Ohmic-contact engineering in few-layer black Phosphorus field effect transistors.

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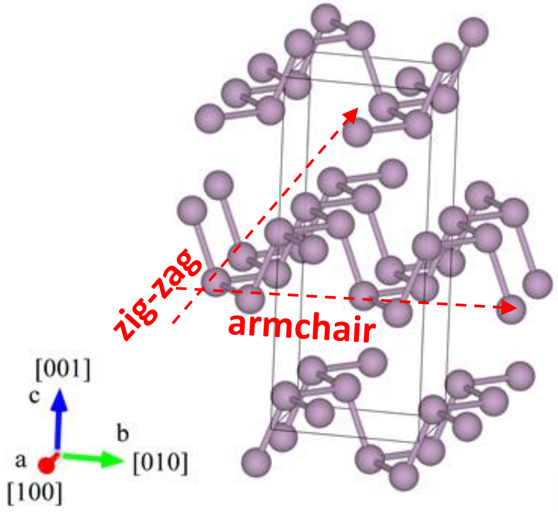
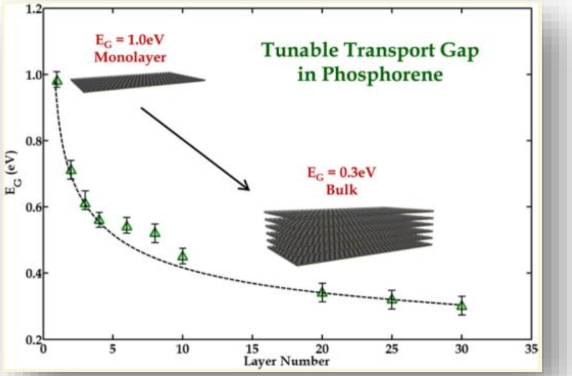
The renaissance of black phosphorus



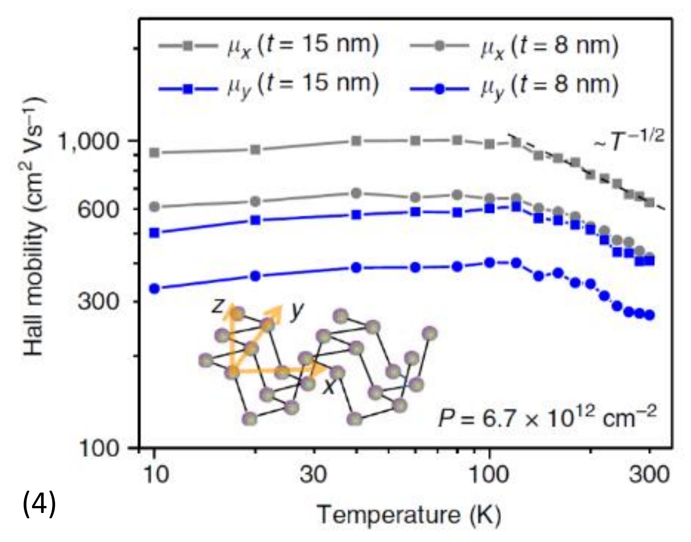
- p-type semiconductor with up to 45000 $cm^2/(Vs)$ mobility at low temperature (1)
- band gap of 0.3 eV in the bulk and tunable with layer number (≈2 eV for the monolayer) (2,3)

(2)

(3)

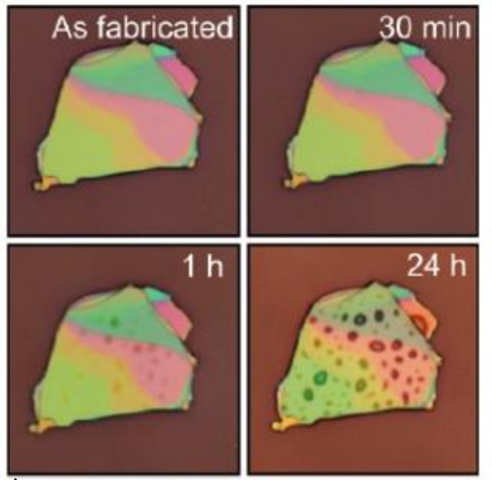


- strong in plane anisotropy of optical, eletrical and thermal transport properties



(4)

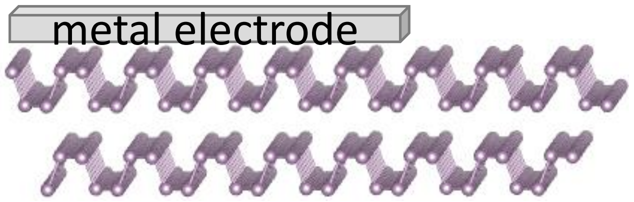
- high reactivity to oxygen and water vapour, enhanced by light exposure



(5)

(1)Long et al., Nano Letters, 2014, 14, 5733; (2) adapted from X. Ling et al., PNAS 112 (2015) 4523; (3) Das et al, Nano Letter, 2014 14, 2733 (5) A. Castellanos-Gomez et al, 2D Mat. 1, (2014); (4) F. Xia et al, Nat Comm 5, (2014)

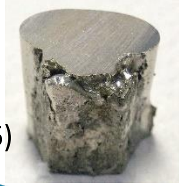
Ohmic contact engineering



- Ohmic contact
- Schottky barrier
- Hard tunneling barrier
- Metallization below the contact

Titanium

Chromium

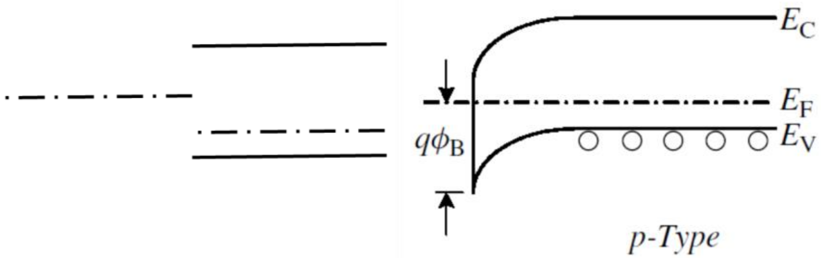


Nickel

(6)

Often used as **stitching layer** for gold electrodes

The simplest model: **Schottky-Mott rule**



(7)

$$\phi_n = (\phi_m - \chi)$$

$$\phi_p = E_g - (\phi_m - \chi)$$

$\chi_{bP} \approx 4.4\ eV$ (8)

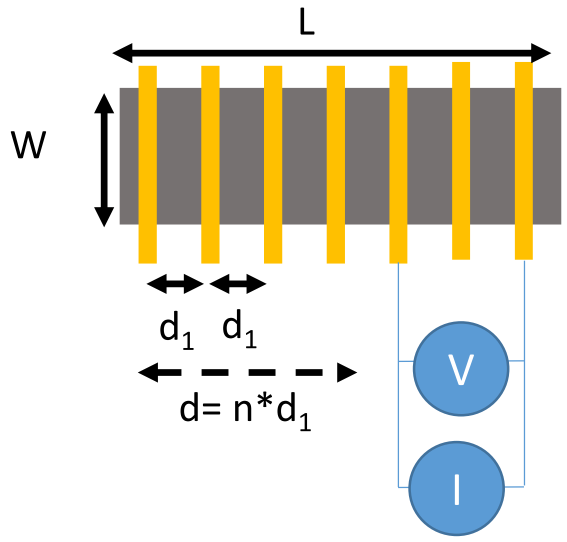
$\phi_{Ti} \approx 4.3\ eV$ (9) less suitable for holes injection

$\phi_{Cr} \approx 4.5\ eV$ (10)

$\phi_{Ni} \approx 5.0\ eV$ (11) best for holes injection

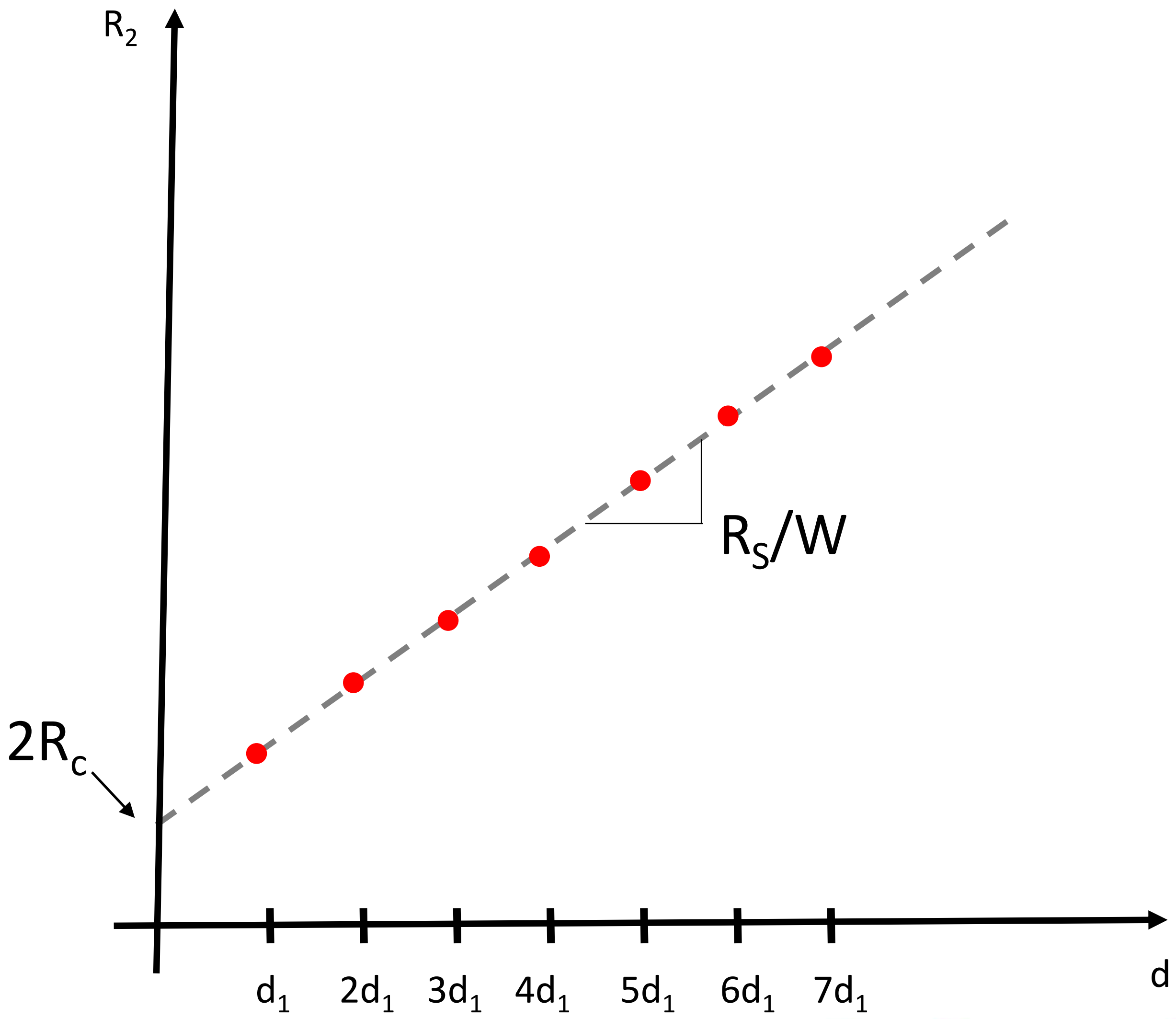
(6) Wikipedia Cc licence; (7) adapted from Schroder, Semiconductor materials and device characterization; (8) Feng et al, Nanoscale, 2016, 8, 2686; (9)Allain et al, Nat Mater, 2015, 14, 1195; (10) Lide, Handbook of Chemistry and Physics, 2008; (11) Du et al, ACS Nano, 2014, 8, 10035

Our approach: Transfer Length Method

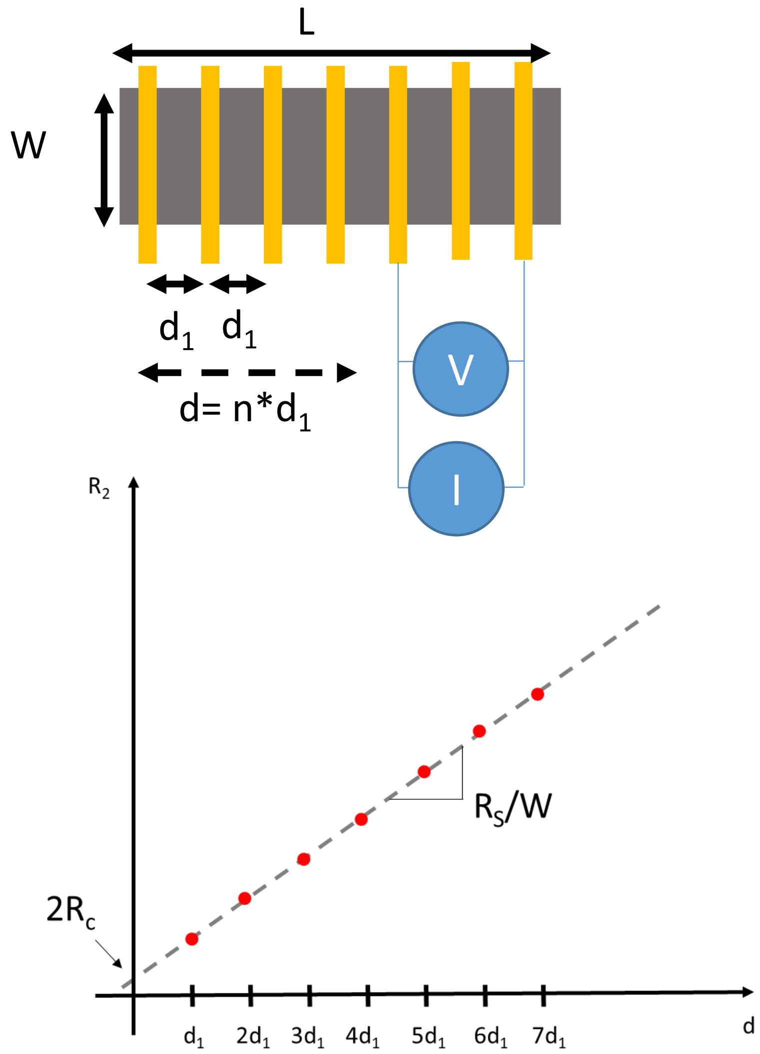


$$R_2 = R_C + R_{bP\ channel} + R_C$$

$$R_{bPchannel} \propto d$$



Our approach: transfer length method

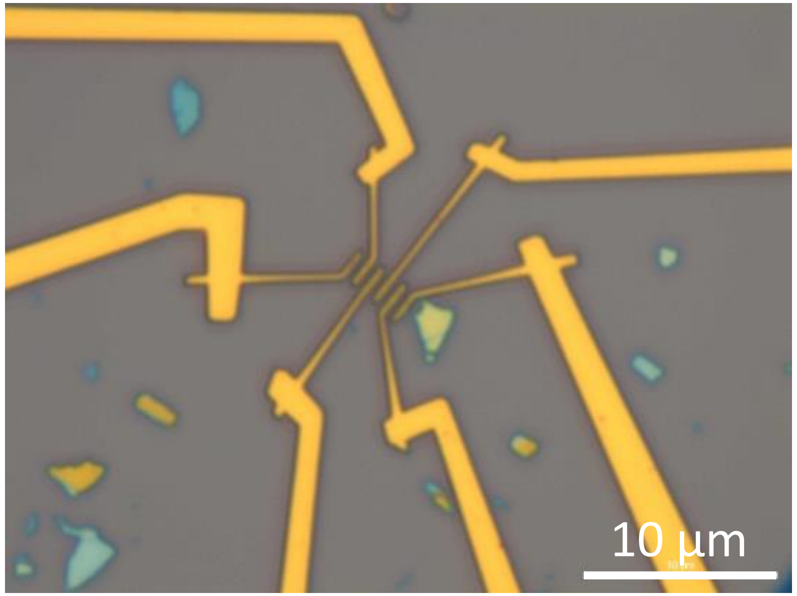


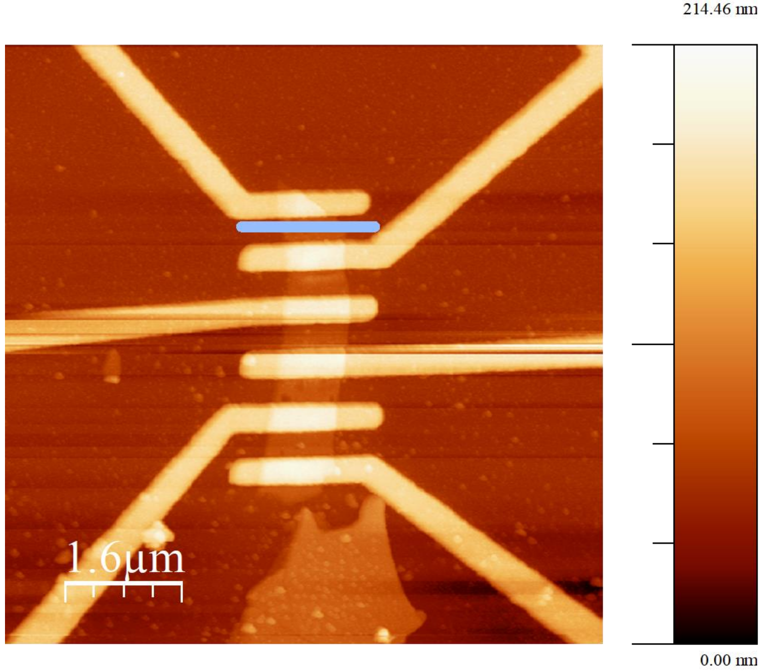
Aggregate data over different devices/samples

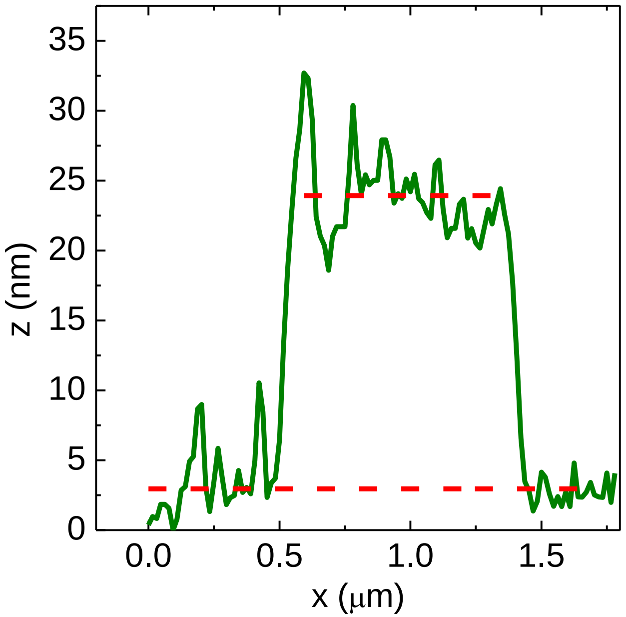
- Normalization of the resistance with contact width to compare different devices
- Average $\overline{R_C W}$
- Propagation of the experimental error
- Standard error of the distribution to get information on the scattering among the devices

Sample preparation

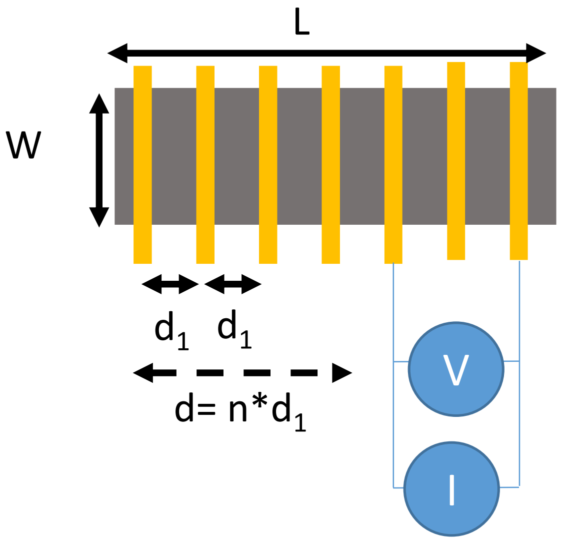
Exfoliation in glove-box or in glove bag → Coating with a MMA:MAA/PMMA bilayer → Flakes identification and EBL → Development & O_2 plasma → Metal evaporation, lift-off, coating

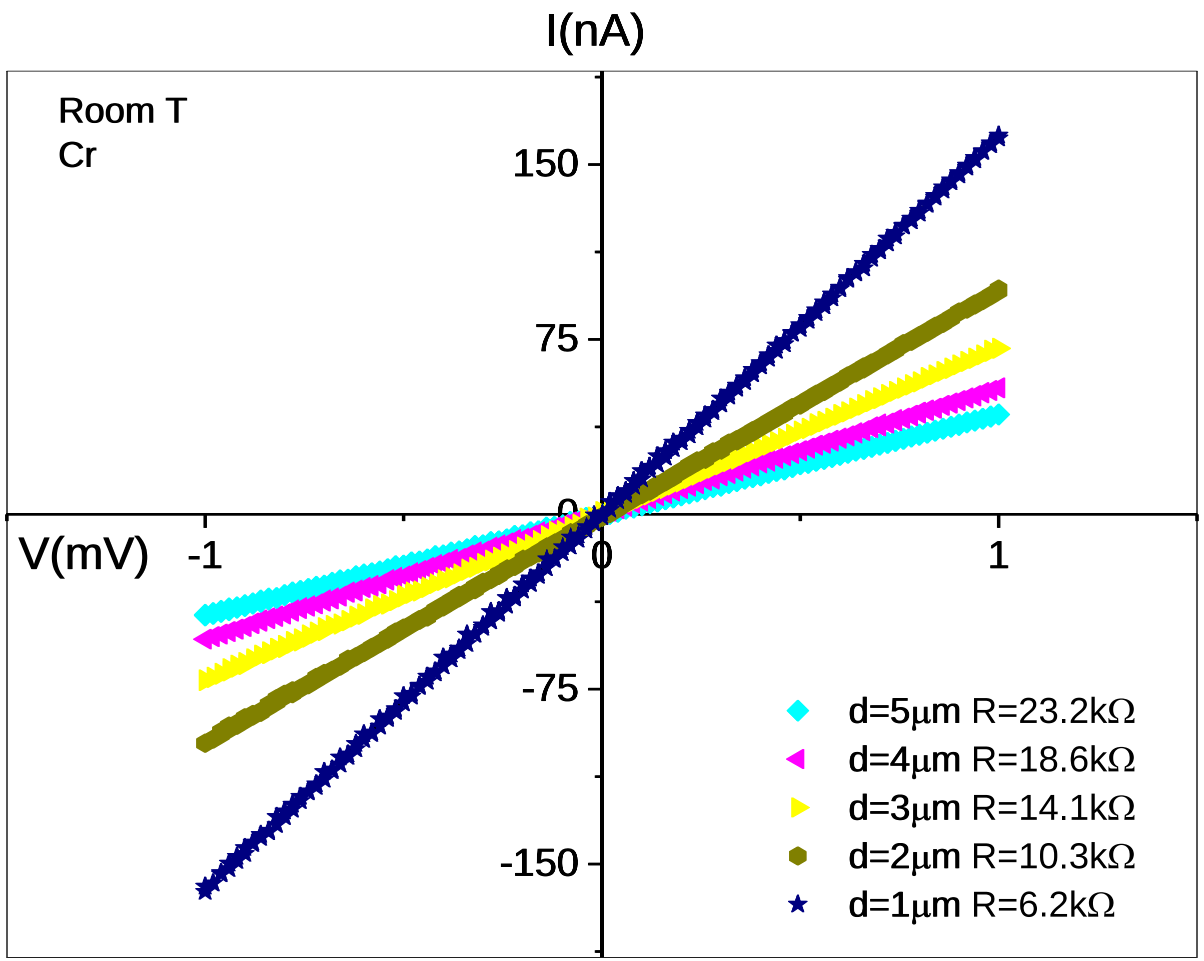






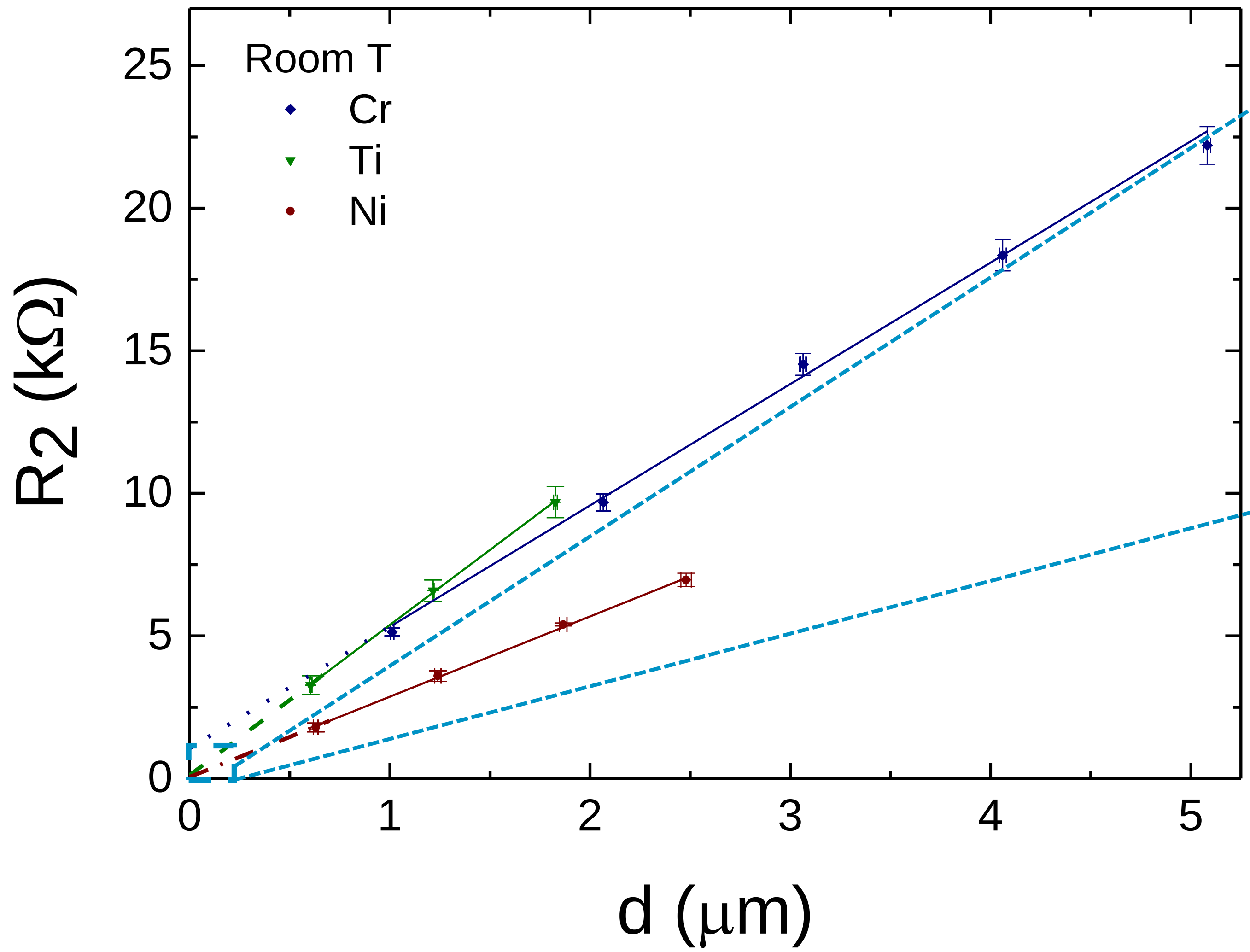
Our approach

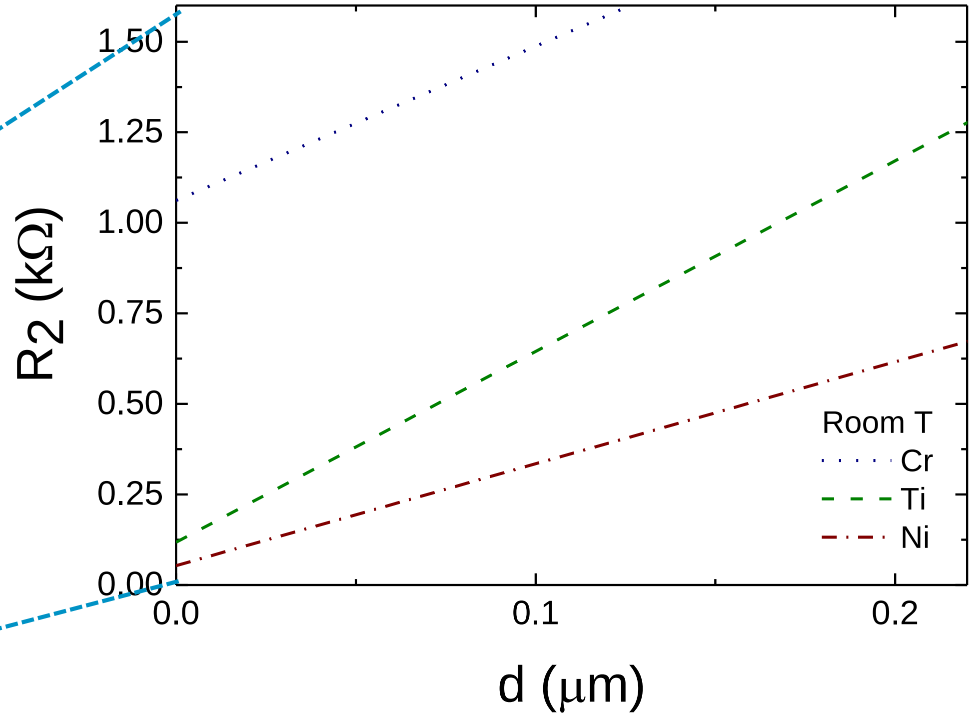




- Ohmic behavior
- We extract a R_2 value

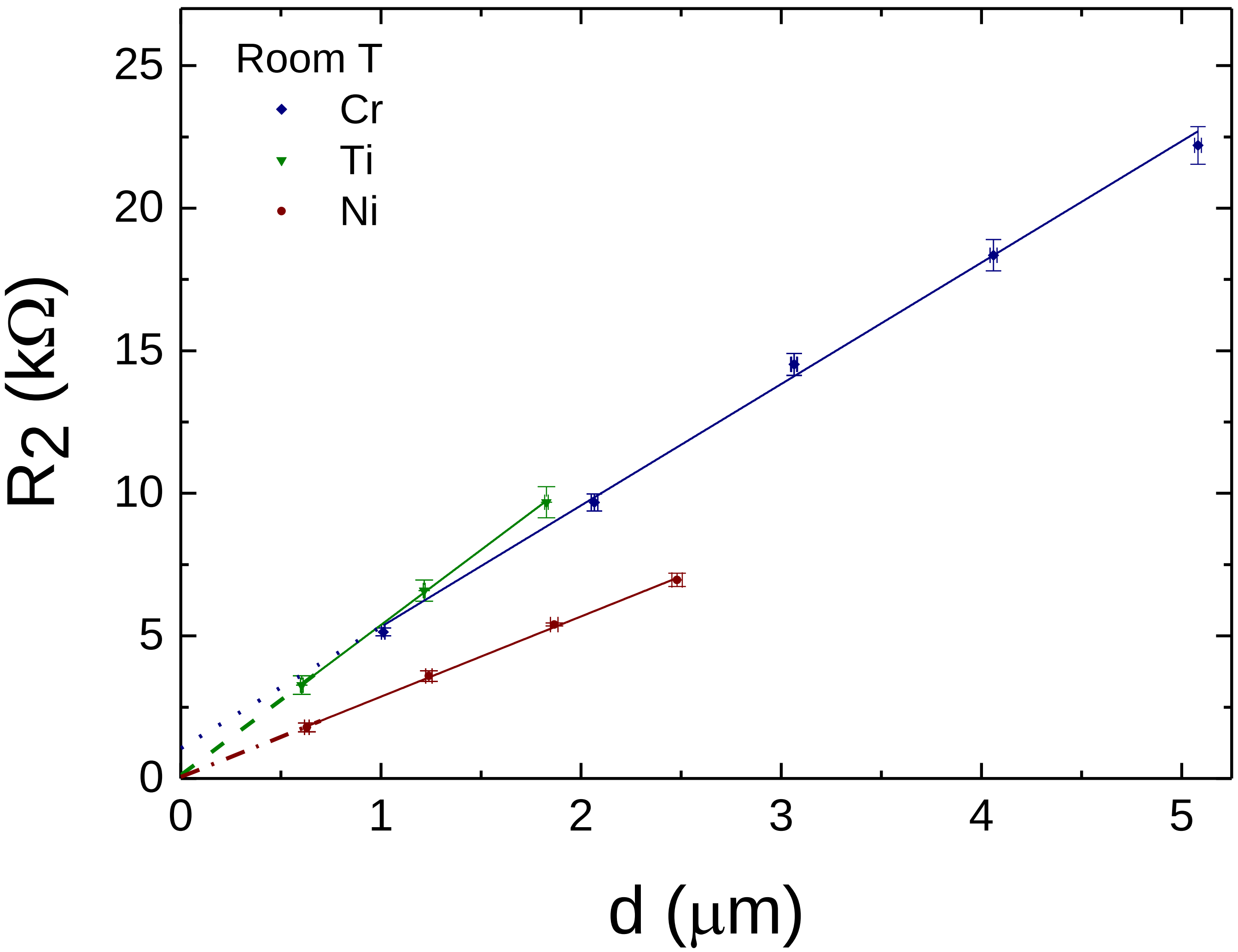
Contact resistance at room temperature

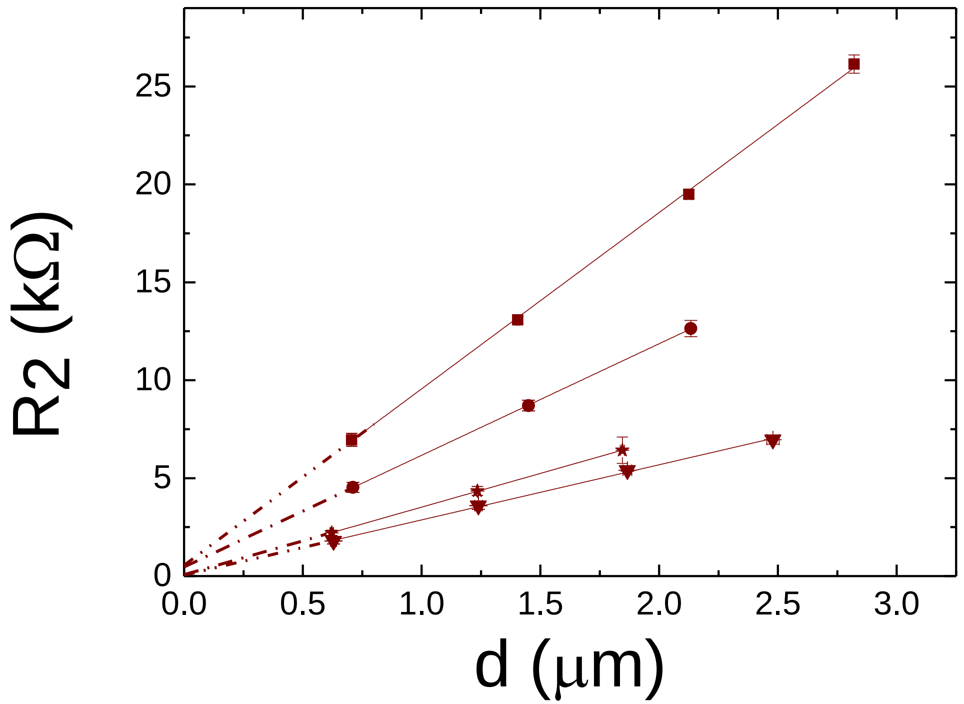




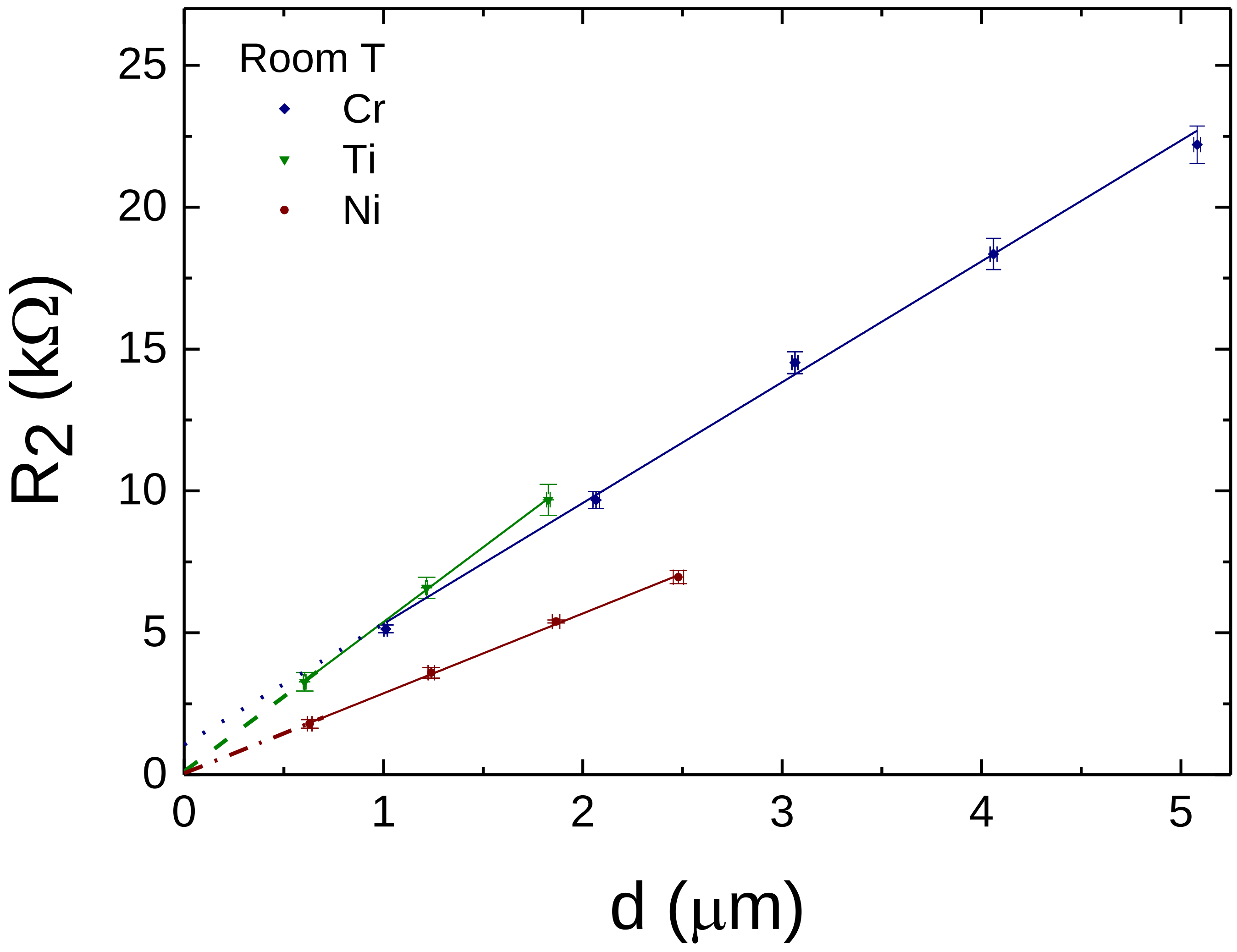
$R_{C|Ni} < R_{C|Ti} < R_{C|Cr}$

Contact resistance at room temperature



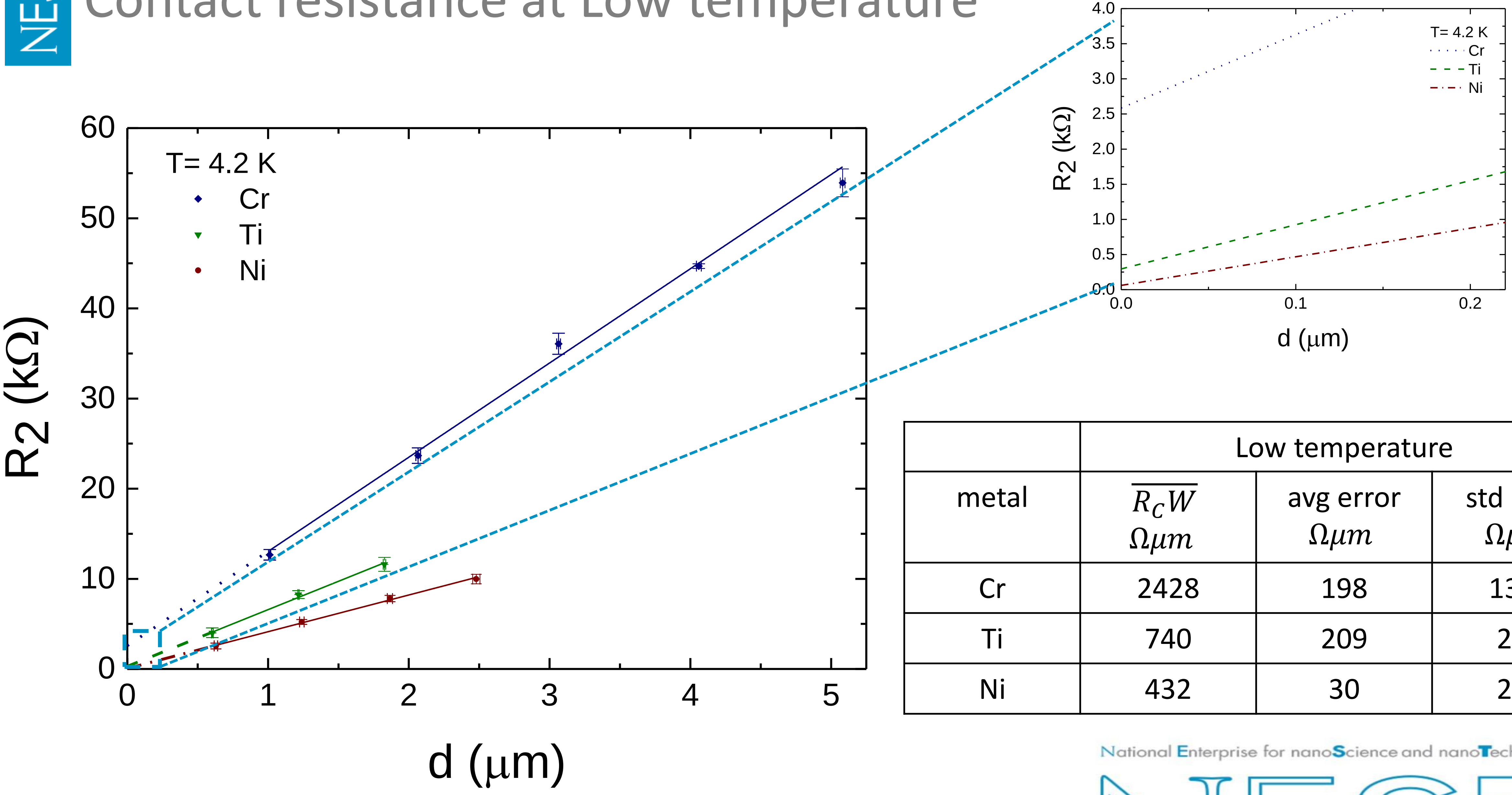


Contact resistance at room temperature



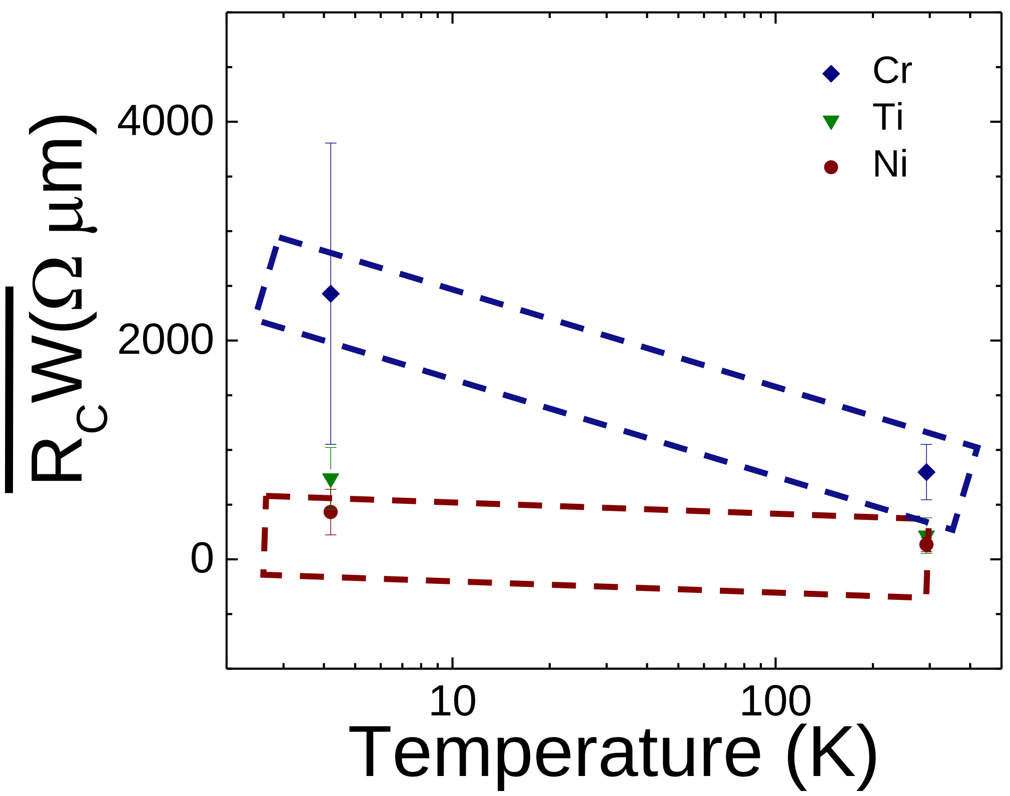
	Room temperature		
metal	$\overline{R_C W}$ $\Omega\mu m$	avg error $\Omega\mu m$	std error $\Omega\mu m$
Cr	797	64	253
Ti	217	88	163
Ni	135	13	64

Contact resistance at Low temperature

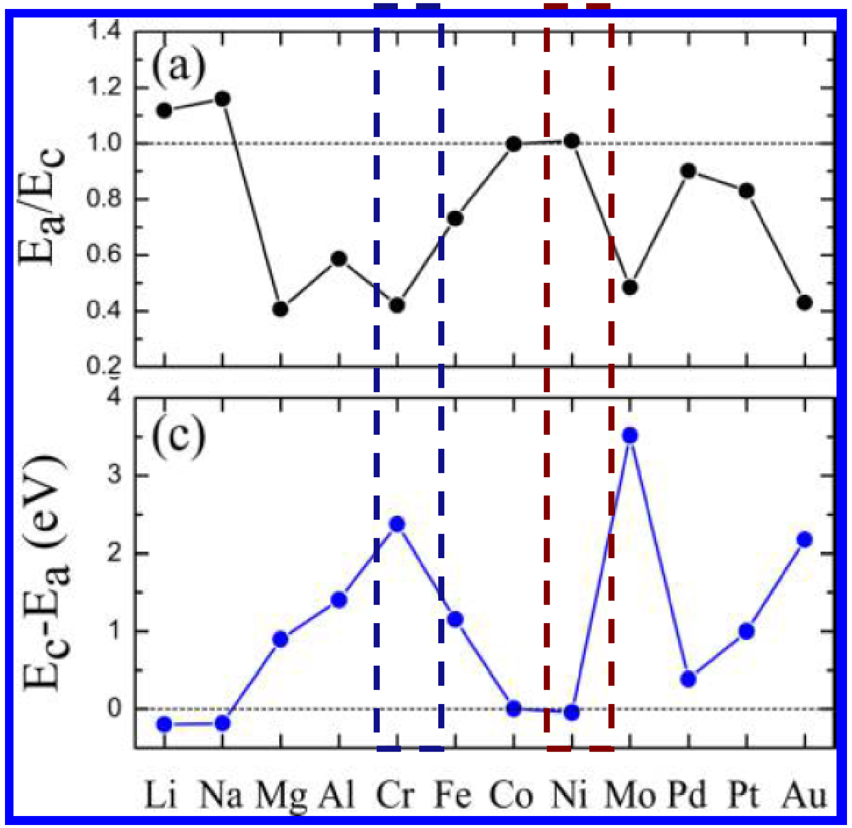


	Low temperature		
metal	$\overline{R_C W}$ $\Omega\mu m$	avg error $\Omega\mu m$	std error $\Omega\mu m$
Cr	2428	198	1377
Ti	740	209	282
Ni	432	30	208

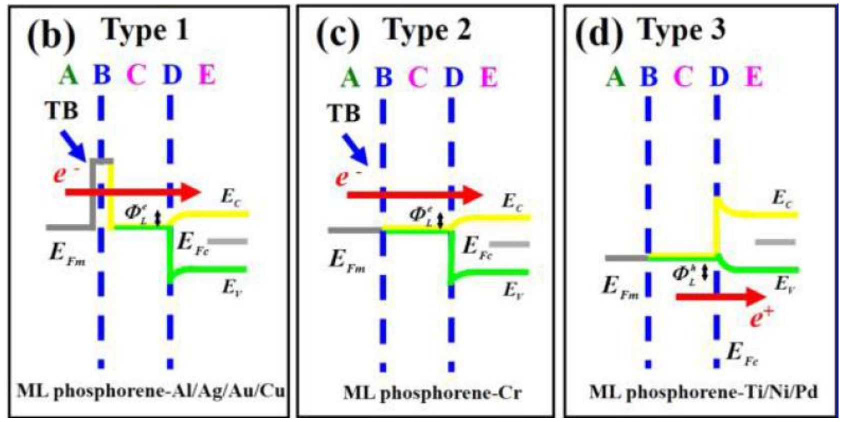
Contact resistance: summary



(12)

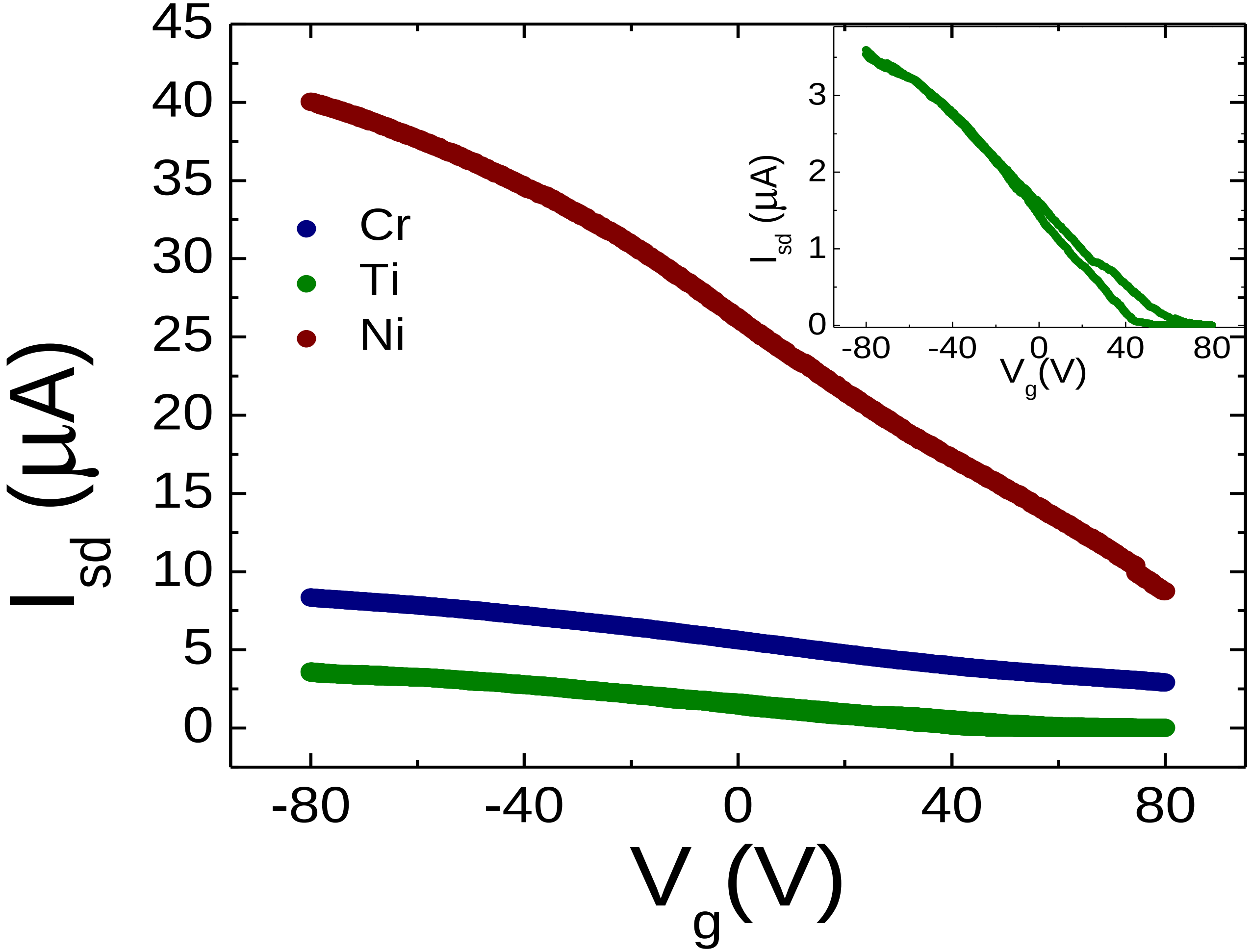


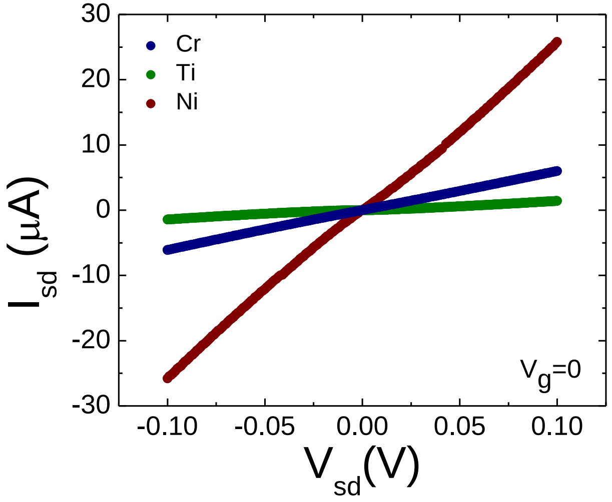
(13)

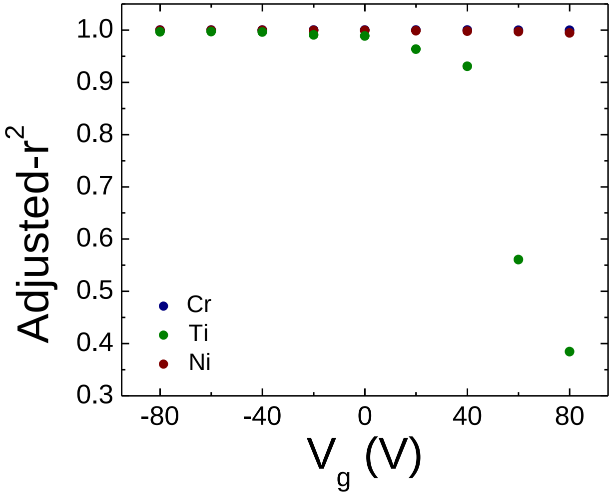


(12) Adapted from Hong et al, J. Phys Chem C, 2015, 119, 8199; (13) Pan et al, Chem Mater, 2016, 28, 2100

High bias and gate voltage dependence







- In accumulation regime all contacts display ohmic behavior even up to ±100 mV
- Reaching depletion regime deviation from Ohmic behaviour is observed, independently of the metal, as observed before (14)

(14) Li et al, Nat. Nanotech, 9, 372

Conclusions

- ✓We studied contact resistance on few-layer bP, on ten devices
- ✓We investigated three technologically relevant metals: **Chromium**, **Titanium** and **Nickel**
- ✓Both at **room temperature** and at **low temperature** the **best** results are obtained for **Nickel**, both for contact resistance and for scattering among the results
- ✓Consistent results are obtained from the comparison of two-probe and four-probe resistance
- ✓All samples displayed a strong **unipolar** p-type behavior
- ✓Ohmic contacts were observed also in the high voltage(±100 mV)range in accumulation regime

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Thank you for your attention!

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