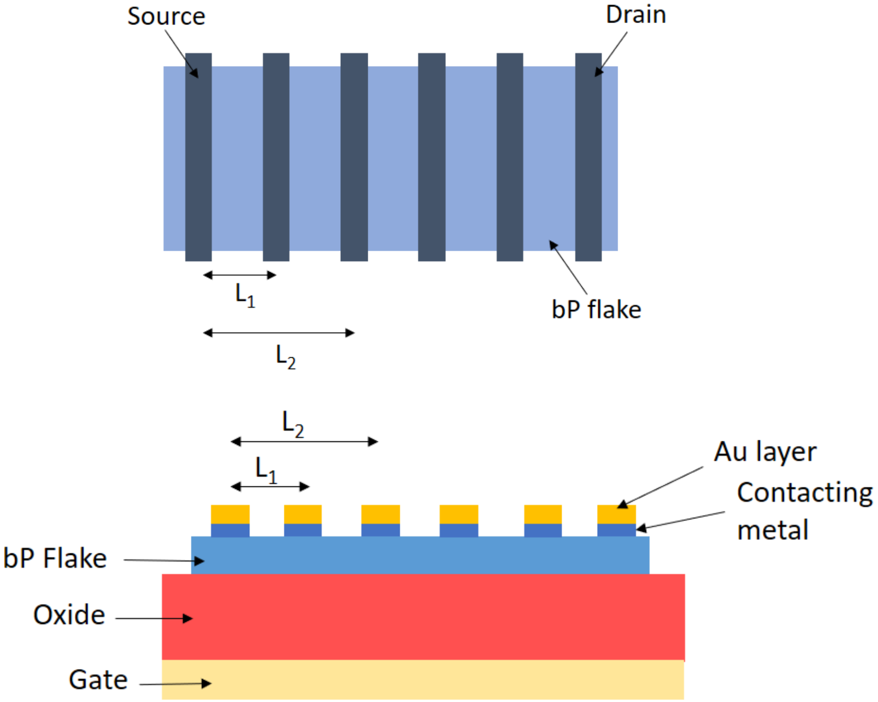
- Schottky barrier for holes at the interface
- Schottky contact
- Thermoionic and tunnel current

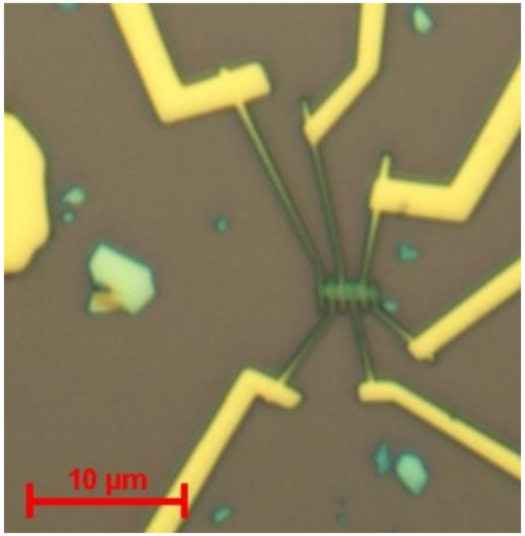
Electrical contact engineering

- 3 different metals : Chromium, Titanium, Nickel

$\Phi_{Cr} \approx 4{,}5$ eV, $\Phi_{Ti} \approx 4{,}3$ eV, $\Phi_{Ni} \approx 5{,}0$ eV, $\Phi_{bP} \approx 4{,}5$ eV (Y. Cai et al., Sci. Rep. 4 (2014) 6677)

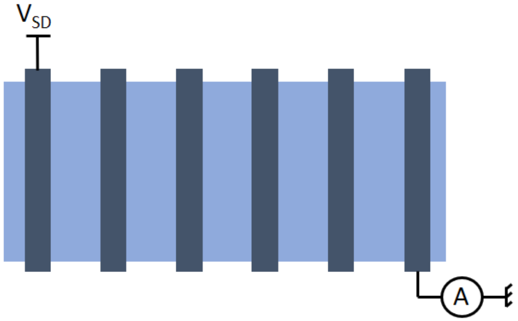
- Needle-shaped flakes for inter-digitated contacts geometry



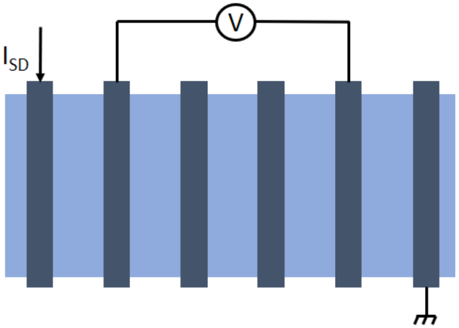


Measurement setup

- 2-probe resistance measurements for Transfer Length Method (TLM)



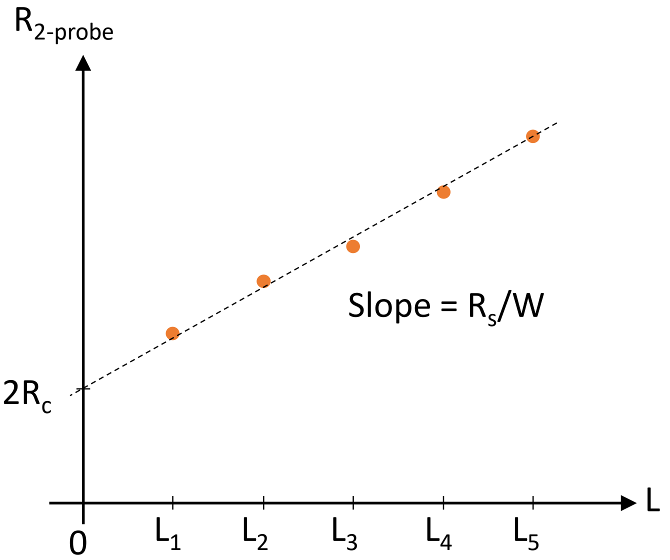
- 4-probe resistance measurements for comparison with TLM

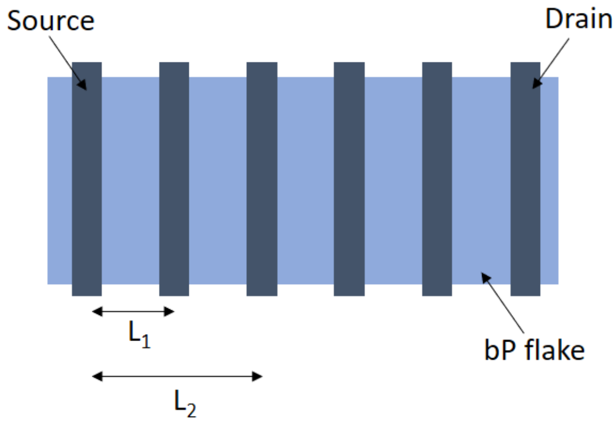


$$2 \times R_C = R_{2-probe} - R_{4-probe}$$

- Room temperature and low temperature measurements in a cryostat at liquid He temperature (4,2 K)

Transfer Length Method





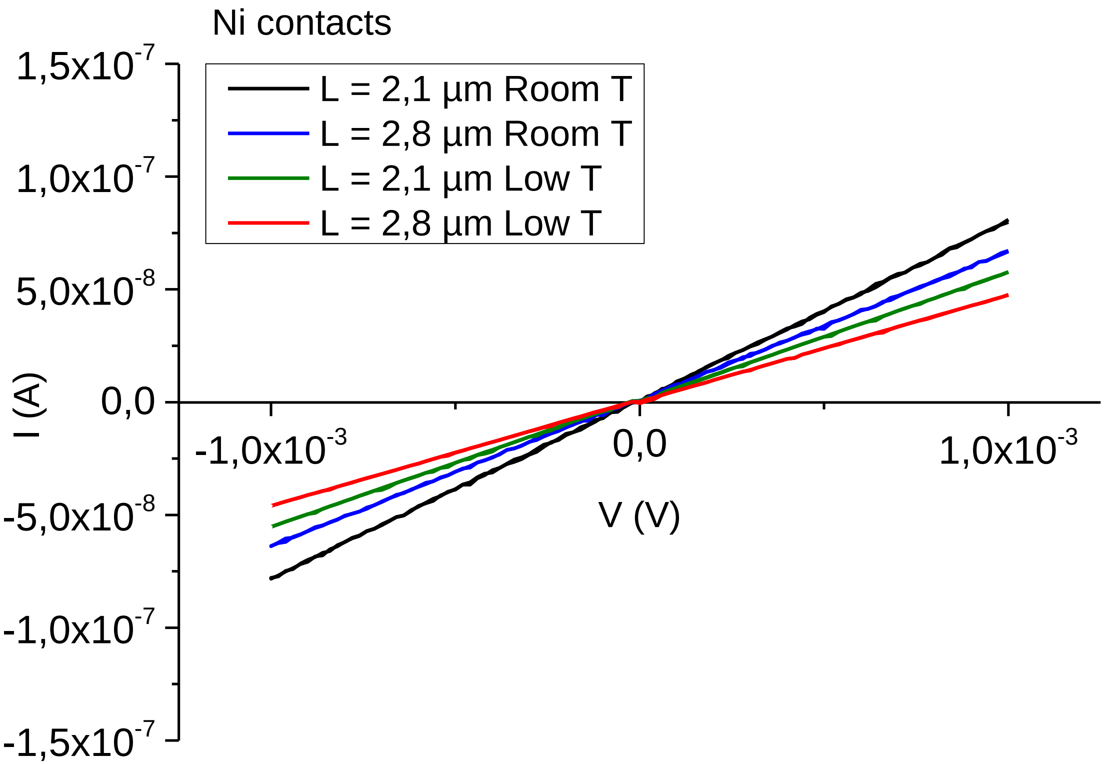
$$R_{2-probe} = \frac{R_s}{W} L + 2R_C$$

R_c : Contact resistance (Ω)
R_s : Sheet resistance (Ω/□)
W : Channel width (m)
L : Channel length (m)

Channel resistivity $\rho_S = R_s \frac{W \times t}{L}$

Contact resistivity $\rho_C = R_C A_C$

I-V curves in 2-probe configuration



For the three contacting metals :

$$\frac{1}{R_{2-probe}} = \frac{dI}{dV}$$

- Ohmic-like contact between -1 mV and 1 mV
- $R_{2\text{-probe}}$ increases with L as expected
- $R_{2\text{-probe}|\text{Room T}} < R_{2\text{-probe}|\text{Low T}}$

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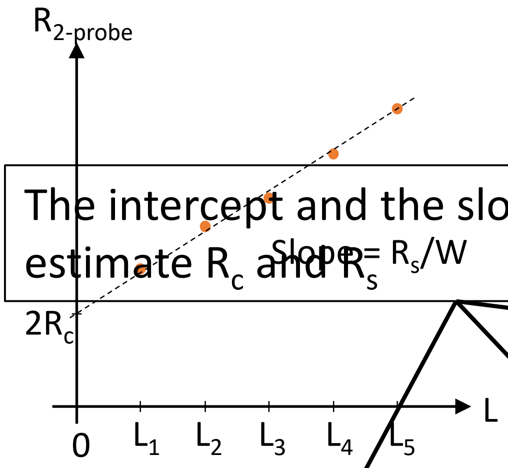
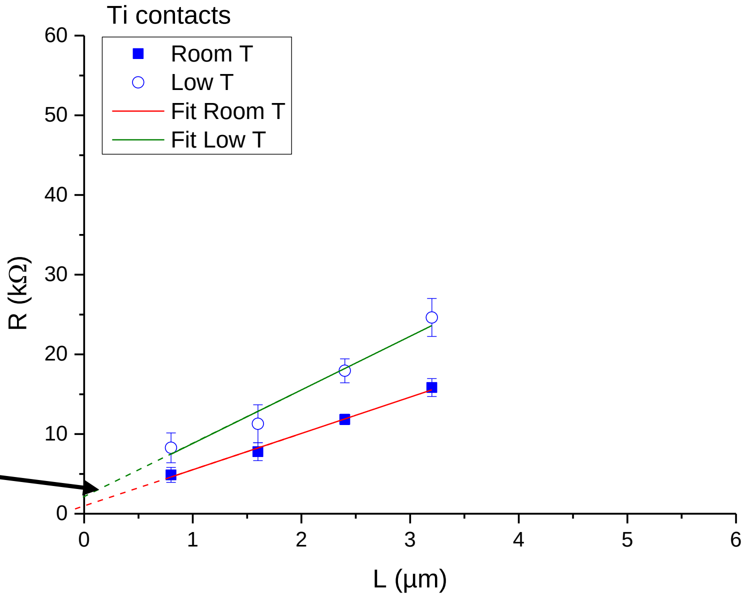
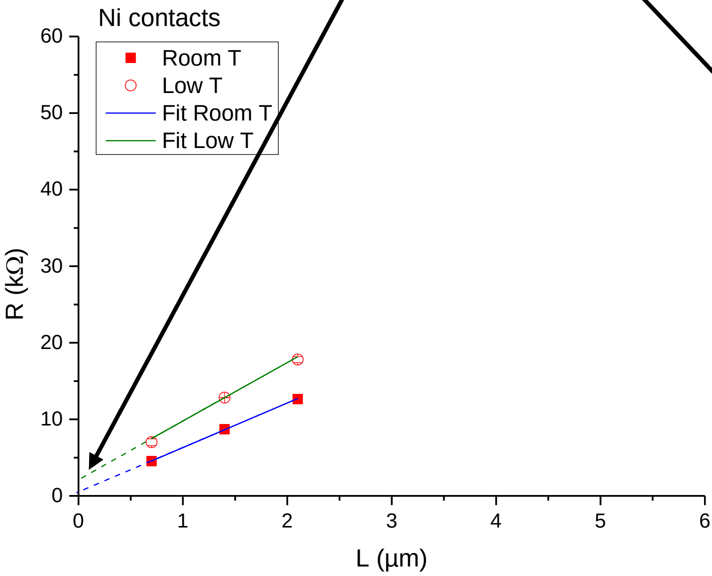
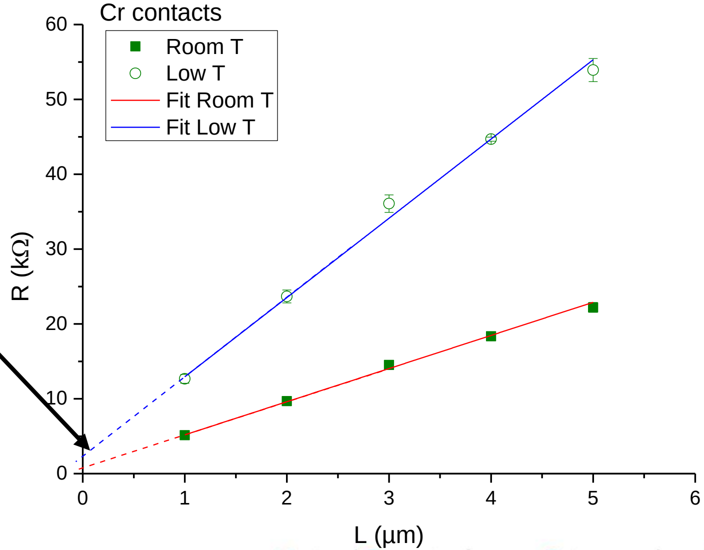
TLM Results



The intercept and the slope are extracted to estimate R_c and R_s

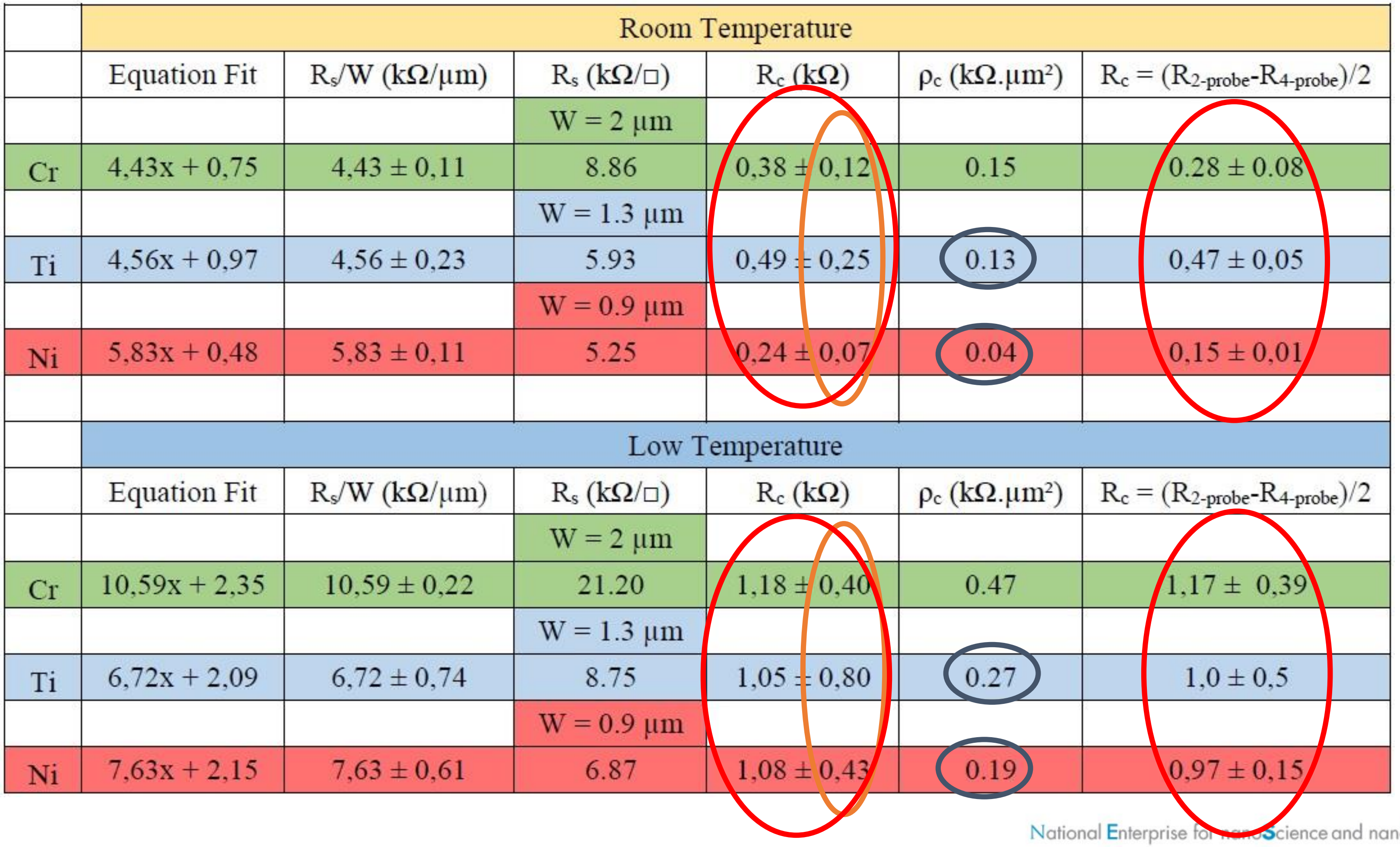






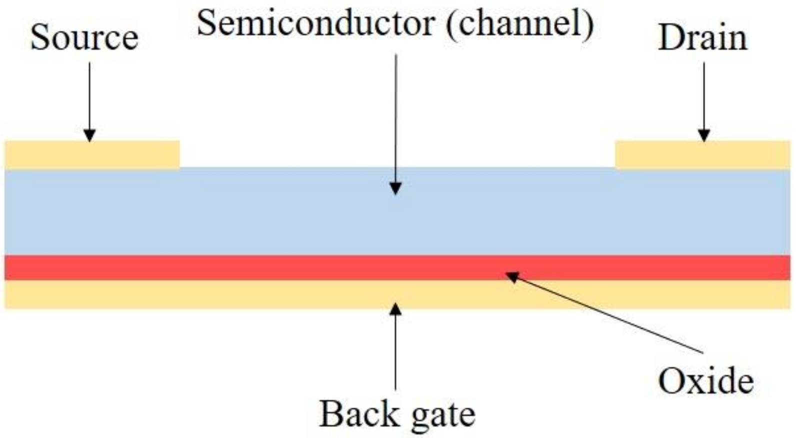
TLM Results

$\Phi_{Cr} \approx 4{,}5$ eV, $\Phi_{Ti} \approx 4{,}3$ eV, $\Phi_{Ni} \approx 5{,}0$ eV, $\Phi_{bP} \approx 4{,}5$ eV



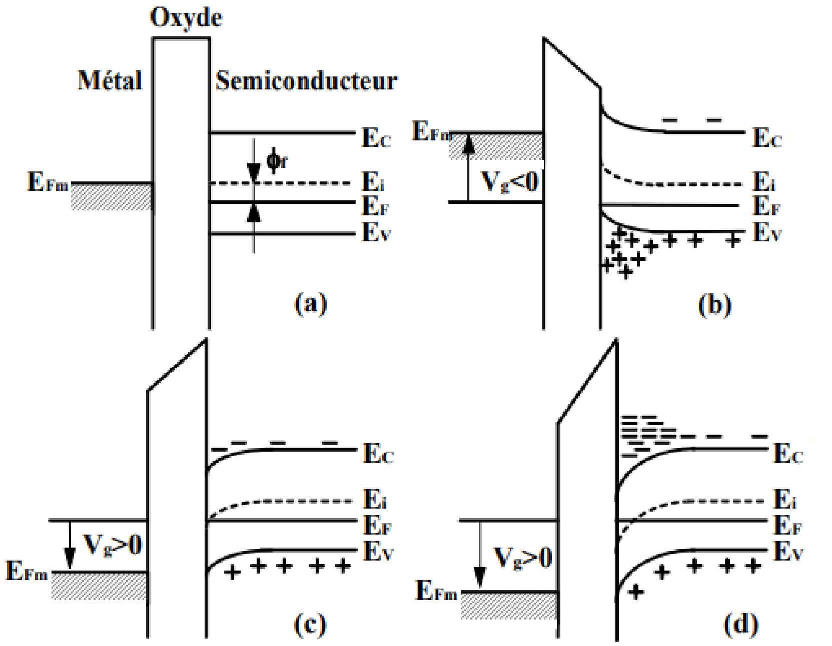
	Room Temperature					
	Equation Fit	R_s/W (kΩ/µm)	R_s (kΩ/□)	R_c (kΩ)	ρ_c (kΩ.µm²)	$R_c = (R_{2\text{-probe}} - R_{4\text{-probe}})/2$
			W = 2 µm			
Cr	4,43x + 0,75	4,43 ± 0,11	8.86	0,38 ± 0,12	0.15	0.28 ± 0.08
			W = 1.3 µm			
Ti	4,56x + 0,97	4,56 ± 0,23	5.93	0,49 ± 0,25	0.13	0,47 ± 0,05
			W = 0.9 µm			
Ni	5,83x + 0,48	5,83 ± 0,11	5.25	0,24 ± 0,07	0.04	0,15 ± 0,01
	Low Temperature					
	Equation Fit	R_s/W (kΩ/µm)	R_s (kΩ/□)	R_c (kΩ)	ρ_c (kΩ.µm²)	$R_c = (R_{2\text{-probe}} - R_{4\text{-probe}})/2$
			W = 2 µm			
Cr	10,59x + 2,35	10,59 ± 0,22	21.20	1,18 ± 0,40	0.47	1,17 ± 0,39
			W = 1.3 µm			
Ti	6,72x + 2,09	6,72 ± 0,74	8.75	1,05 ± 0,80	0.27	1,0 ± 0,5
			W = 0.9 µm			
Ni	7,63x + 2,15	7,63 ± 0,61	6.87	1,08 ± 0,43	0.19	0,97 ± 0,15

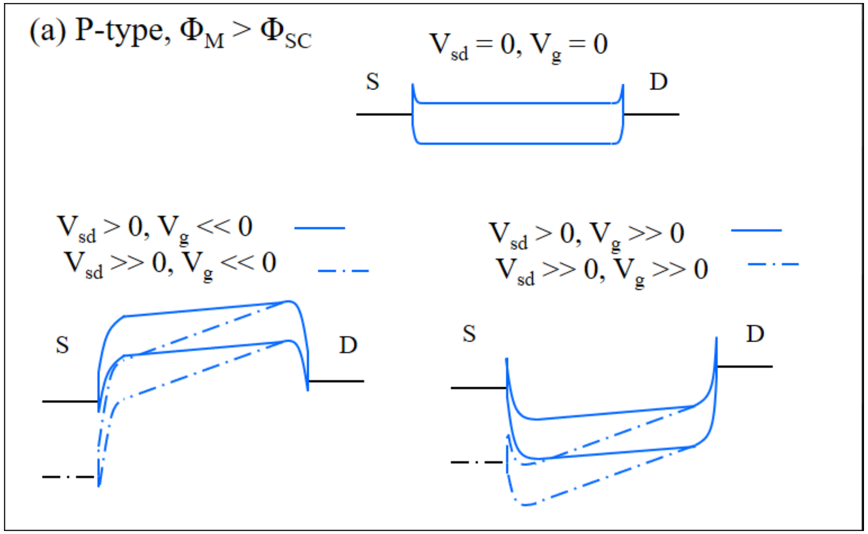
Field-Effect Transistor



With P-doped semiconductor :

- $V_g < 0$: holes accumulation in the channel and easier hole injection at the contact
- $V_g > 0$: depletion and inversion in the channel, easier electron injection at the contact

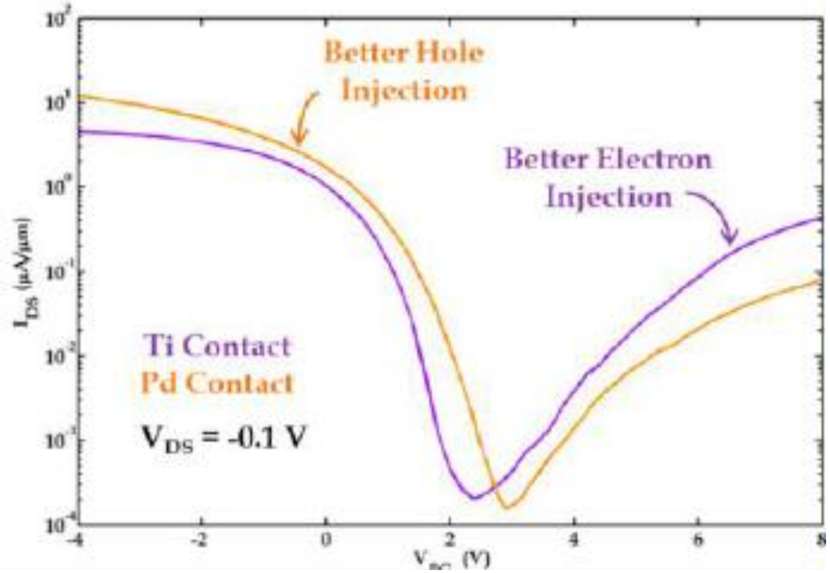




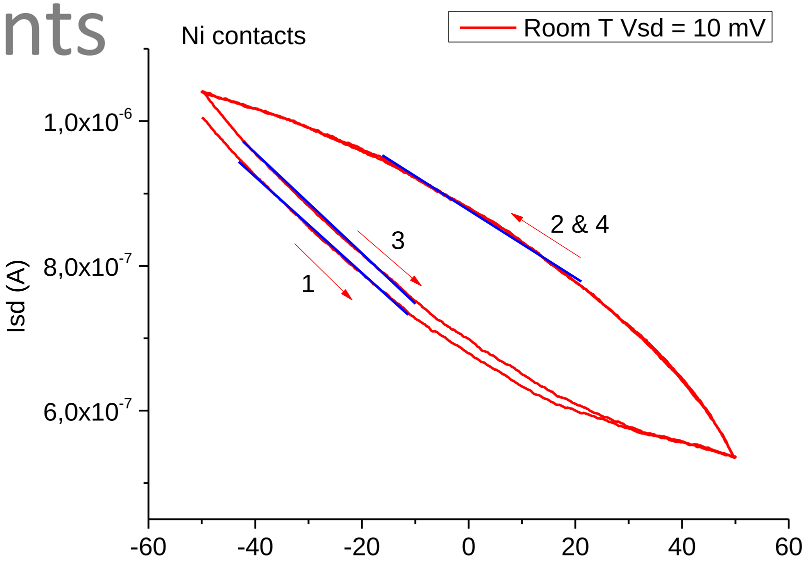
S.M. Sze, *Physics of semiconductor devices*, Ed. John Wiley & Sons, 1981

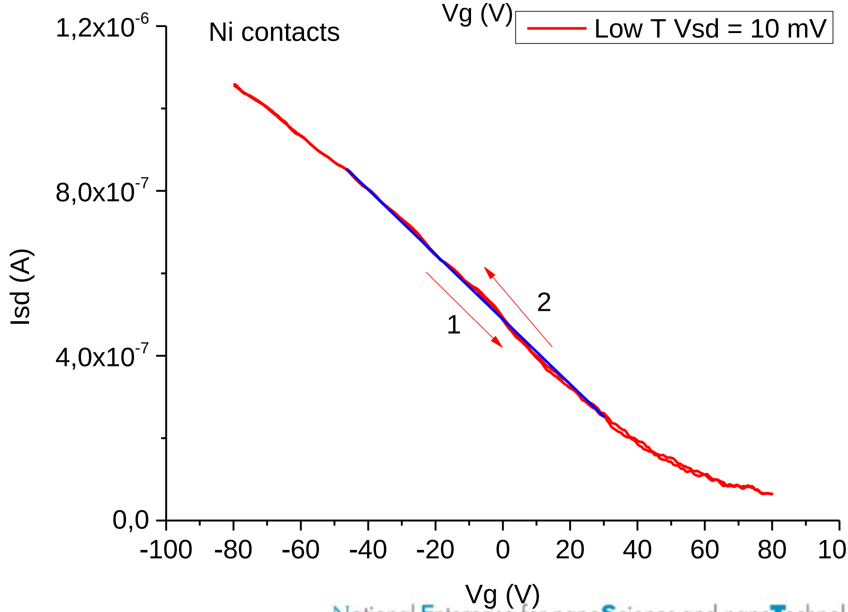
Field-Effect Measurements

- I_{SD} vs V_G characteristics

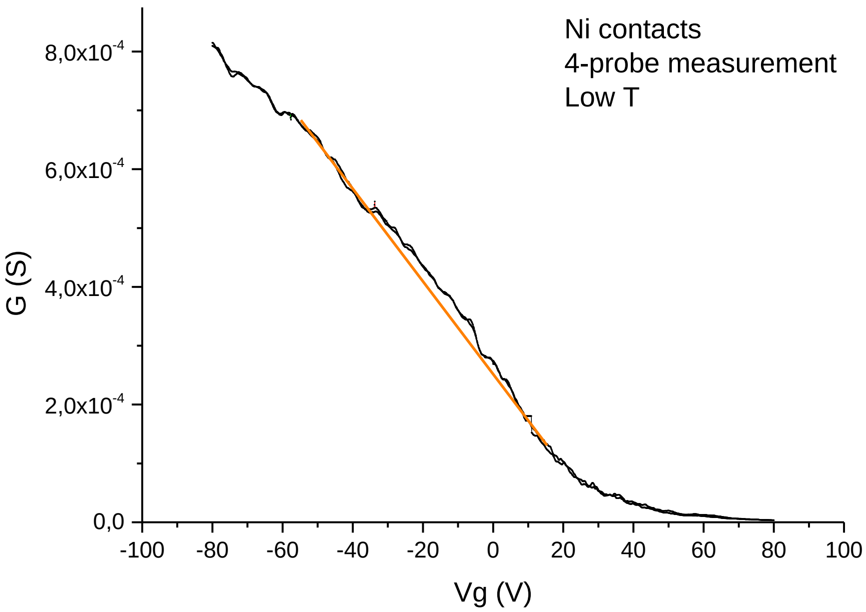


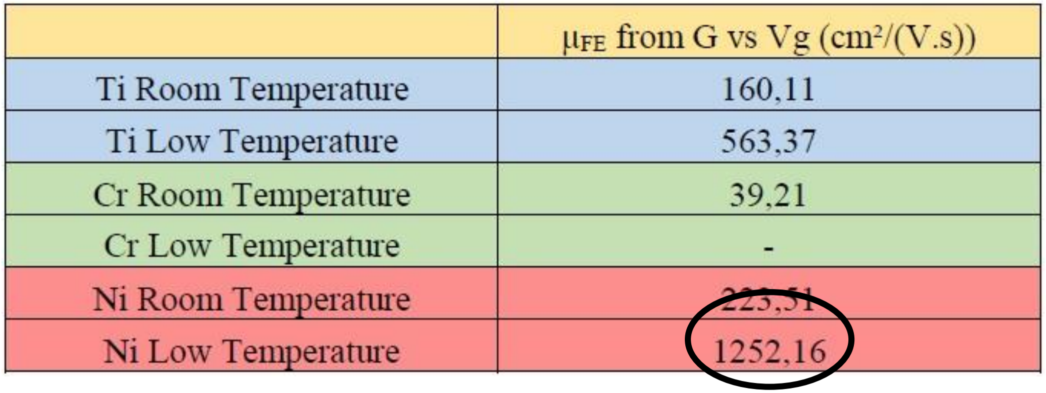
S. Das et al., ACS Nano 8 (2014) 11730





Field-Effect Mobility





	μ_{FE} from G vs Vg (cm²/(V.s))
Ti Room Temperature	160,11
Ti Low Temperature	563,37
Cr Room Temperature	39,21
Cr Low Temperature	-
Ni Room Temperature	223,51
Ni Low Temperature	1252,16

4-probe conductance (G) measurement :

- Mobility of the semiconductor
- No contribution from the contacts

$$\mu_{FE} = \frac{dG}{dV_g}\frac{L}{W}\frac{1}{C_{OX}}$$

L : gate length (m)
W : gate width (m)
C_{ox} : Oxide capacitance per unit of area (F/m²)

Summary

- Ohmic contact gives lower contact resistance :
  - More scattering in Titanium datas
  - Nickel has the lowest contact resistivity
- In this framework Nickel gives the best results with a good ohmic contact
- More scattering in Titanium datas and more defects, the one to avoid
- All our FETs displayed unipolar behaviour
- Good mobility values according to what is found in the literature

Outlooks

- Extraction of Schottky barrier height to see the real nature of the contact
- Simulations of the interface to theoritically confirm those results
- Try with other metals to see if we can find better than Nickel
- Ambipolar behaviour is expected for thinner flakes (close to monolayer)

Acknowledgement

Grenoble INP
phelma

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SCUOLA
NORMALE
SUPERIORE

Thank you for your attention

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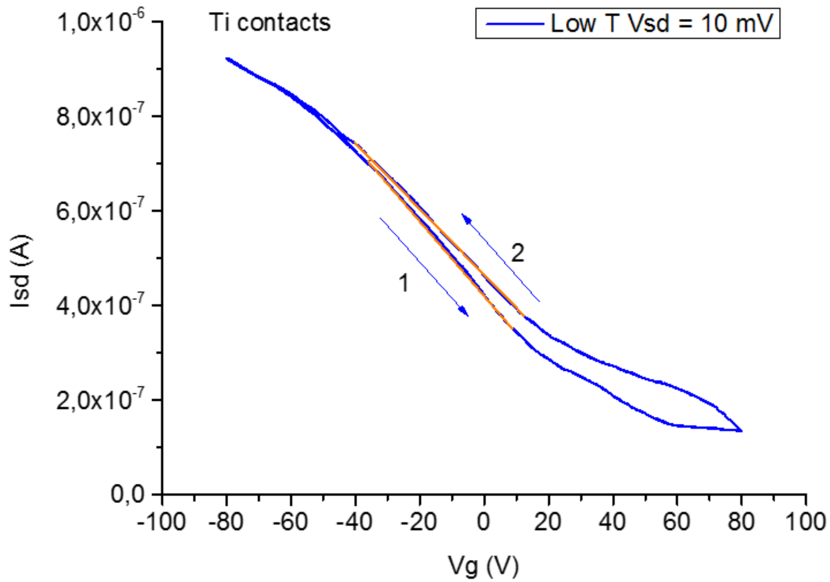
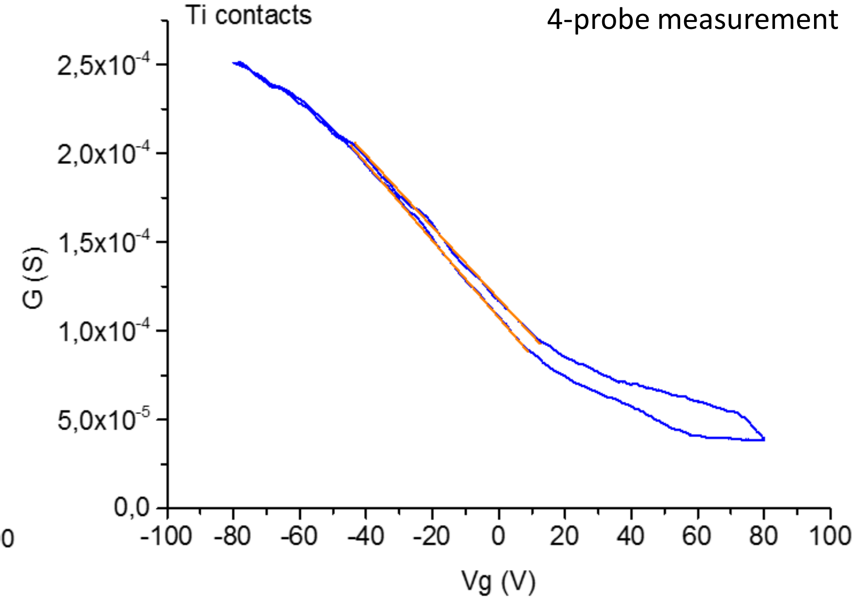
Field-Effect Measurements

- Field-effect mobility





4-probe measurement

Extracted μ_{FE} (cm²/(V.s))		
	I_{SD} vs V_g	G vs V_g
Ti Room Temperature	61,51	160,11
Ti Low Temperature	216,43	563,37
Cr Room Temperature	23,46	39,21
Cr Low Temperature	101,46	-
Ni Room Temperature	78,30	223,51
Ni Low Temperature	391,17	1252,16

$$\mu_{FE} = \frac{dI_{SD}}{dV_g}\frac{L}{W}\frac{1}{C_{OX}V_{SD}}$$

$$\mu_{FE} = \frac{dG}{dV_g}\frac{L}{W}\frac{1}{C_{OX}}$$