The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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IAEA
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1960-3

ICTP Conference Graphene Week 2008

25 - 29 August 2008

Current-induced cleaning of graphene

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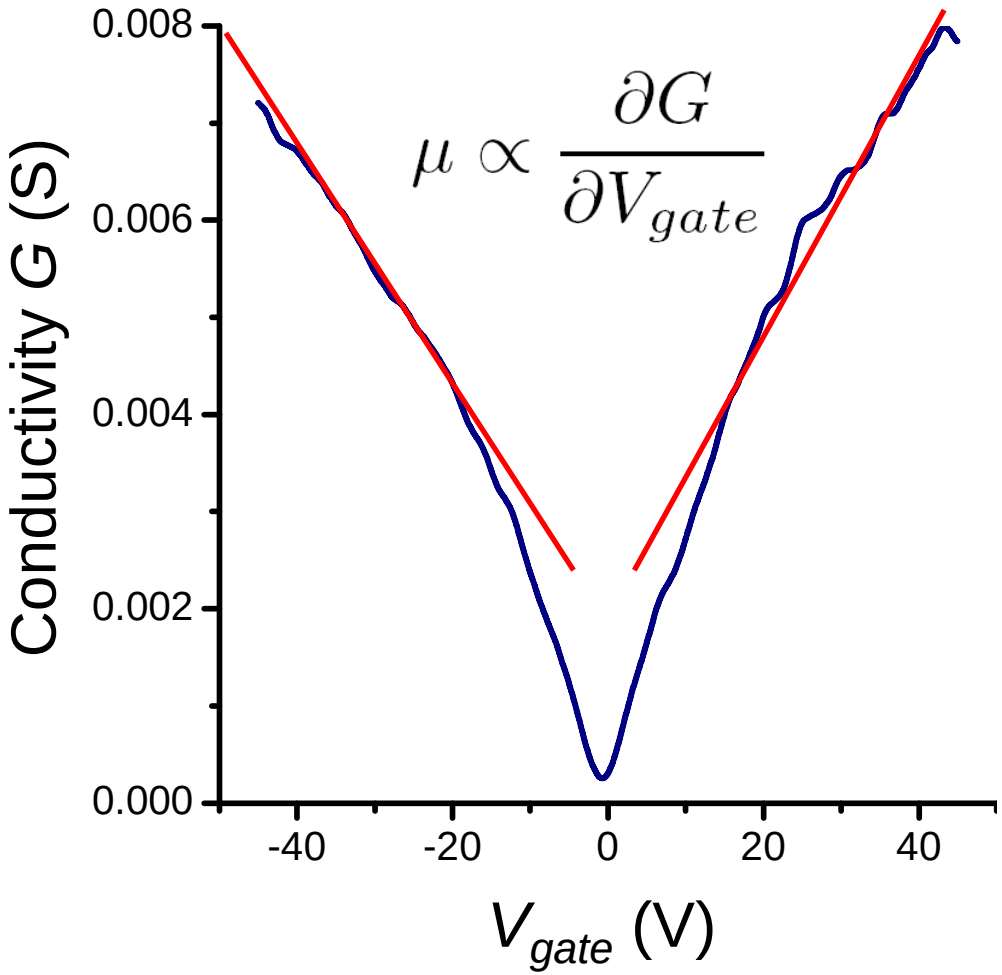
Current-induced cleaning of graphene

J. Moser, A. Barreiro, and A. Bachtold

CIN2 Barcelona, Campus UAB, E-08193 Bellaterra, Spain

Motivation



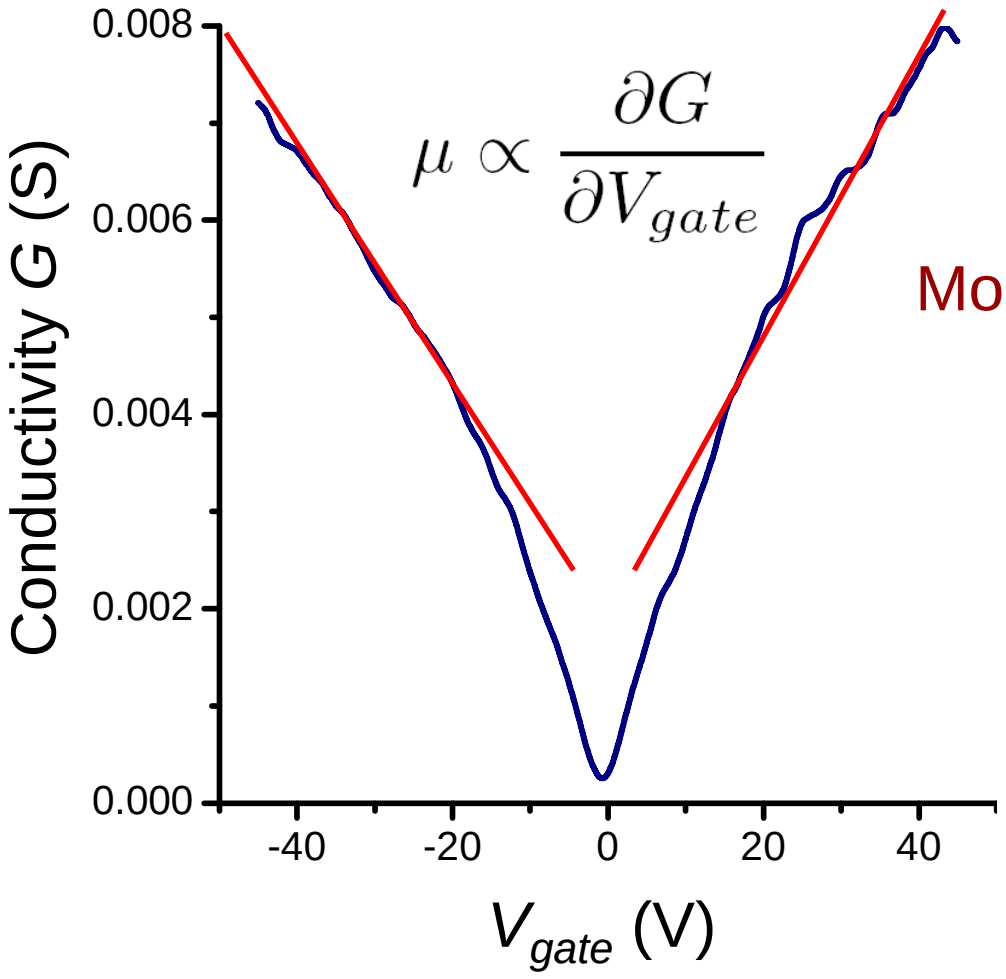
Typical mobilities:

~20,000 $cm^2V^{-1}s^{-1}$ on SiO_2

~200,000 $cm^2V^{-1}s^{-1}$ suspended

K. I. Bolotin, K. J. Sikes, Z. Jiang, G. Fudenberg, J. Hone, P. Kim, and H. L. Stormer, **Solid State Communications 146, 351-355 (2008).** X. Du, I. Skachko, A. Barker, E. Y. Andrei, **arXiv:0802.2933.**

Motivation



Typical mobilities:

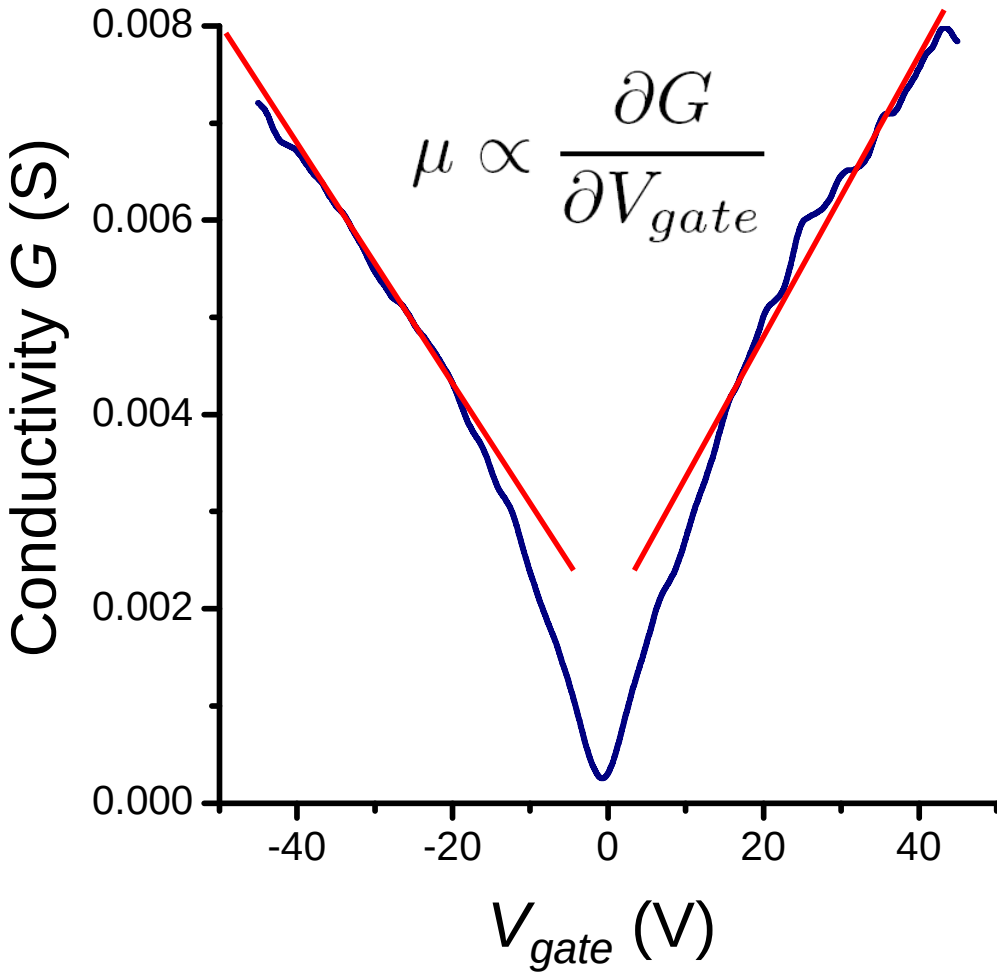
~20,000 $cm^2V^{-1}s^{-1}$ on SiO_2

~200,000 $cm^2V^{-1}s^{-1}$ suspended

Mobility μ was shown to be limited by charge disorder

J. H. Chen, C. Jang, M. S. Fuhrer, E. D. Williams, and M. Ishigami
Nature Physics 4, 377 (2008).

Motivation



Typical mobilities:

~20,000 $cm^2V^{-1}s^{-1}$ on SiO_2

~200,000 $cm^2V^{-1}s^{-1}$ suspended

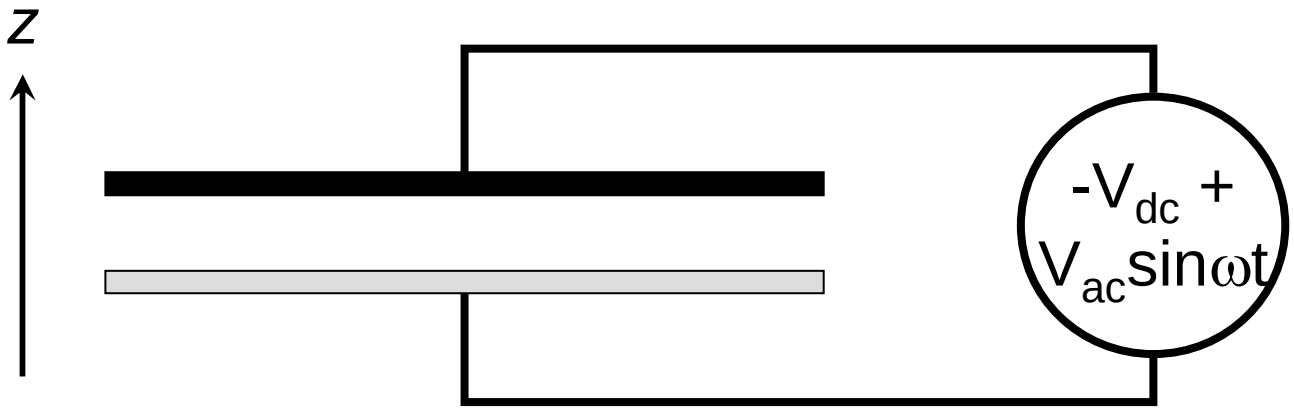
F. Schedin, A. K. Geim, S. V. Morozov, E. W. Hill, P. Blake, M. I. Katsnelson, and D. K. S. Novoselov, **Nature Material 6, 652 (2007)**

Shaffique Adam, E. H. Hwang, Victor Galitski, S. Das Sarma, **Proc. Natl. Acad. Sci. USA 104, 18392 (2007)**

Outline:

1) Characterizing contaminants by Electrostatic Force Microscopy (EFM)

2) Current-induced cleaning (annealing) of graphene

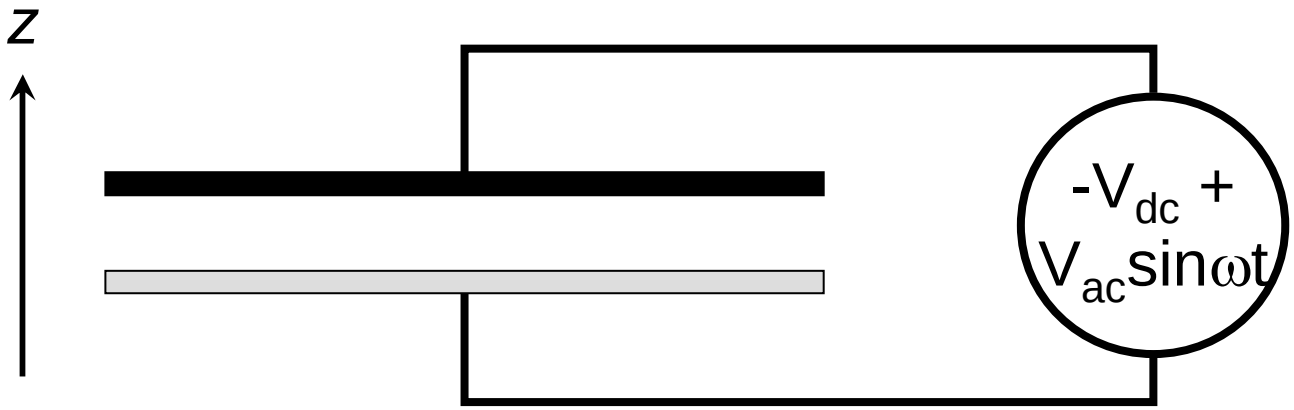


$$\Delta V = \Delta\phi - V_{dc} + V_{ac} \times \sin(\omega t)$$

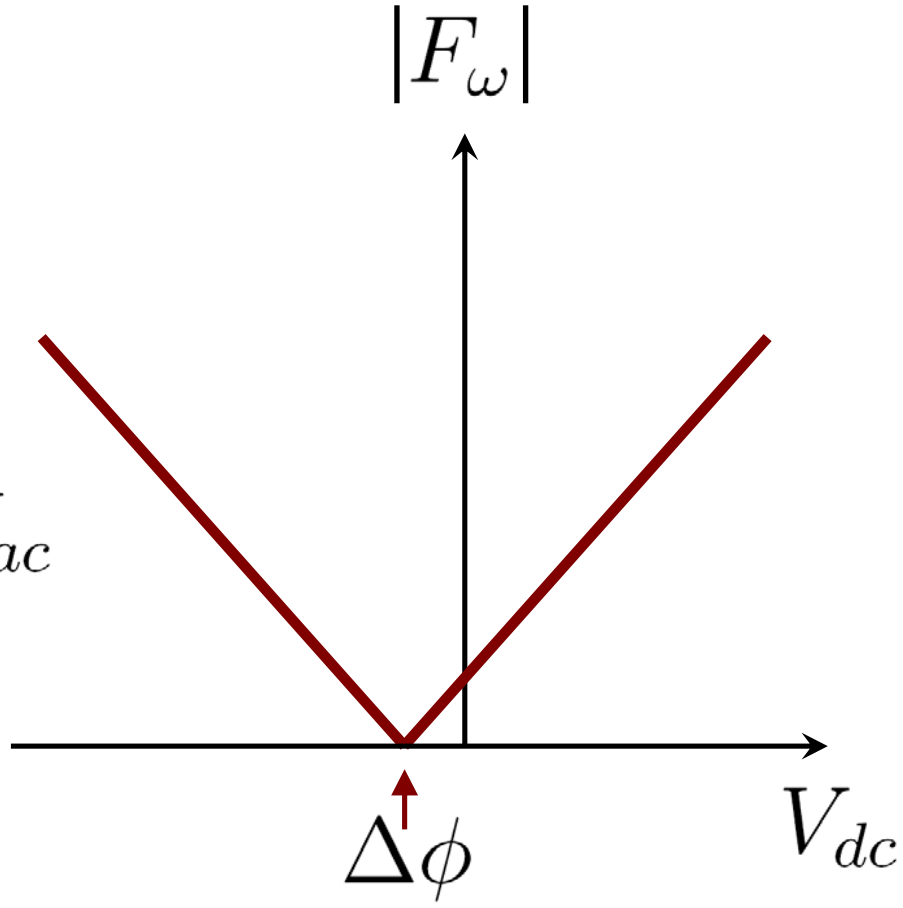
$$U = \frac{1}{2} C \left(\Delta V\right)^2$$

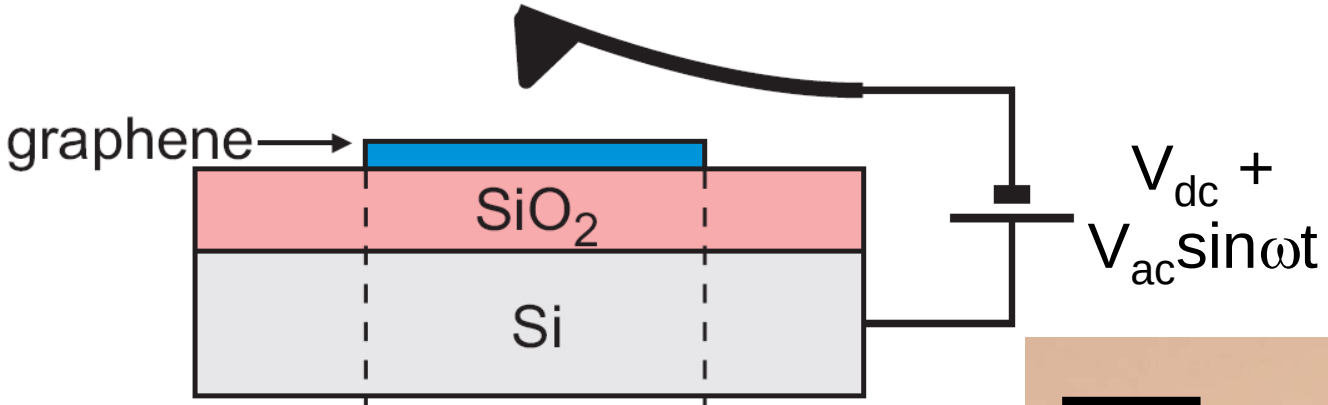
$$F = -\frac{\partial U}{\partial z}$$

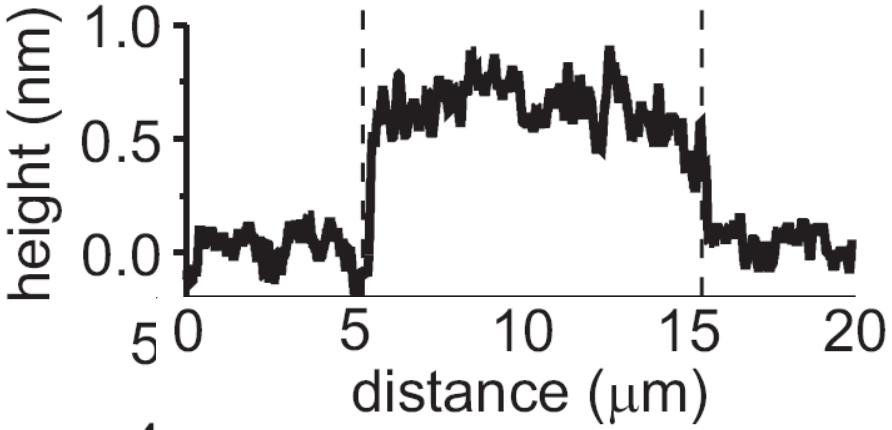
Difference between surface potentials on the plates

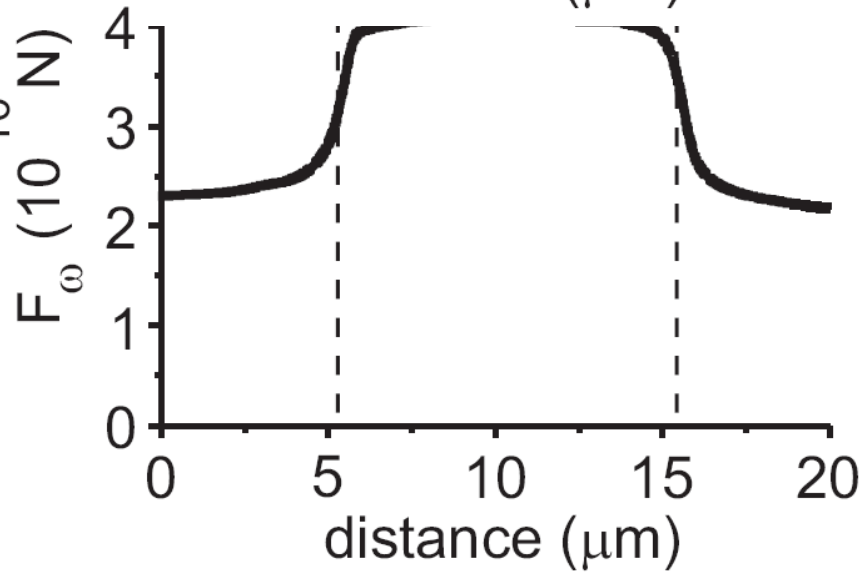


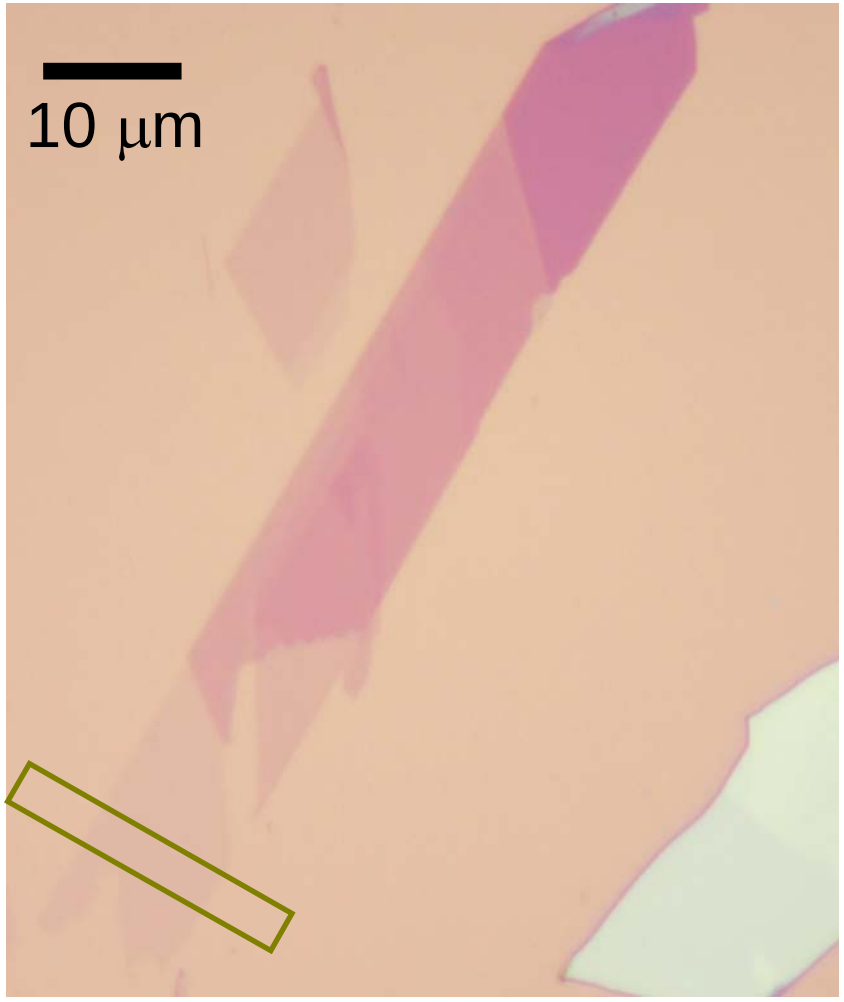
$$F_\omega = \frac{\partial C}{\partial z}(V_{dc} - \Delta\phi)V_{ac}$$

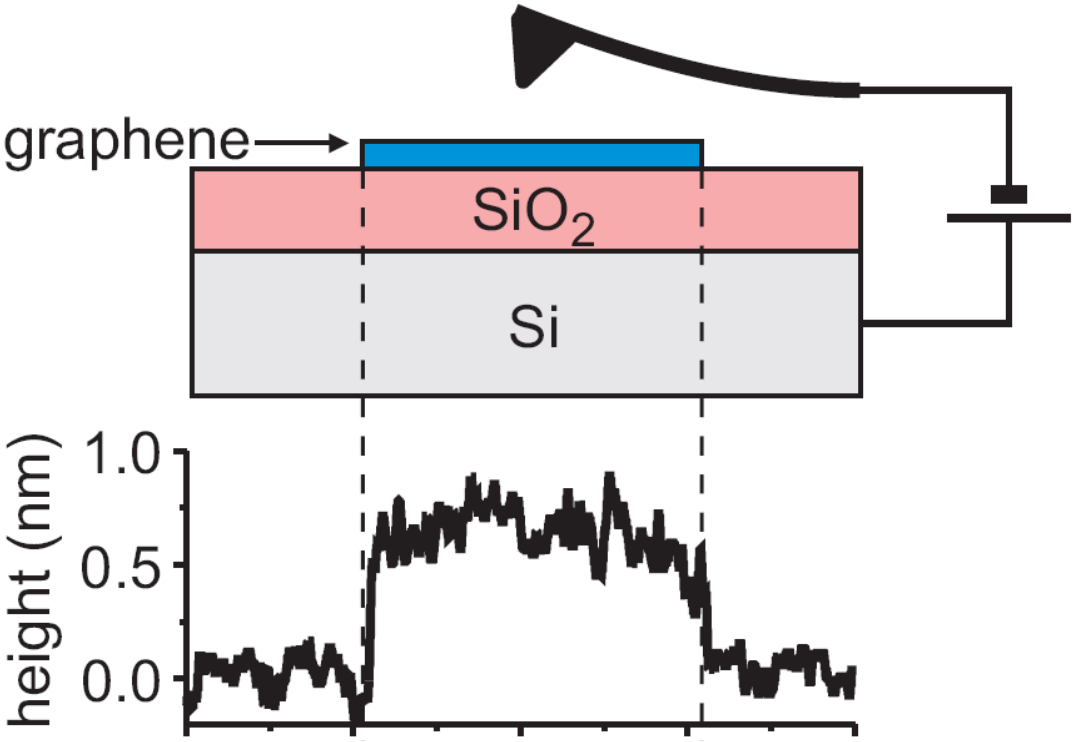


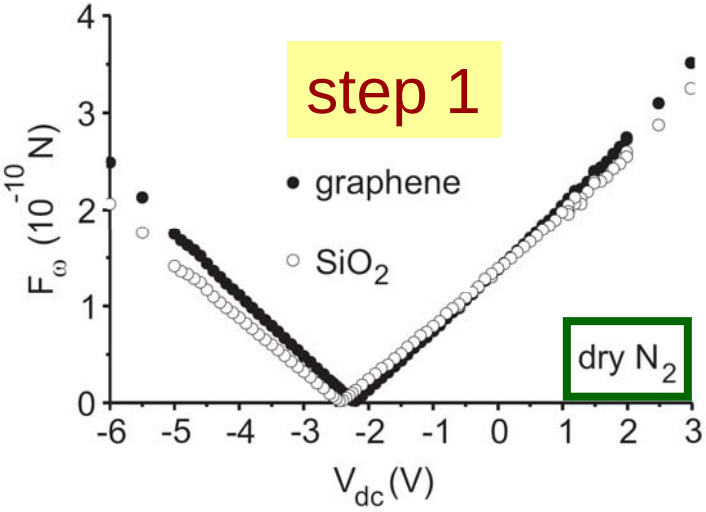

graphene
SiO_2
Si
V_{dc} +
$V_{ac}\sin\omega t$

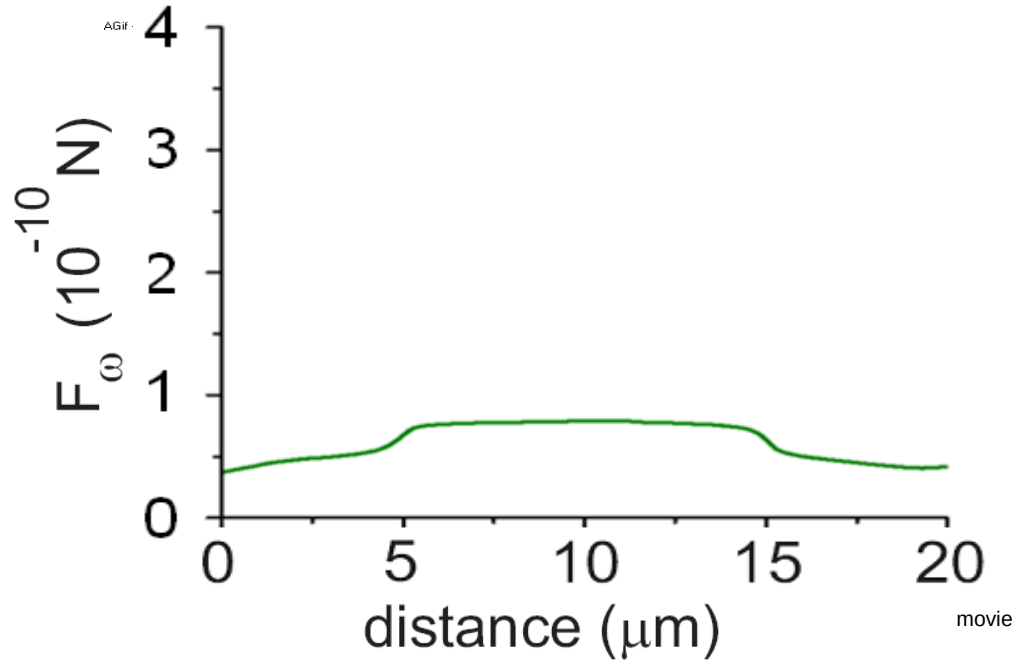

height (nm)
1.0
0.5
0.0
0
5
10
15
20
distance (μm)


F_ω (10^{-10} N)
4
3
2
1
0
0
5
10
15
20
distance (μm)


10 μm



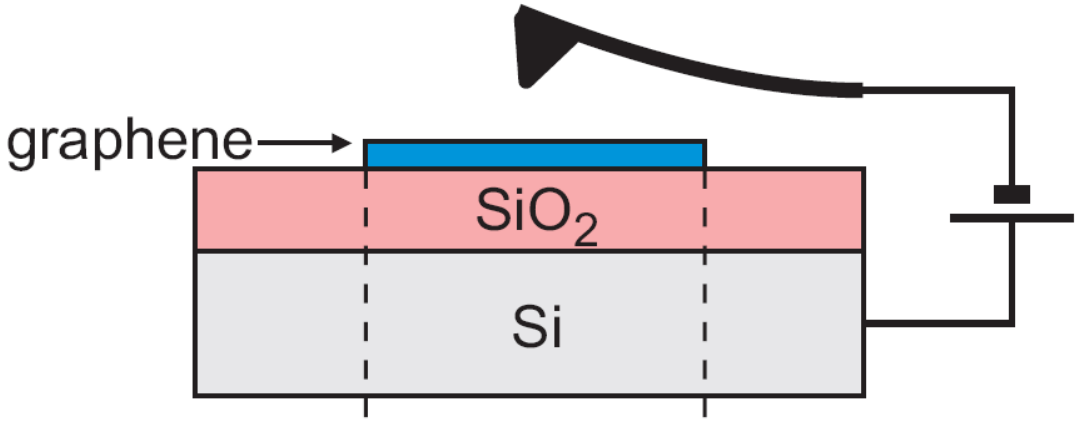


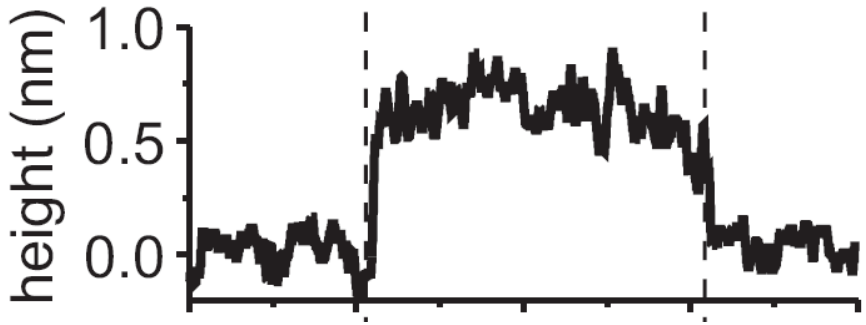


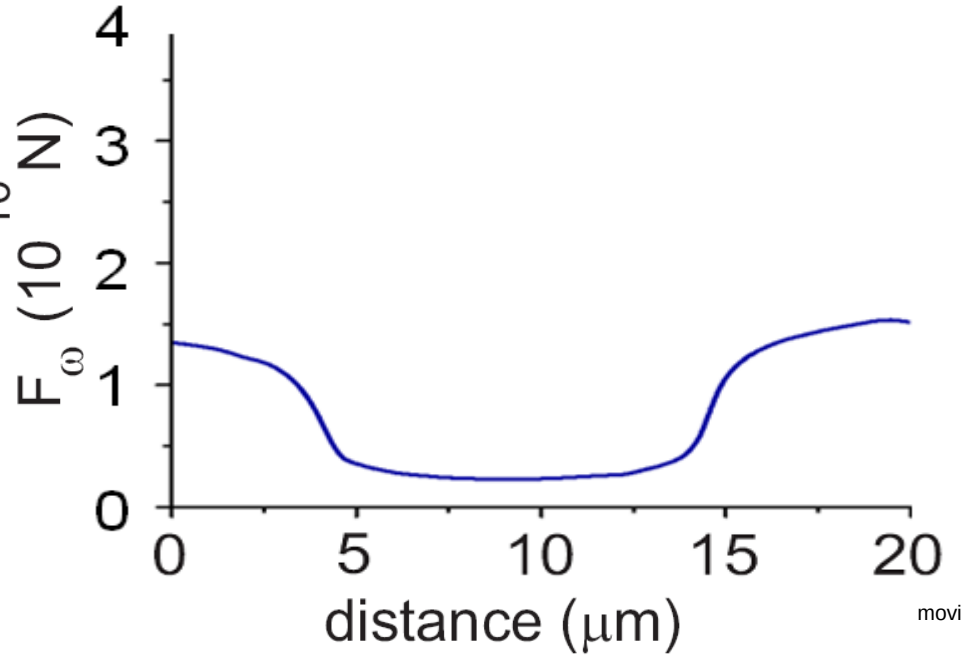
movie

flowing N_2

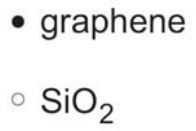
varying V_{dc}, measuring F_ω

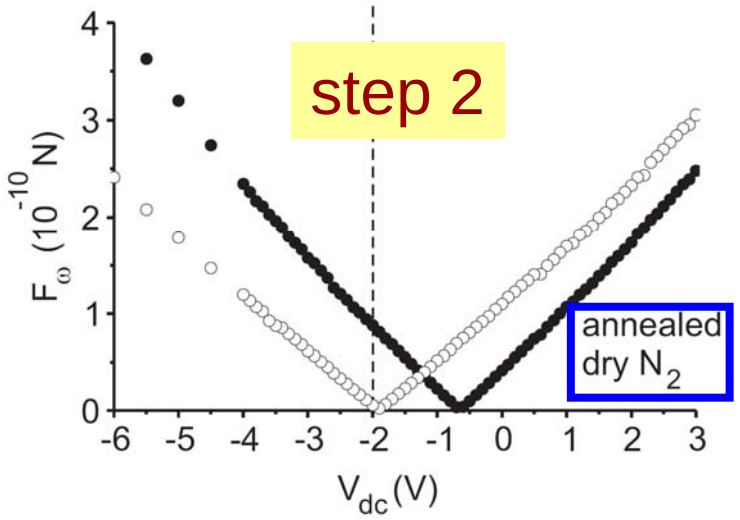






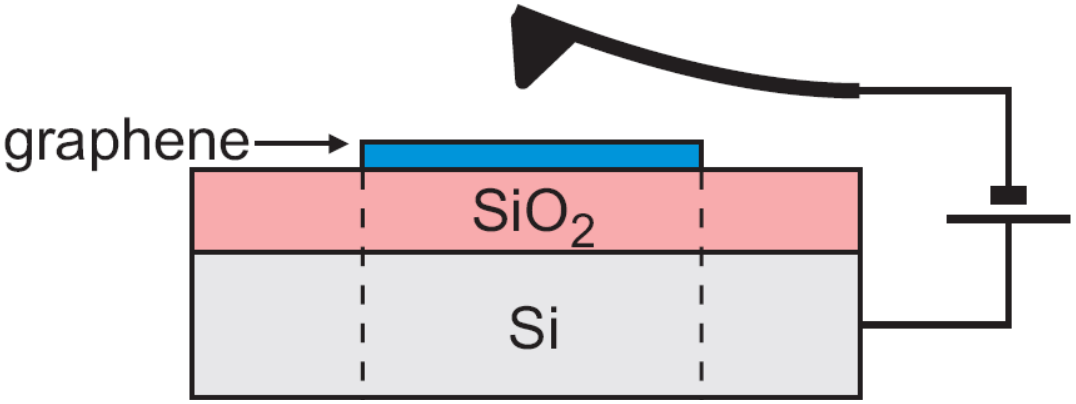
movie





graphene annealed at 150 deg C for 1 hour in flowing N_2

varying V_{dc}, measuring F_ω

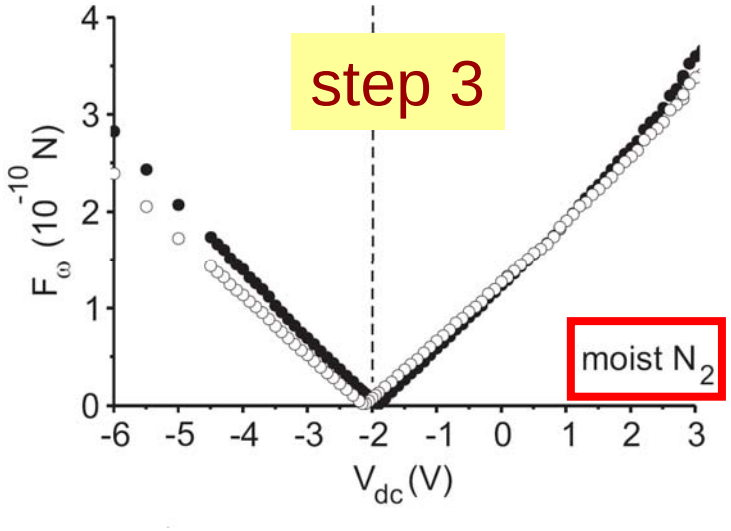


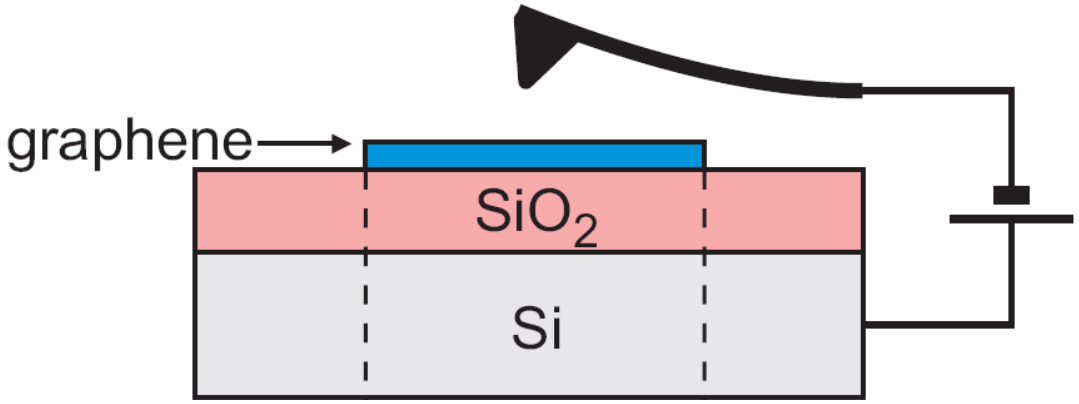
graphene

SiO_2

flowing, moist N_2

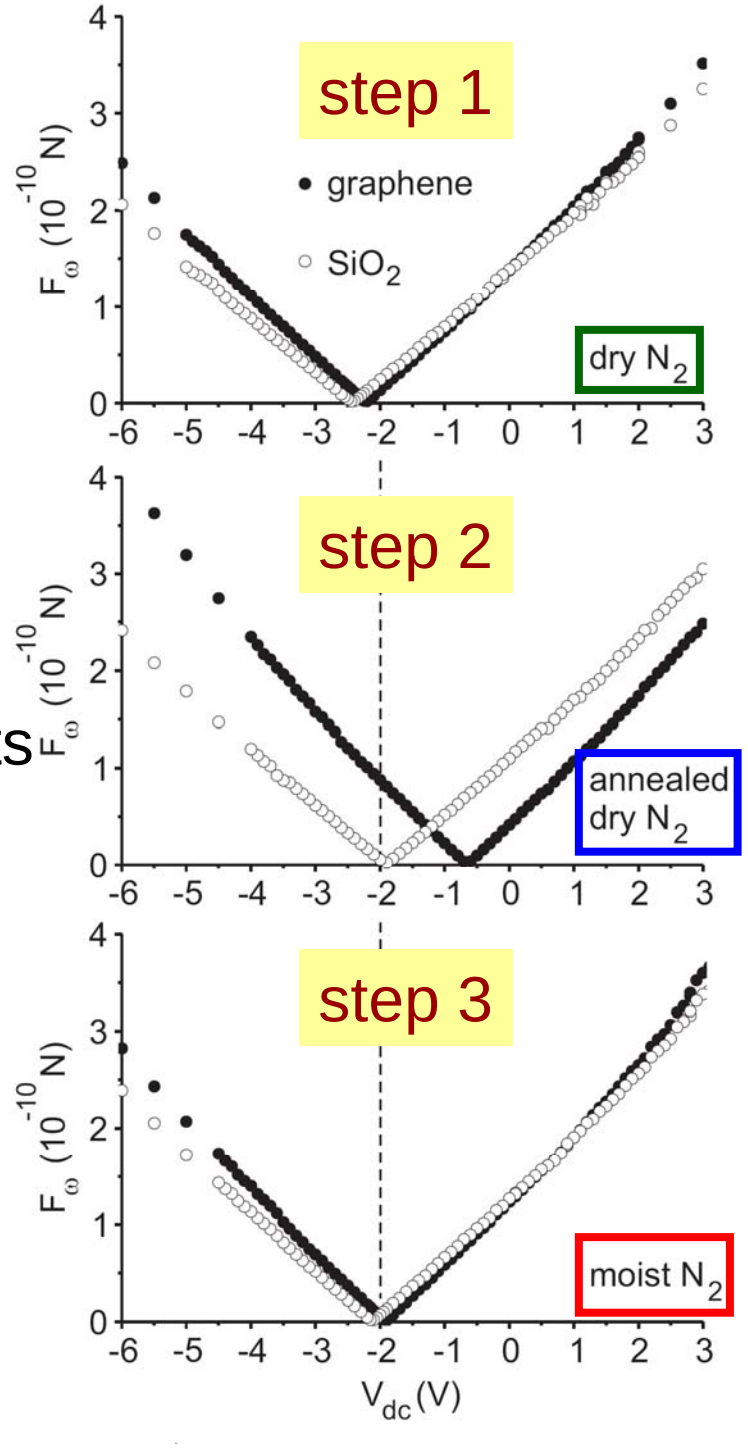
varying V_{dc}, measuring F_ω

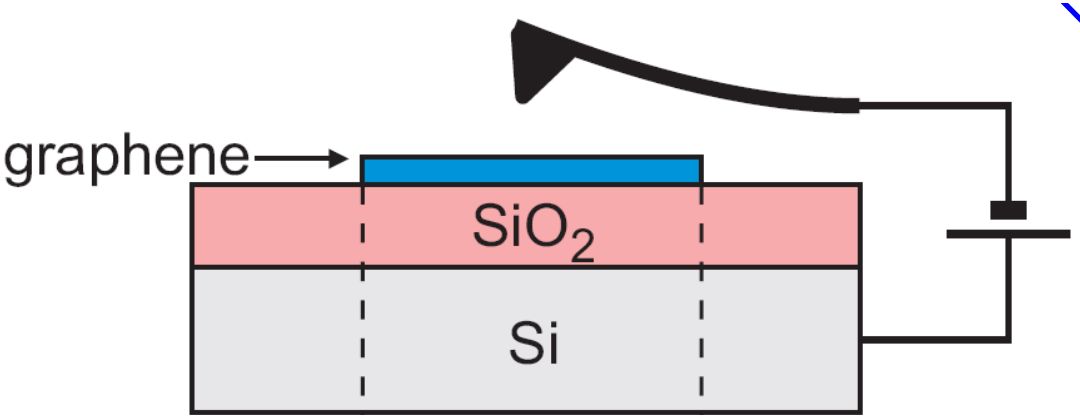




Dry N_2 and moist N_2 yield similar results

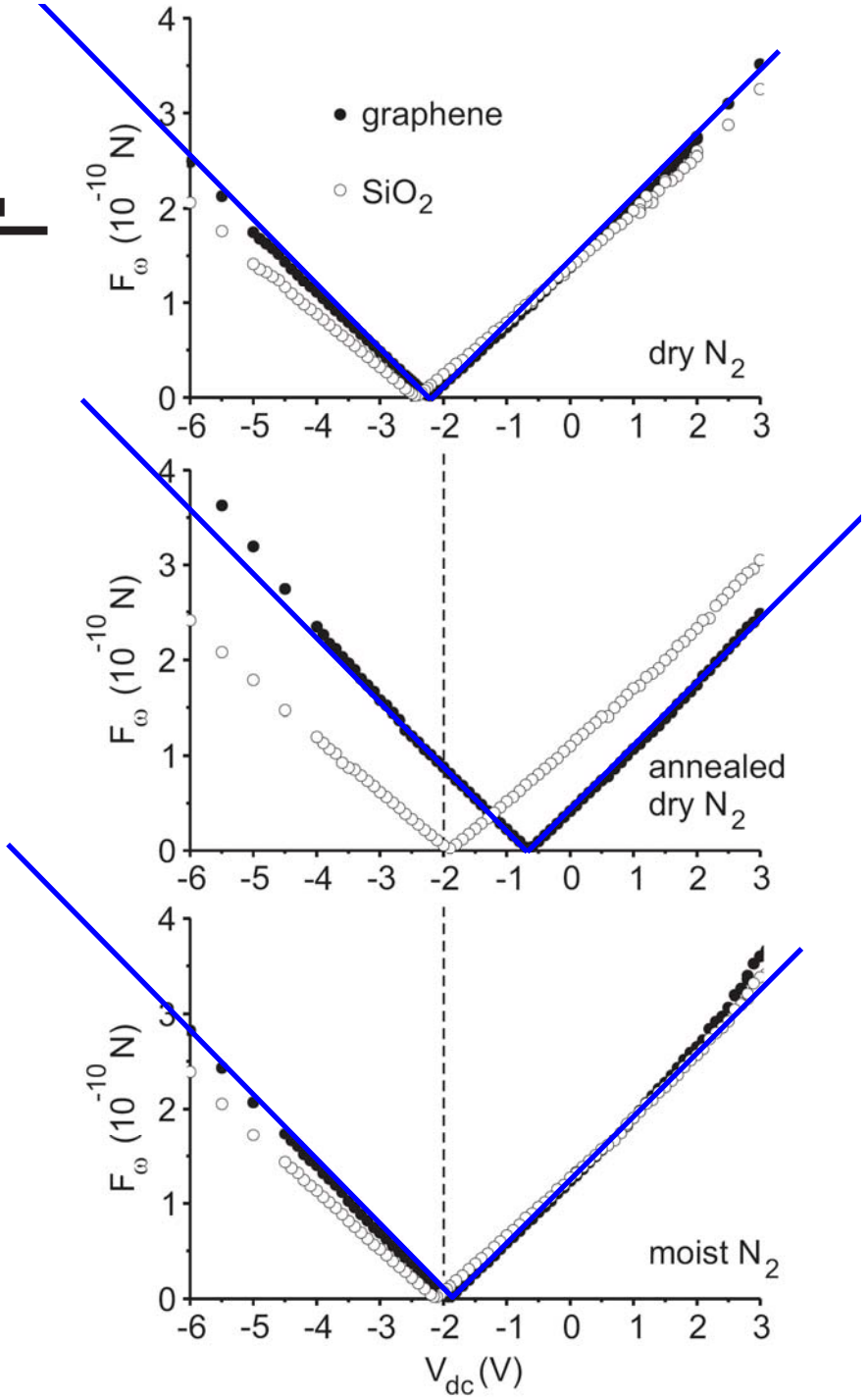
Annealed sample in dry N_2 stands out

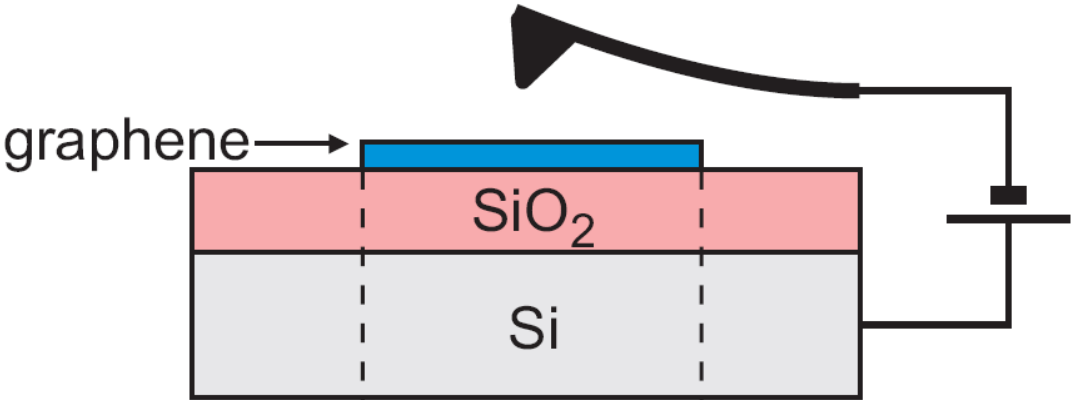




$$F_\omega = \frac{\partial C}{\partial z}(V_{dc} - \Delta\phi)V_{ac}$$

(e.g., for graphene)



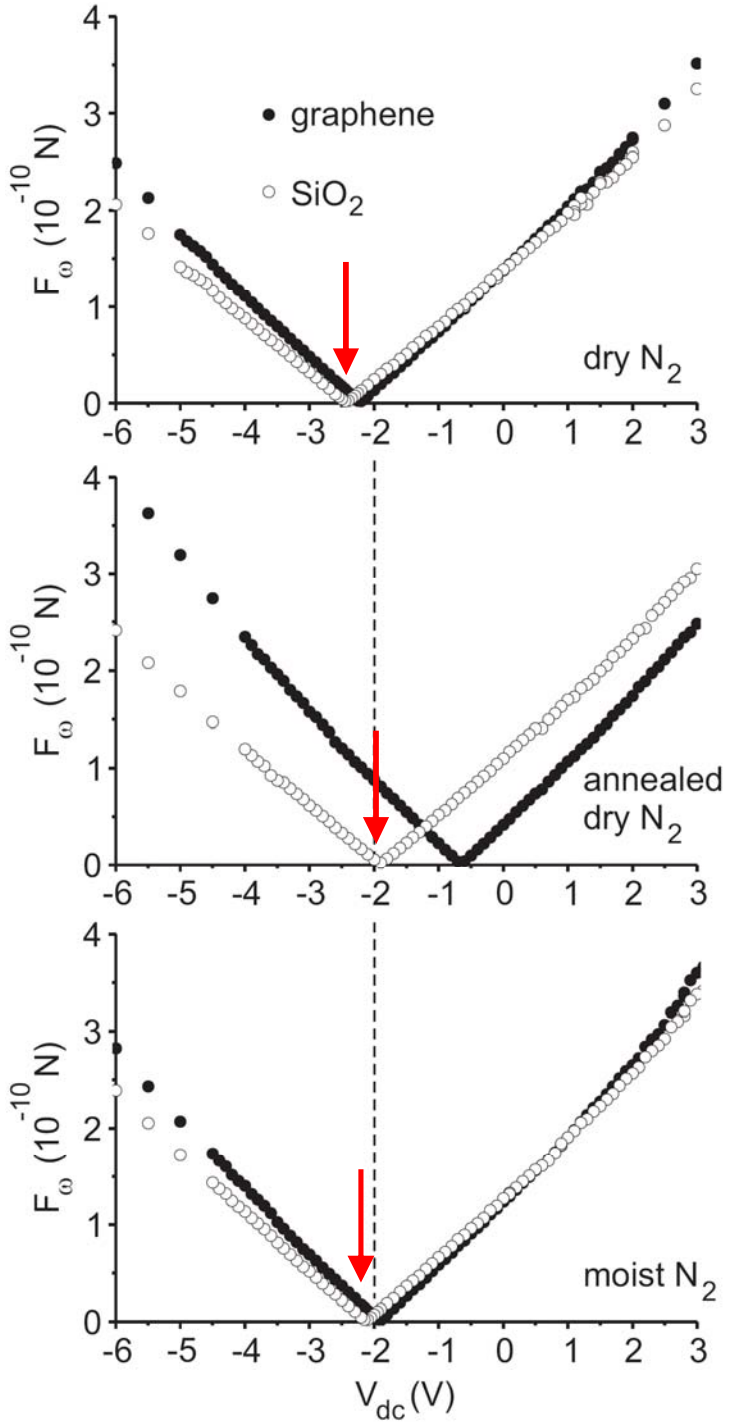


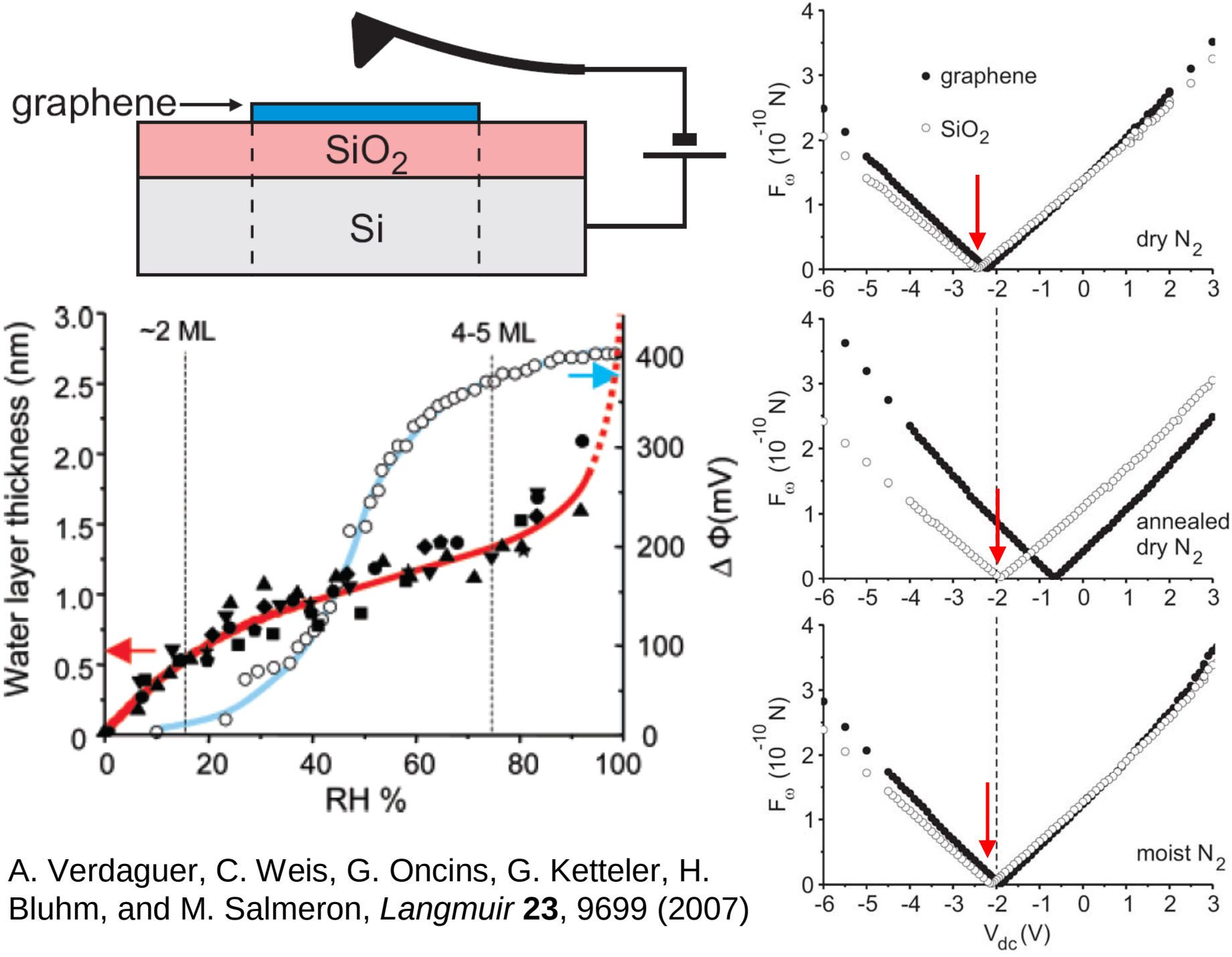
$$F_\omega = \frac{\partial C}{\partial z}(V_{dc} - \Delta\phi)V_{ac}$$

tip above SiO_2:

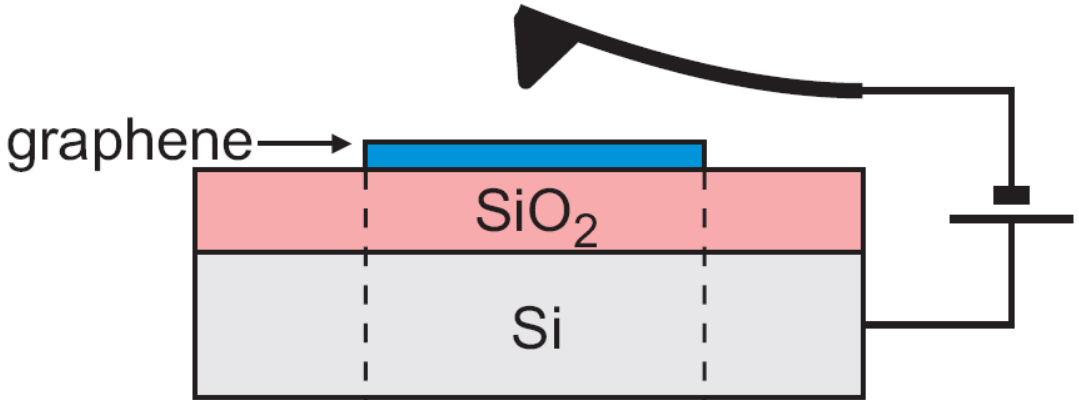
$$\Delta\phi = \phi_{Si}^{no\ graphene} - \phi_{tip}$$

Varies by a few 100mV





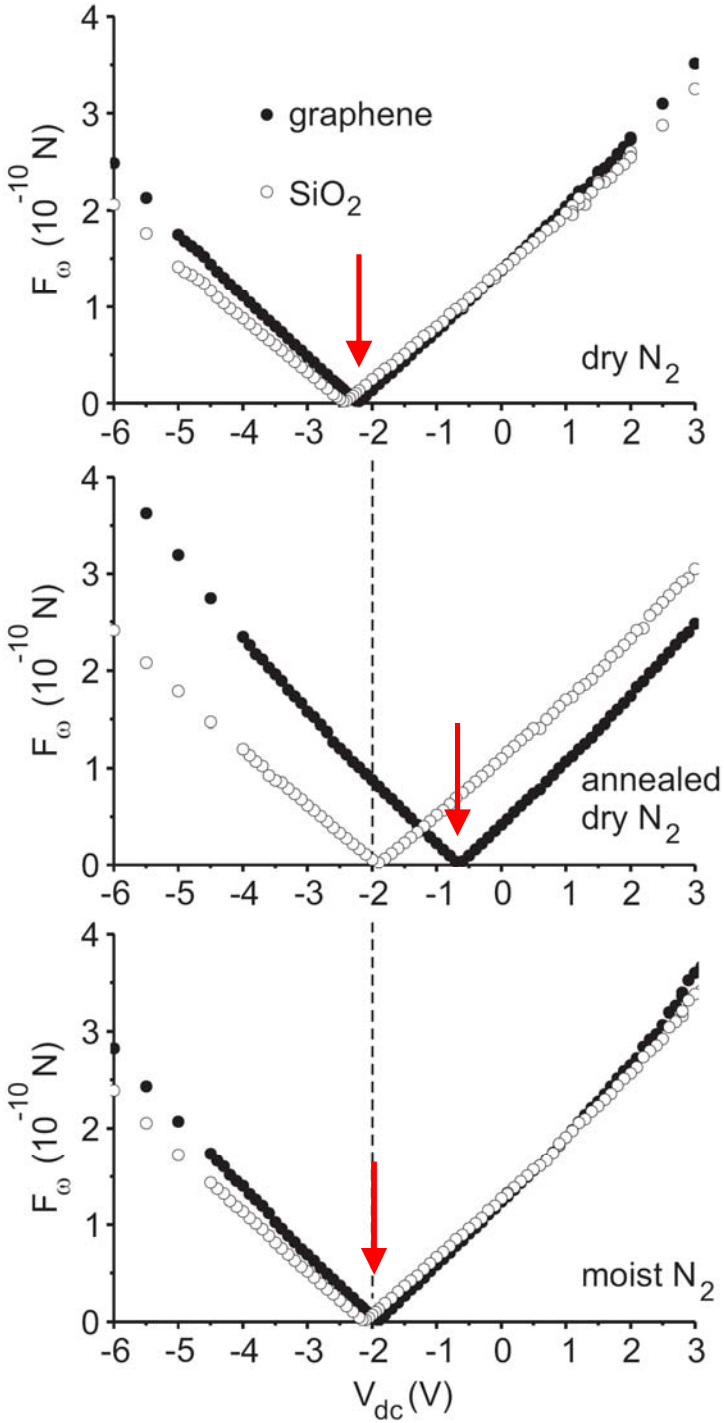
A. Verdaguer, C. Weis, G. Oncins, G. Ketteler, H. Bluhm, and M. Salmeron, *Langmuir* **23**, 9699 (2007)



$$F_\omega = \frac{\partial C}{\partial z}(V_{dc} - \Delta\phi)V_{ac}$$

tip above graphene:

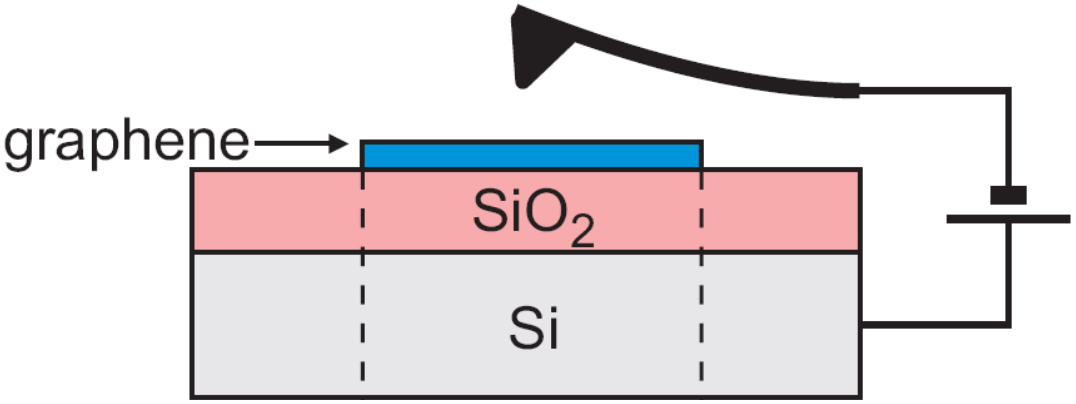
$$\Delta\phi = \phi_{Si}^{graphene} - \phi_{tip}$$



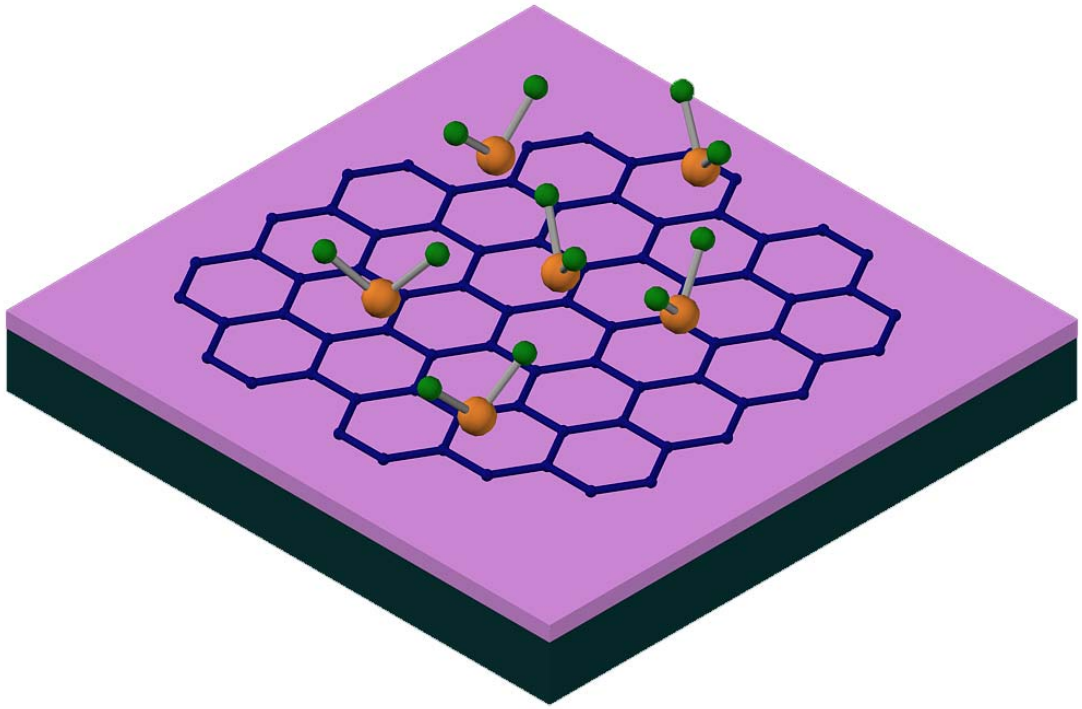
What's in $\Delta\phi$?

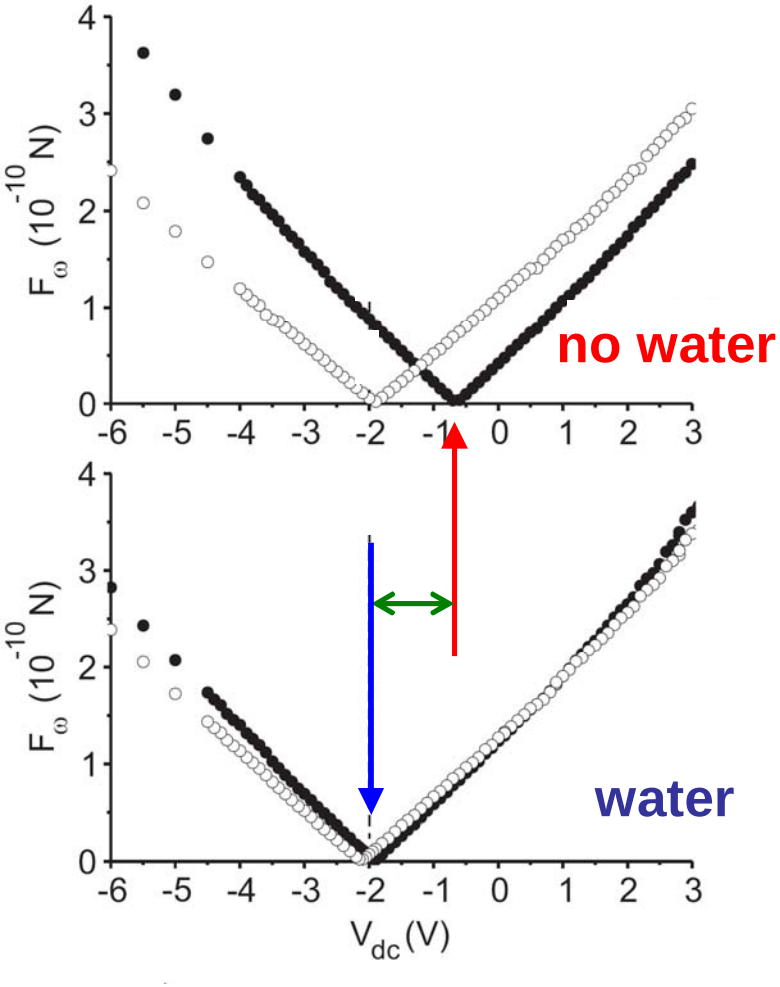
$$\phi_{Si}^{graphene} = W_{Si} + \chi^{graphene}$$

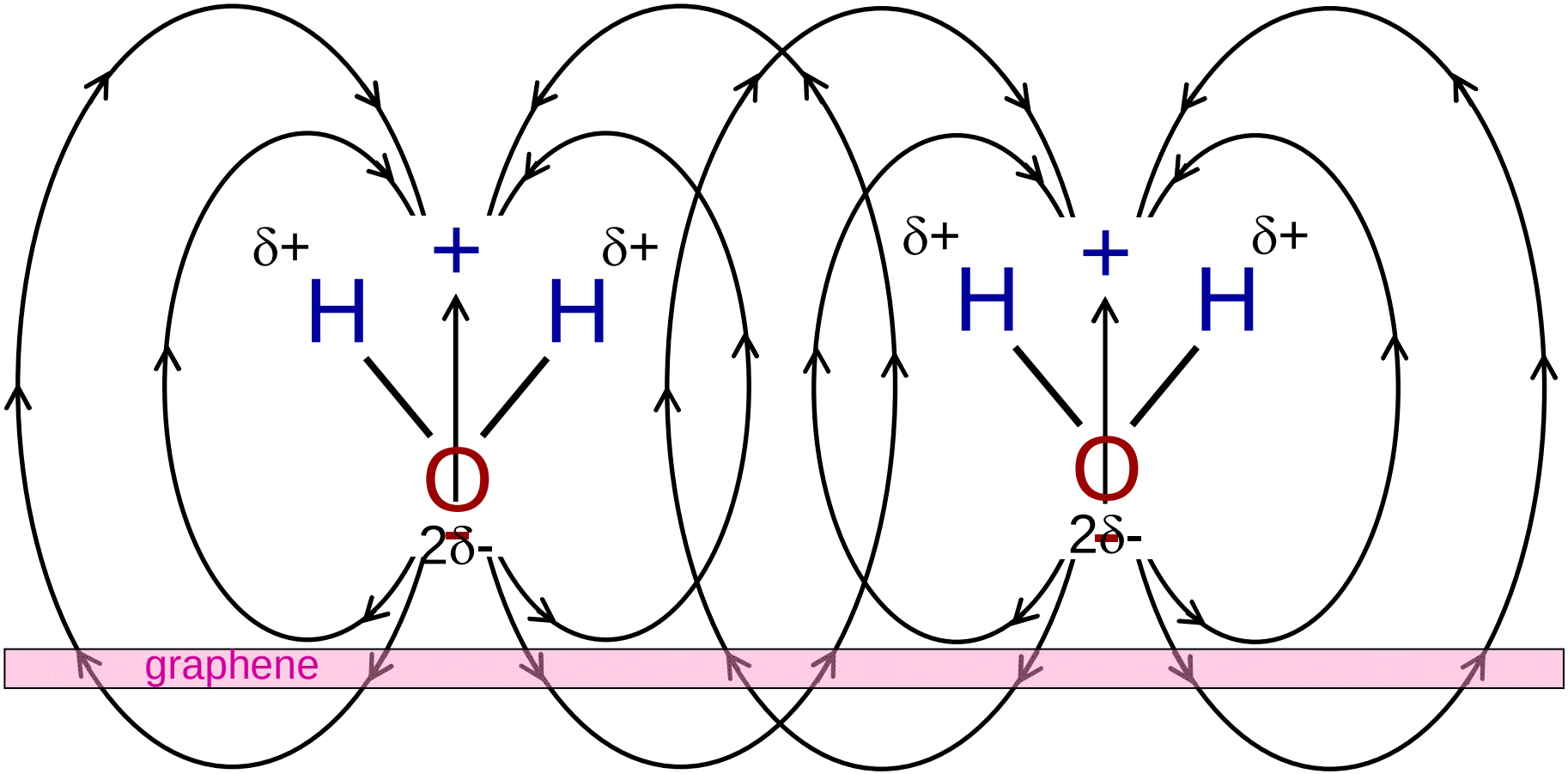
$$\phi_{Si}^{no\ graphene} = W_{Si} + \chi^{no\ graphene}$$



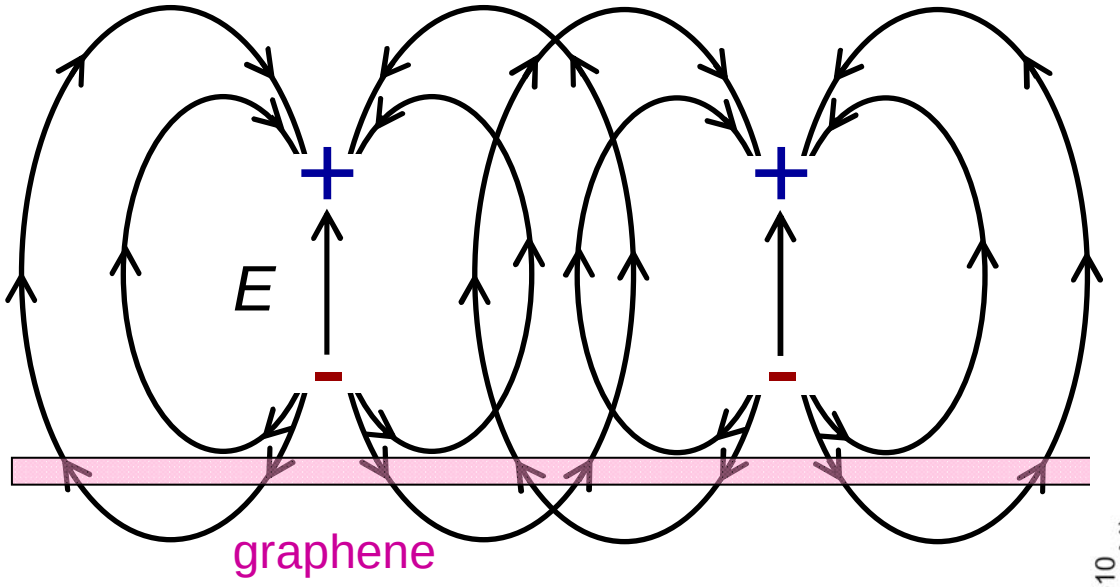
difference in $\Delta\phi$ *comes from influence of water on* $\chi^{graphene}$



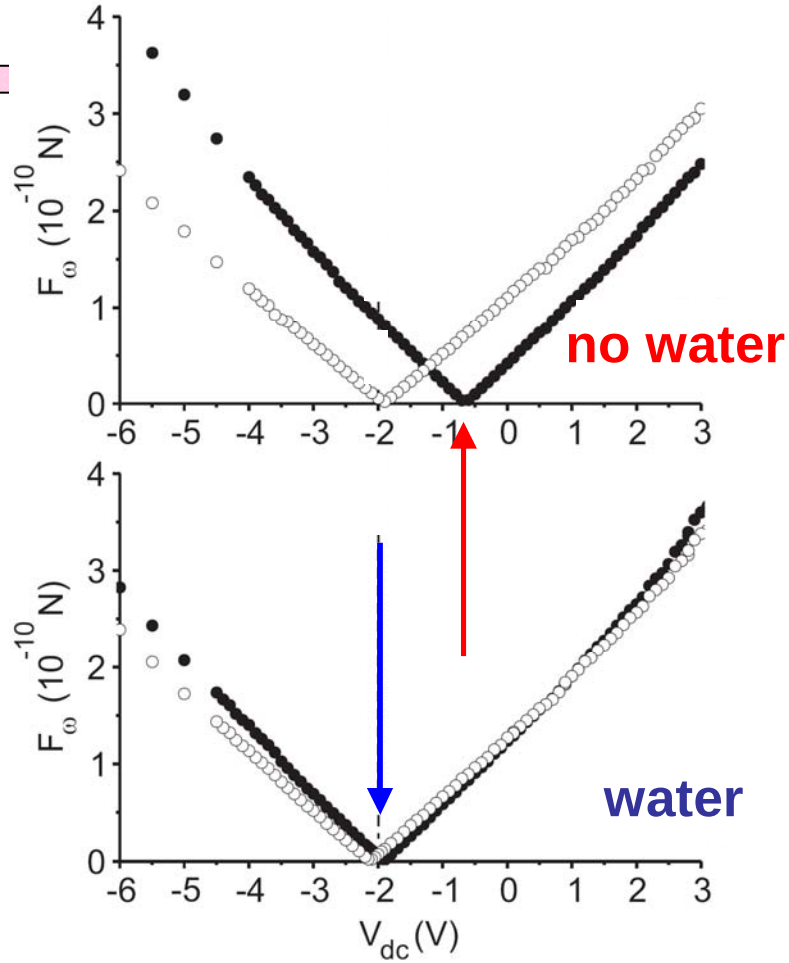


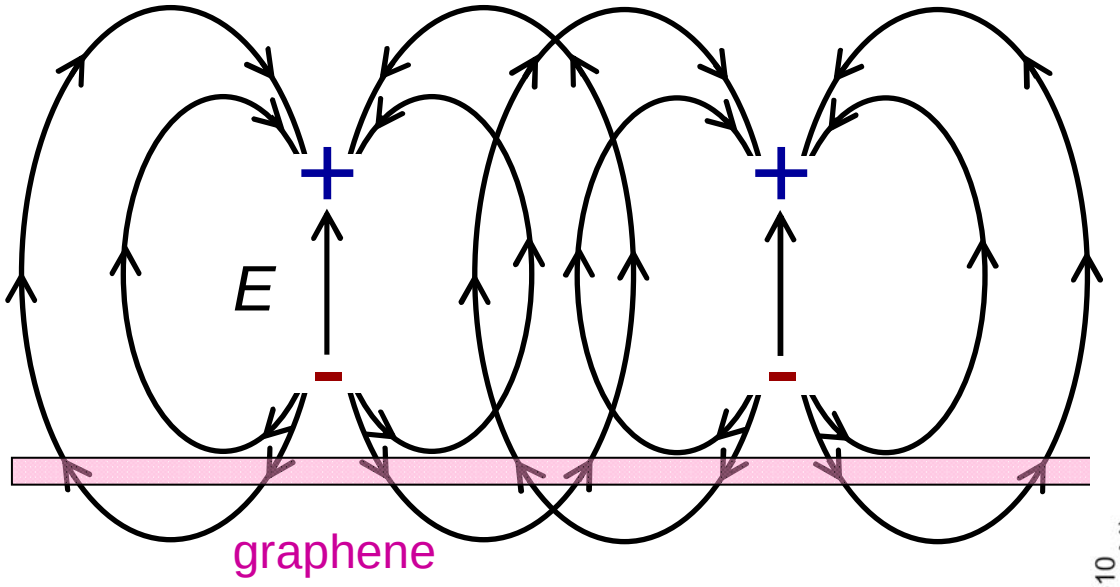


- Electric field vanishes rapidly far from dipole layer
- Inhomogeneous charge distribution at the Dirac point

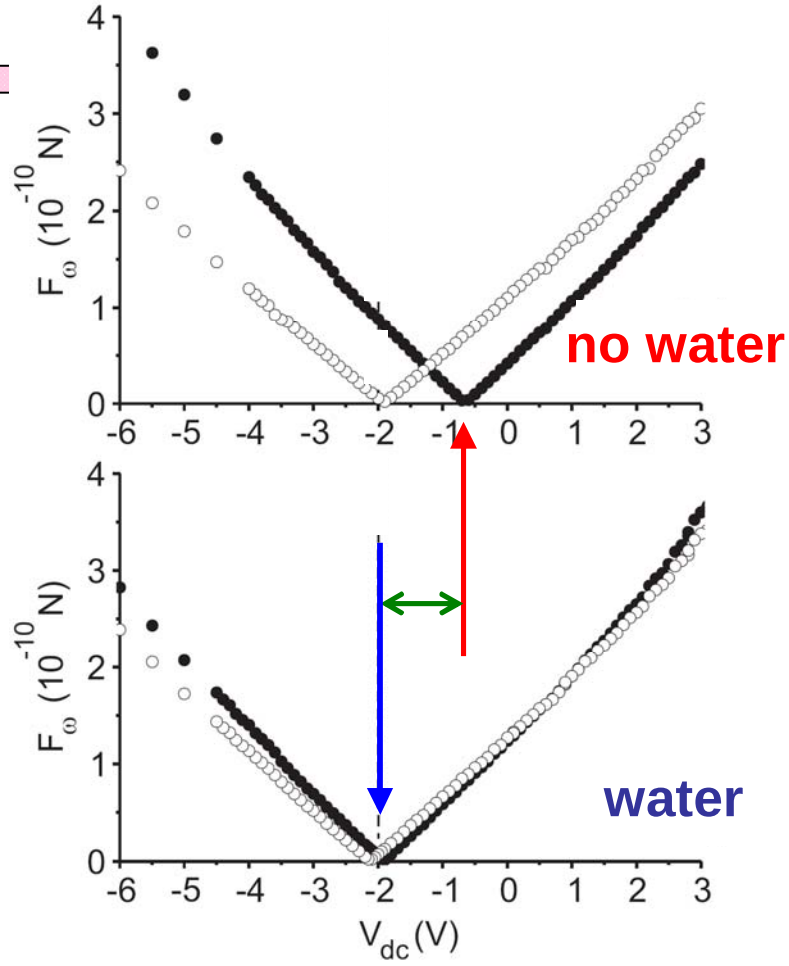


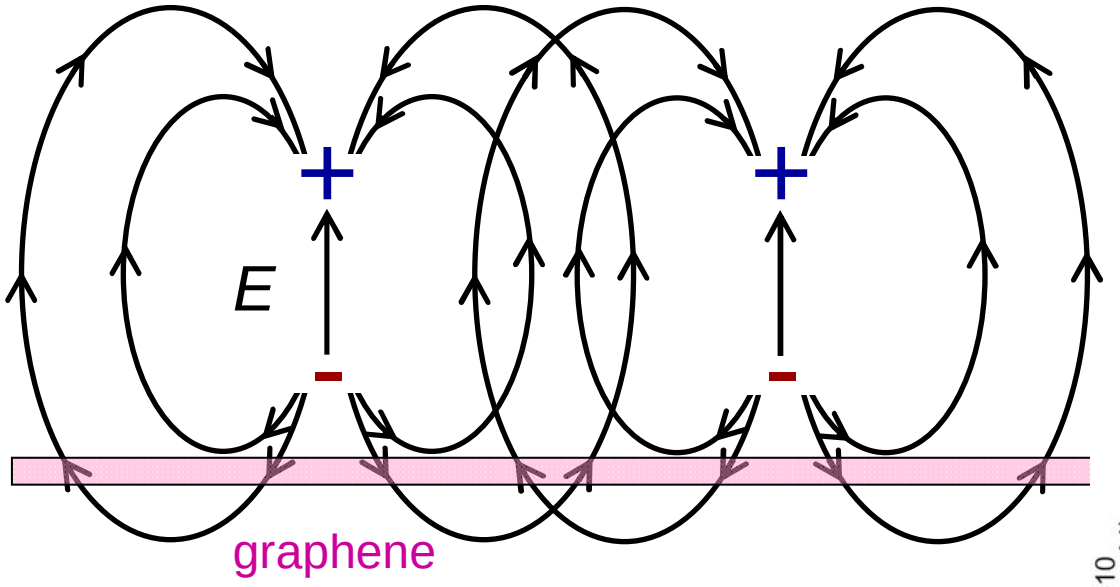
$$E \simeq \Delta\chi^{graphene}/d$$



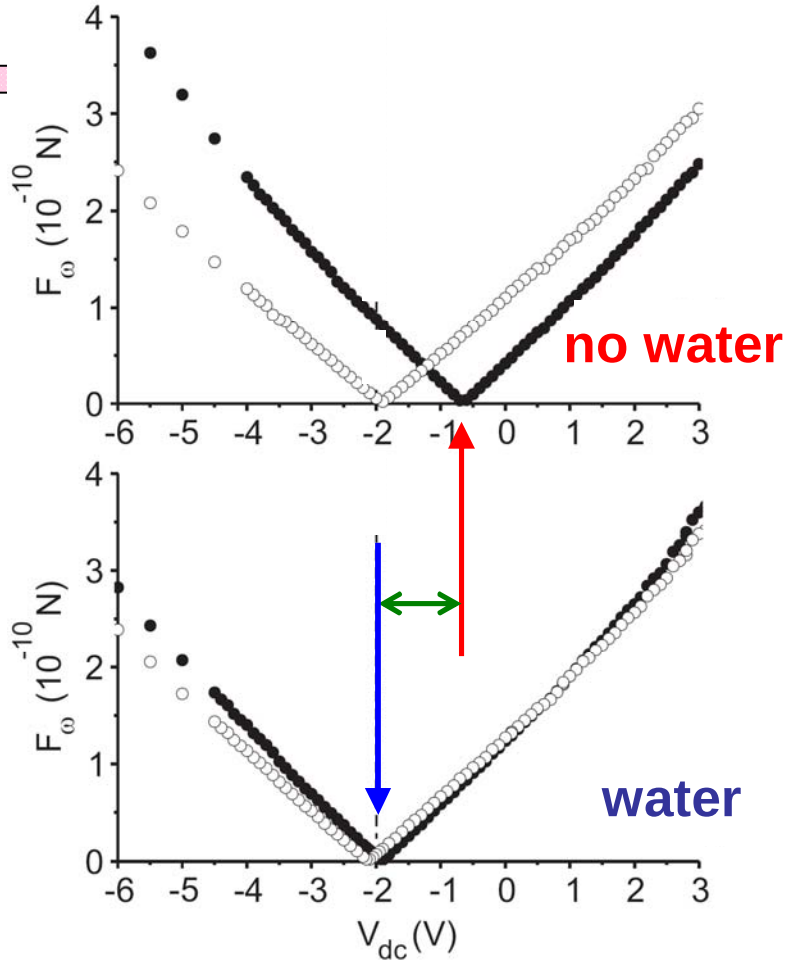


$$E \simeq \Delta\chi^{graphene}/d$$





$$E \simeq \Delta\chi^{graphene}/d \simeq 10^9\ \mathrm{V}\cdot\mathrm{m}^{-1}$$



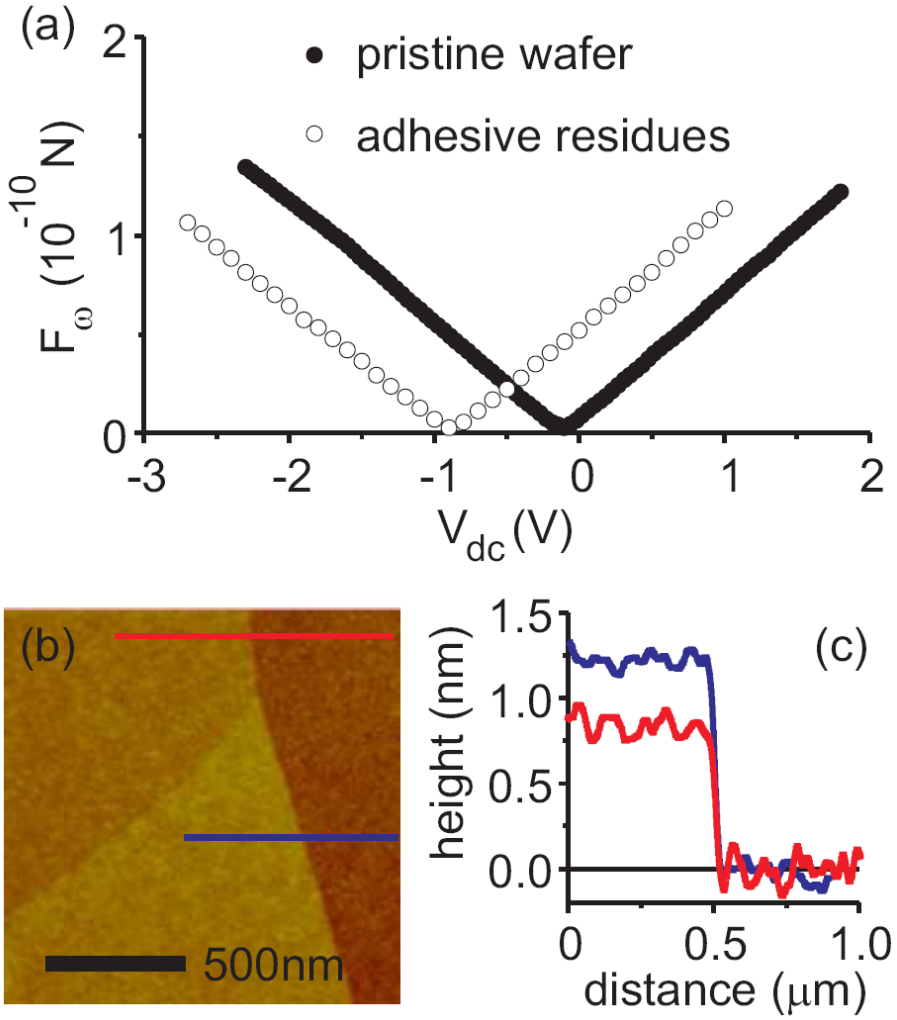
More about water on graphene:

Tuning the effective fine structure constant in graphene: opposing effects of dielectric screening on short- and long-range potential scattering
C. Jang, S. Adam, J.-H. Chen, E. D. Williams, S. Das Sarma, and M. S. Fuhrer
arXiv:0805.3780

Detection of individual gas molecules adsorbed on graphene
F. Schedin, A. K. Geim, S. V. Morozov, E. W. Hill, P. Blake, M. I. Katsnelson, and D. K. S. Novoselov
Nature Material 6, 652 (2007)

Electrostatic interactions between graphene layers and their environment
J. Sabio, C. Seoánez, S. Fratini, F. Guinea, A. H. Castro Neto, and F. Sols
Phys. Rev. B 77, 195409 (2008)

Other possible contaminant: adhesive residues



Unavoidable contaminants: nanofabrication residues

M. Ishigami, J. H. Chen, W. G. Cullen, M. S. Fuhrer, and E. D. Williams
Nano Lett. 7, 1643 (2007).

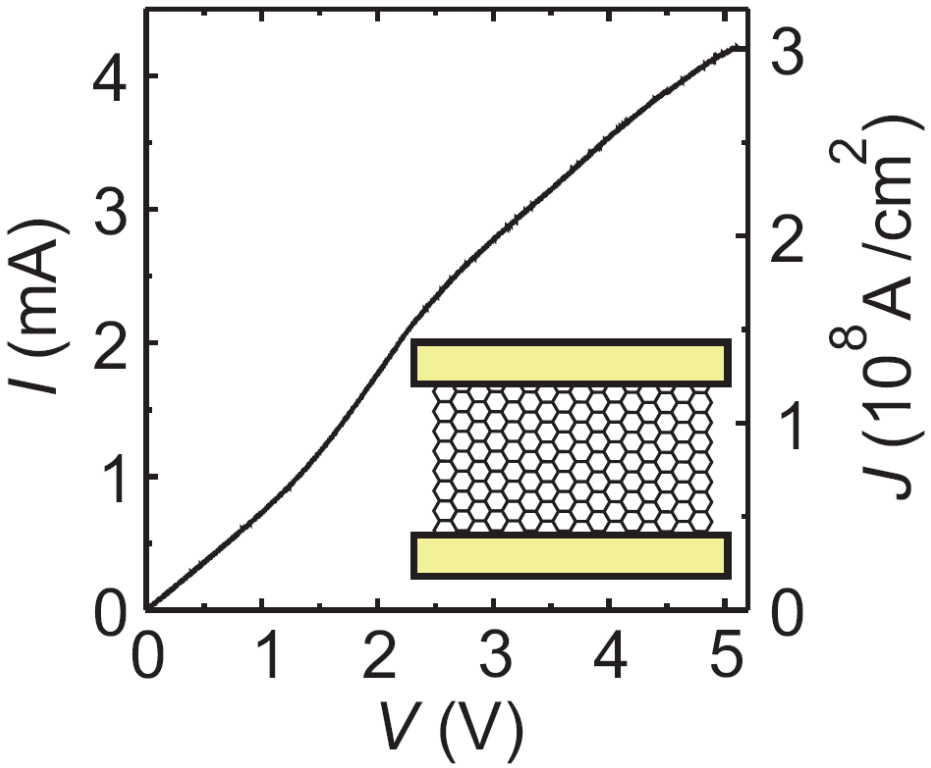
E. Stolyarova, K. T. Rim, S. Ryu, J. Maultzsch, P. Kim, L. E. Brus, T. F. Heinz, M. S. Hybertsen, and G. W. Flynn
PNAS 104, 9209 (2007).

Outline:

1) Characterizing contaminants by Electrostatic Force Microscopy (EFM)

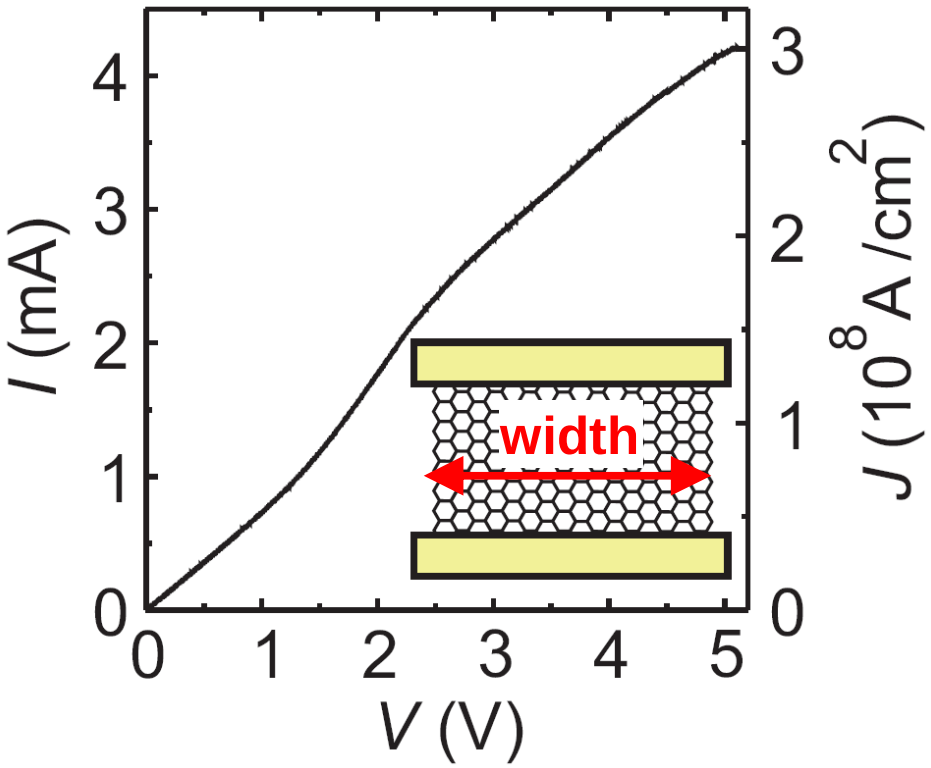
2) Current-induced cleaning (annealing) of graphene

Graphene can sustain very high current densities



Saturates at $J \sim 10^9$ A/cm^2
(like in metallic SWCNT)

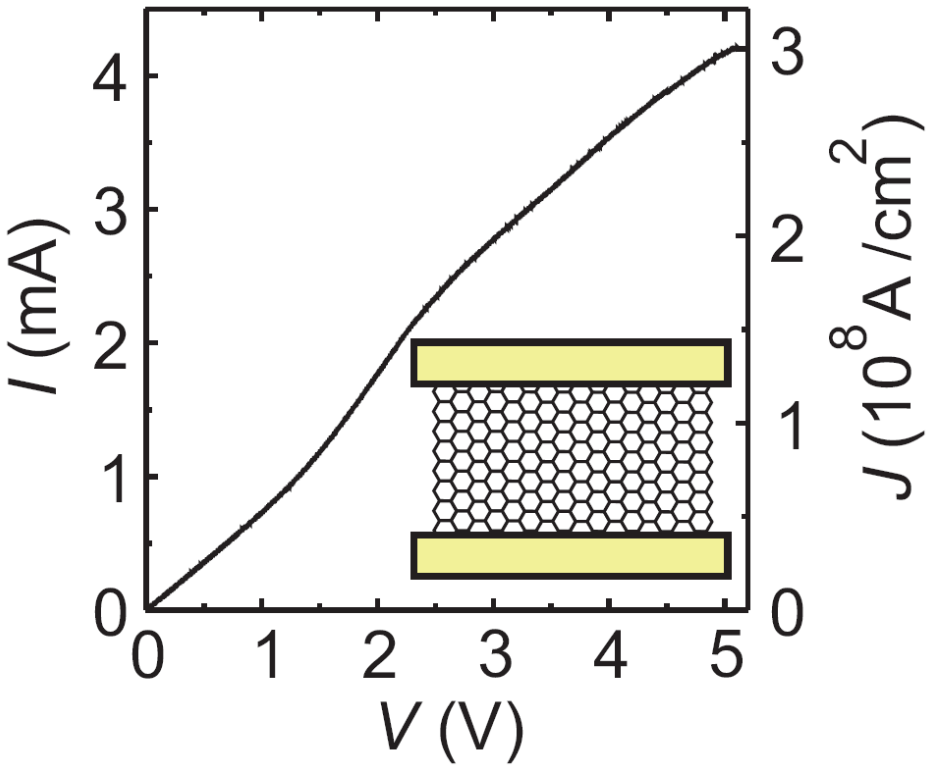
Graphene can sustain very high current densities

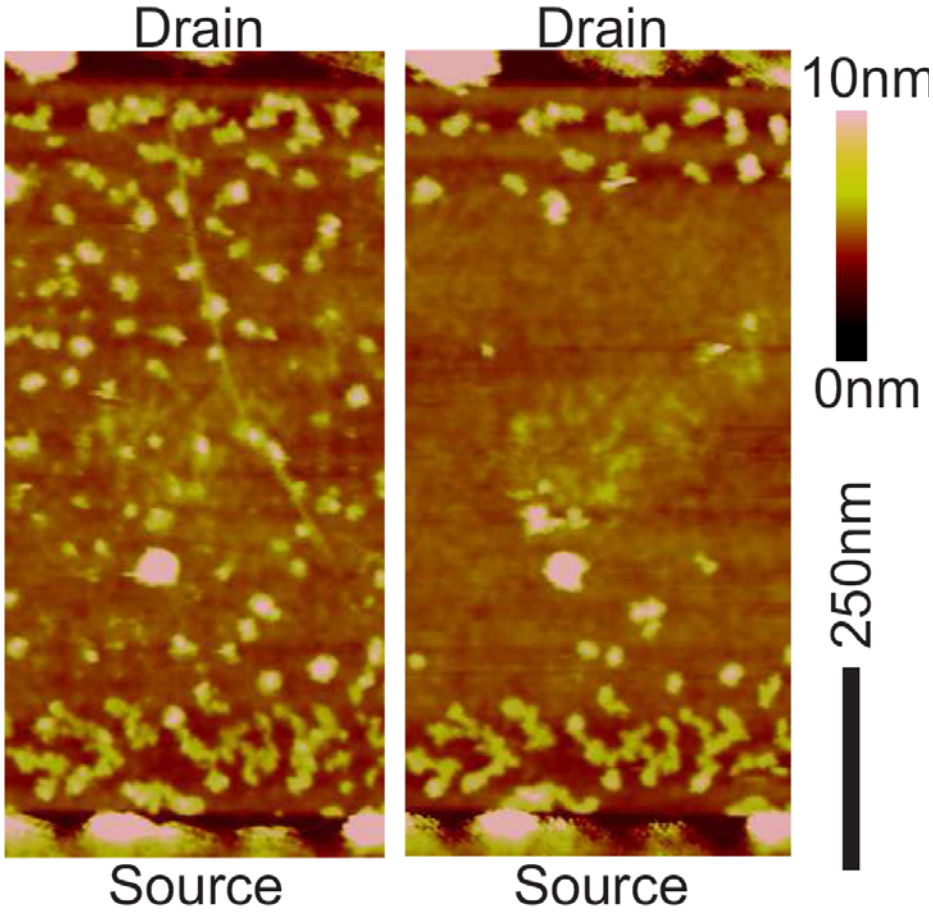


Saturates at $J \sim 10^9$ A/cm^2
(like in metallic SWCNT)

that is $J \sim \mu$A/nm

High heat melts CdSe particles away



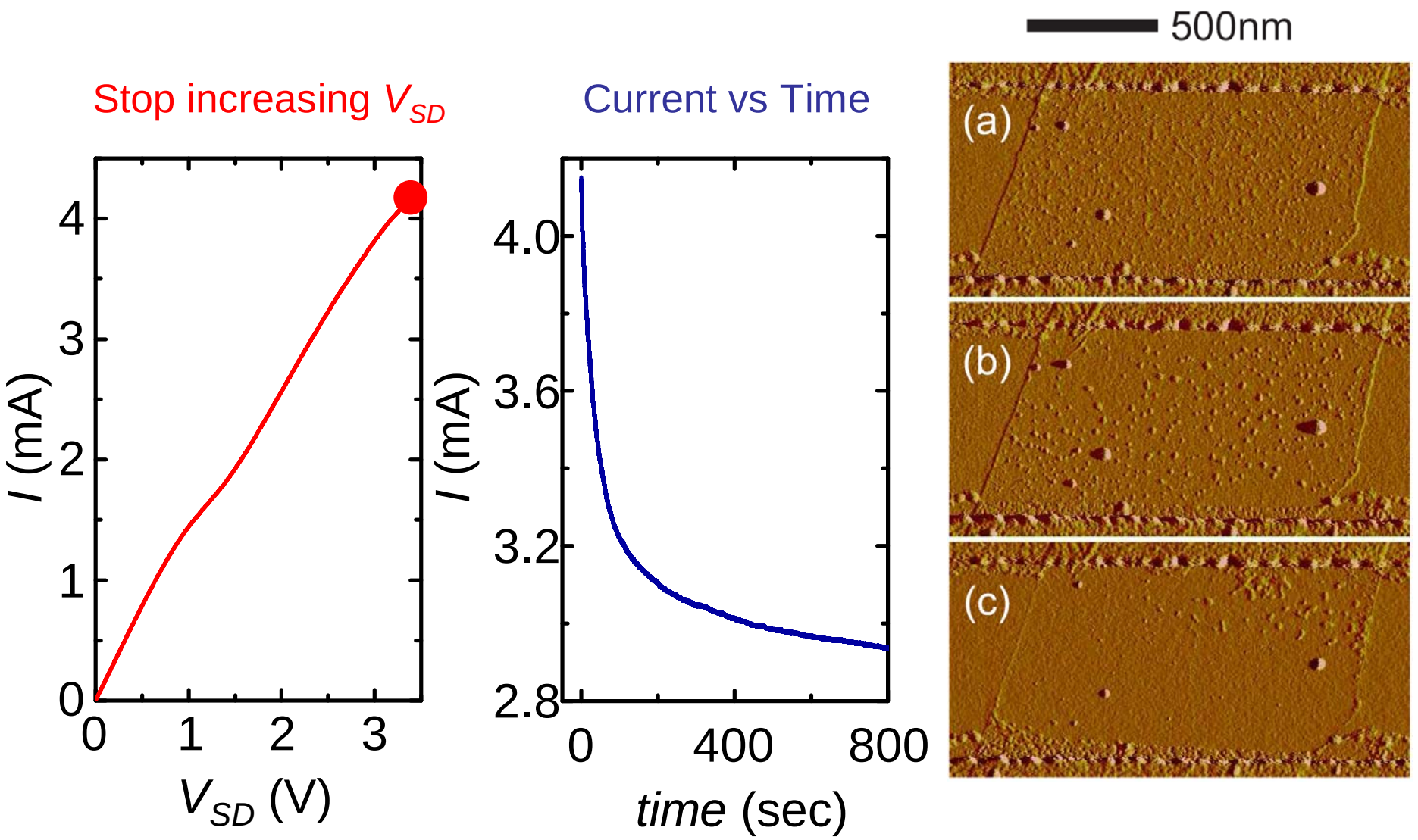


before

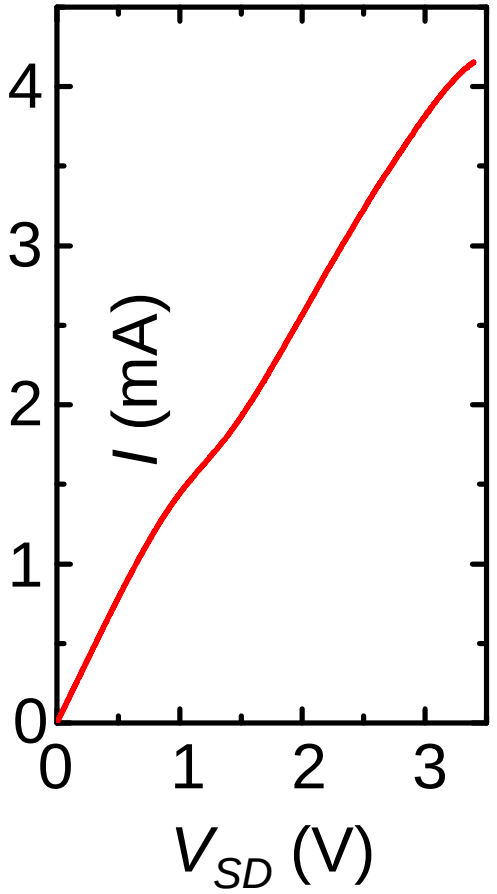
after

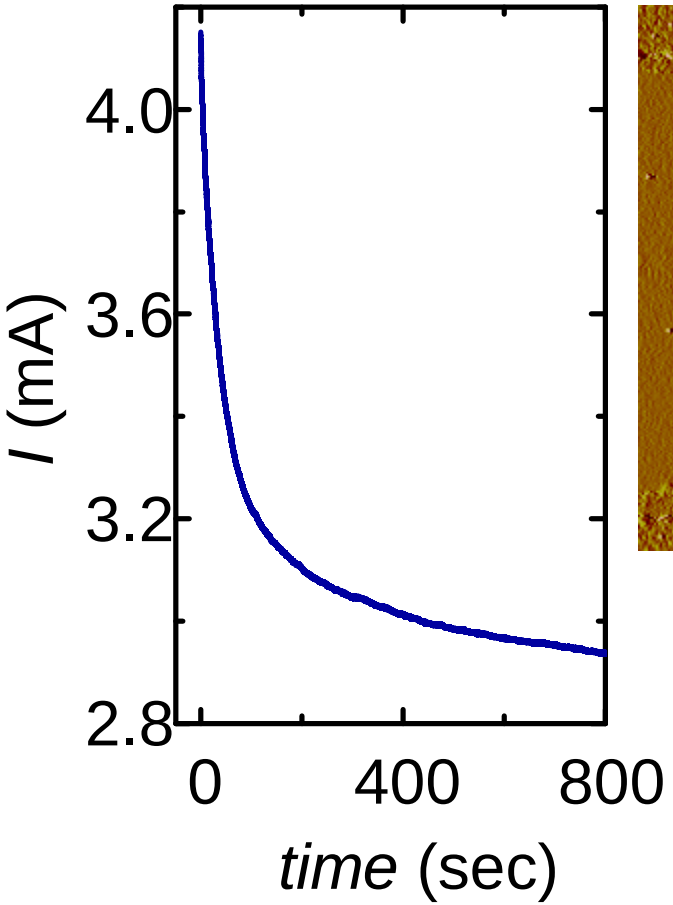
Current-induced cleaning technique

PMMA residues
melt away

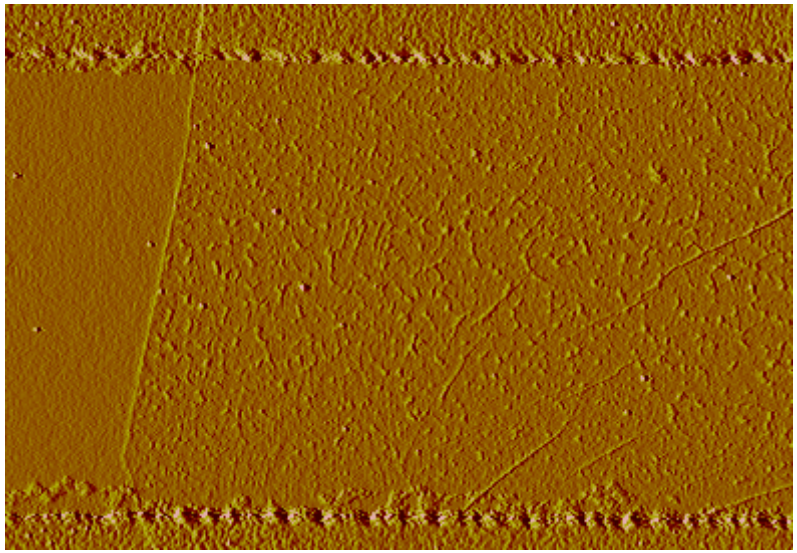


Current-induced cleaning technique

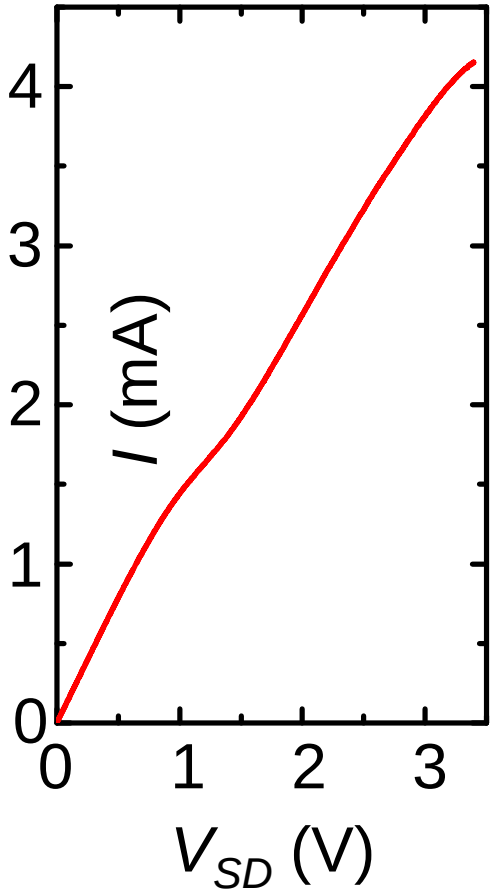


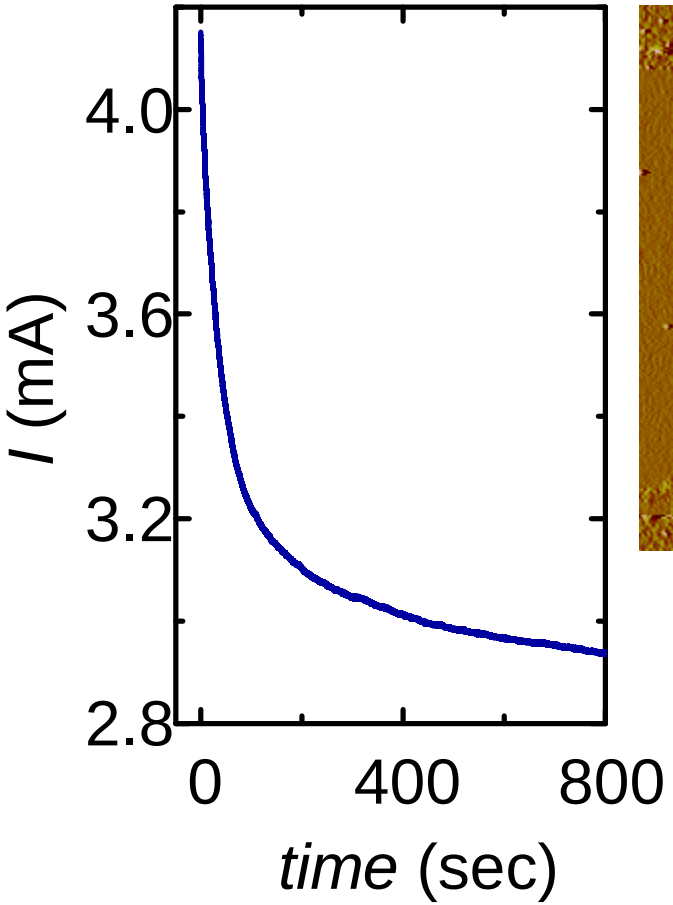


Another possible cleaning mechanism: *electro-migration*

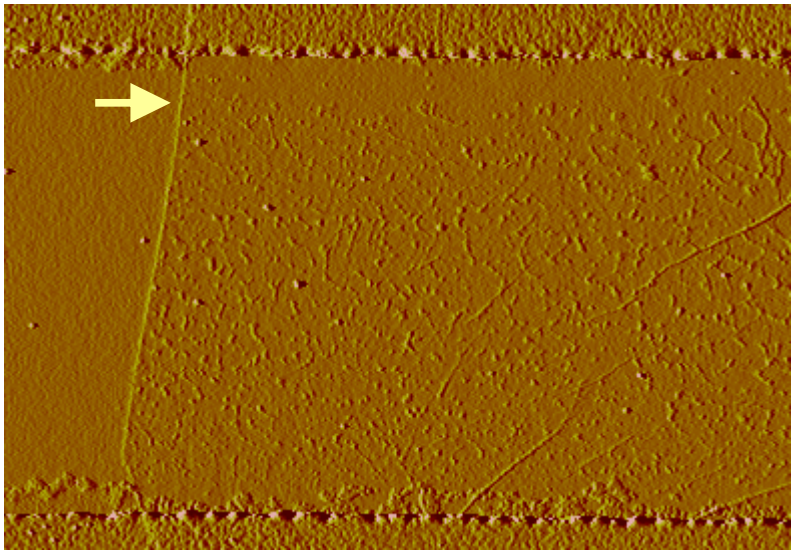


Current-induced cleaning technique

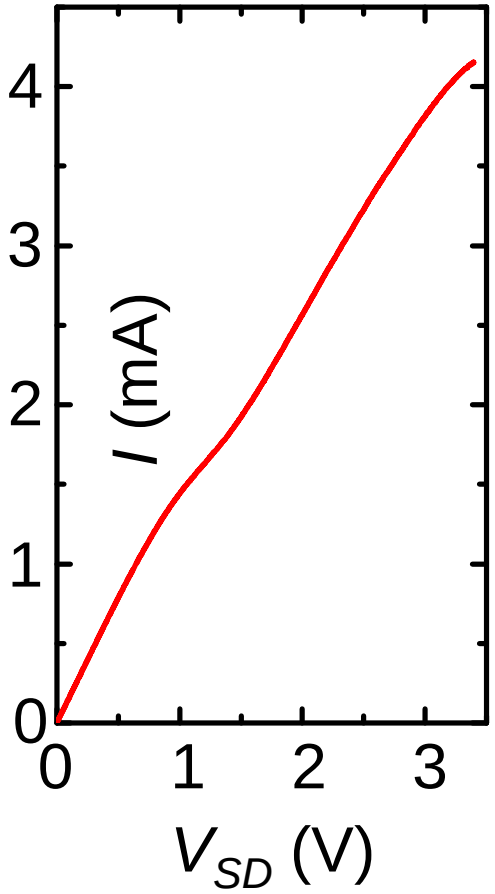


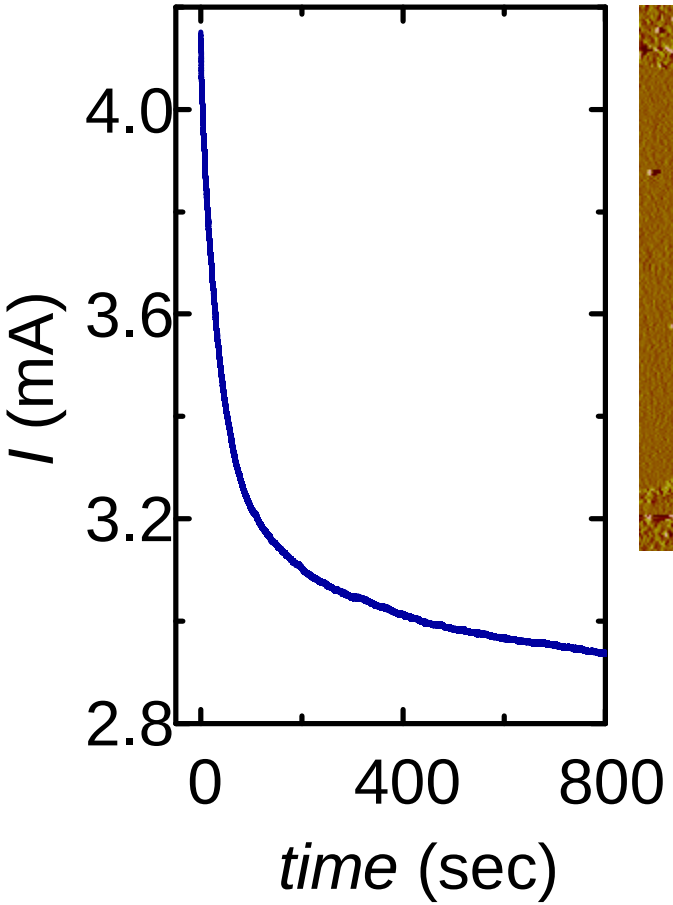


Another possible cleaning mechanism: *electro-migration*

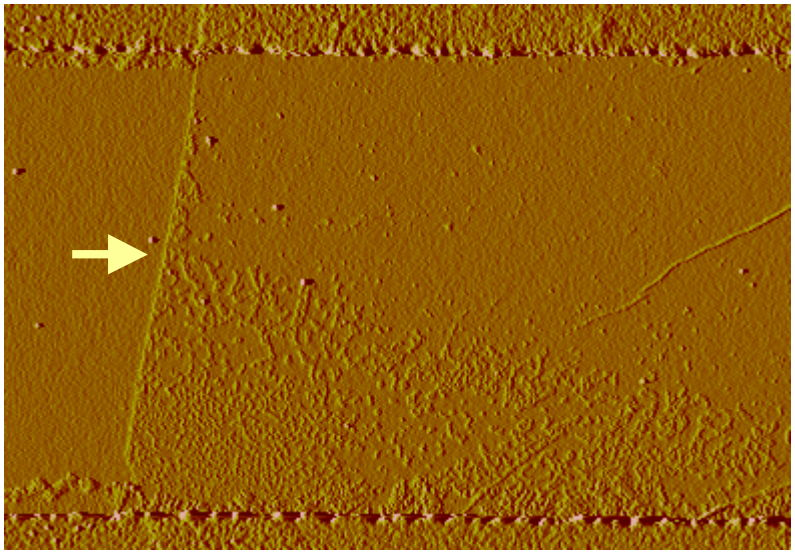


Current-induced cleaning technique

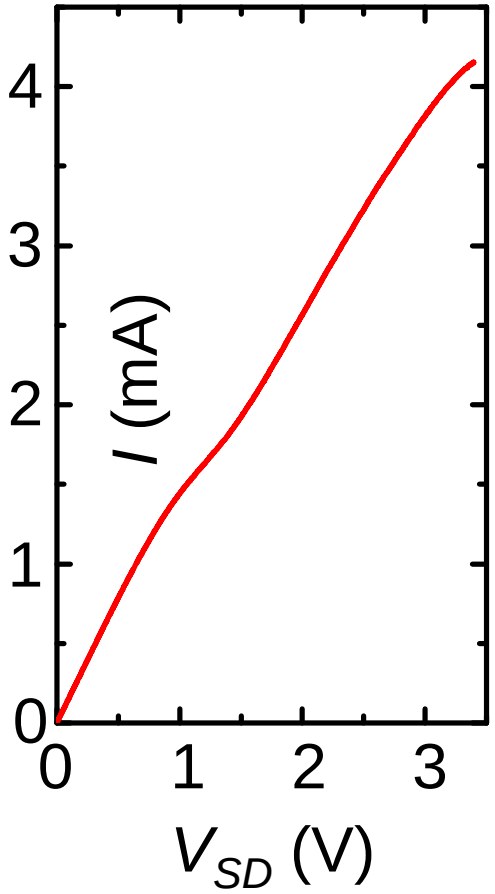


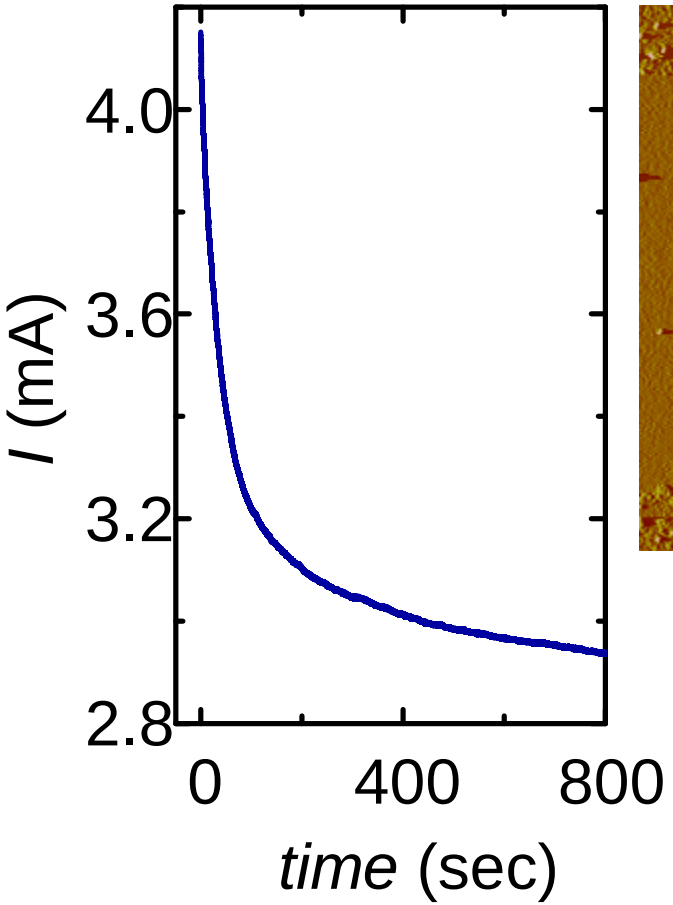


Another possible cleaning mechanism: *electro-migration*

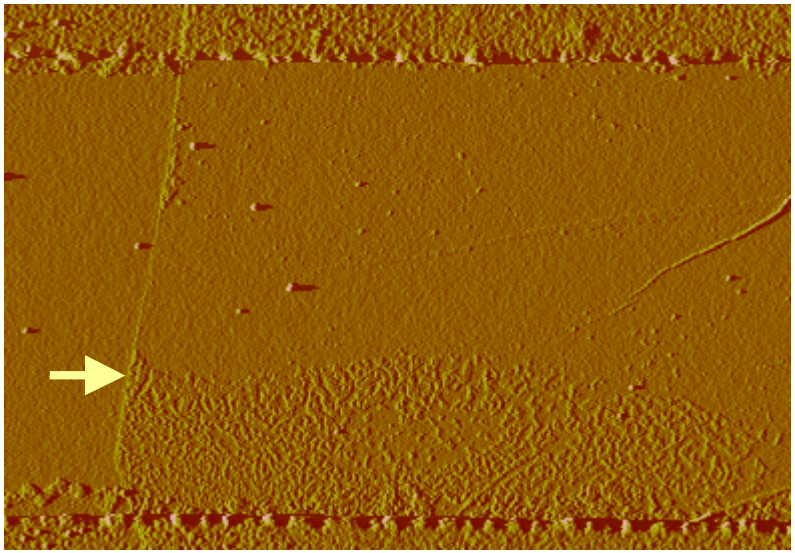


Current-induced cleaning technique

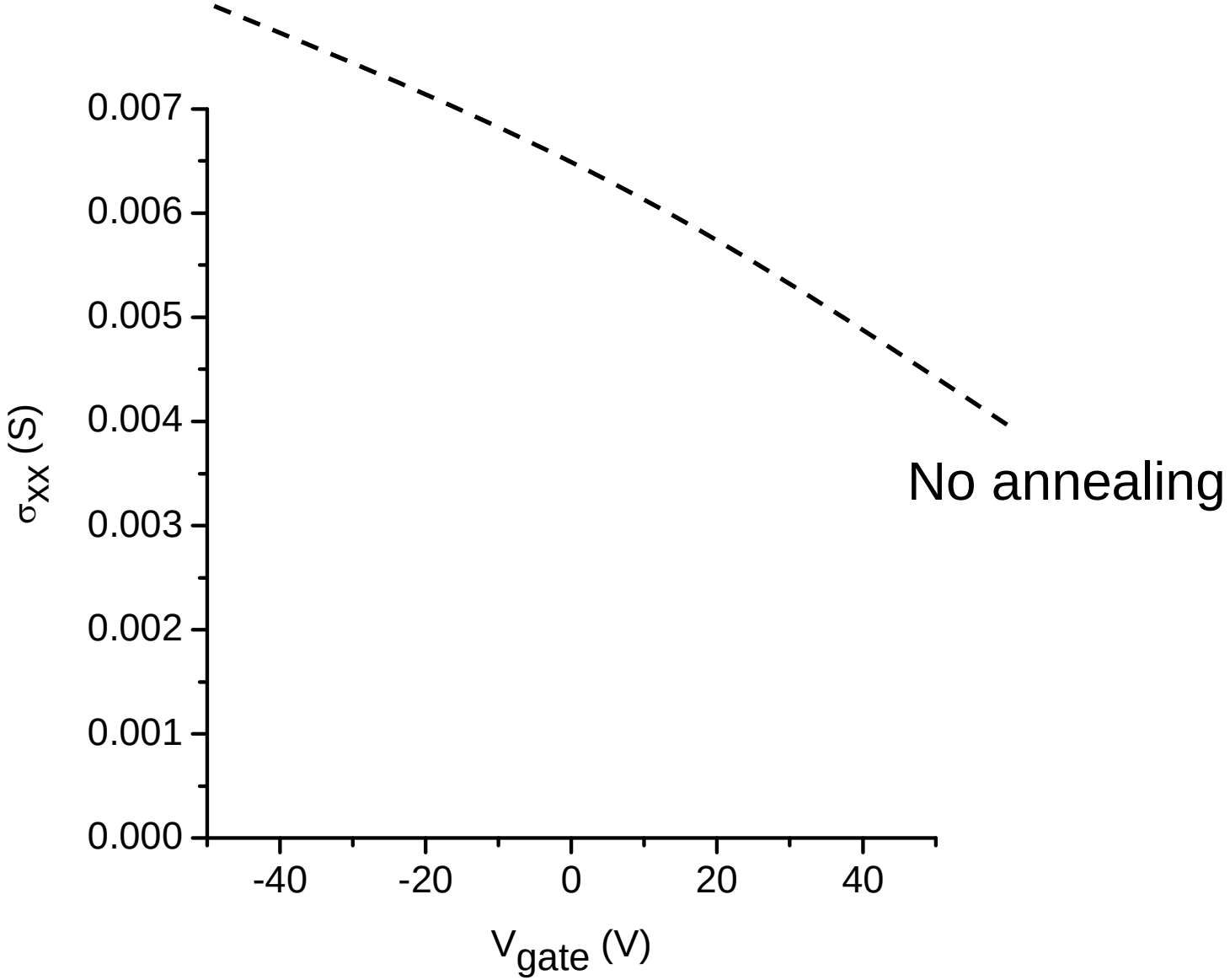




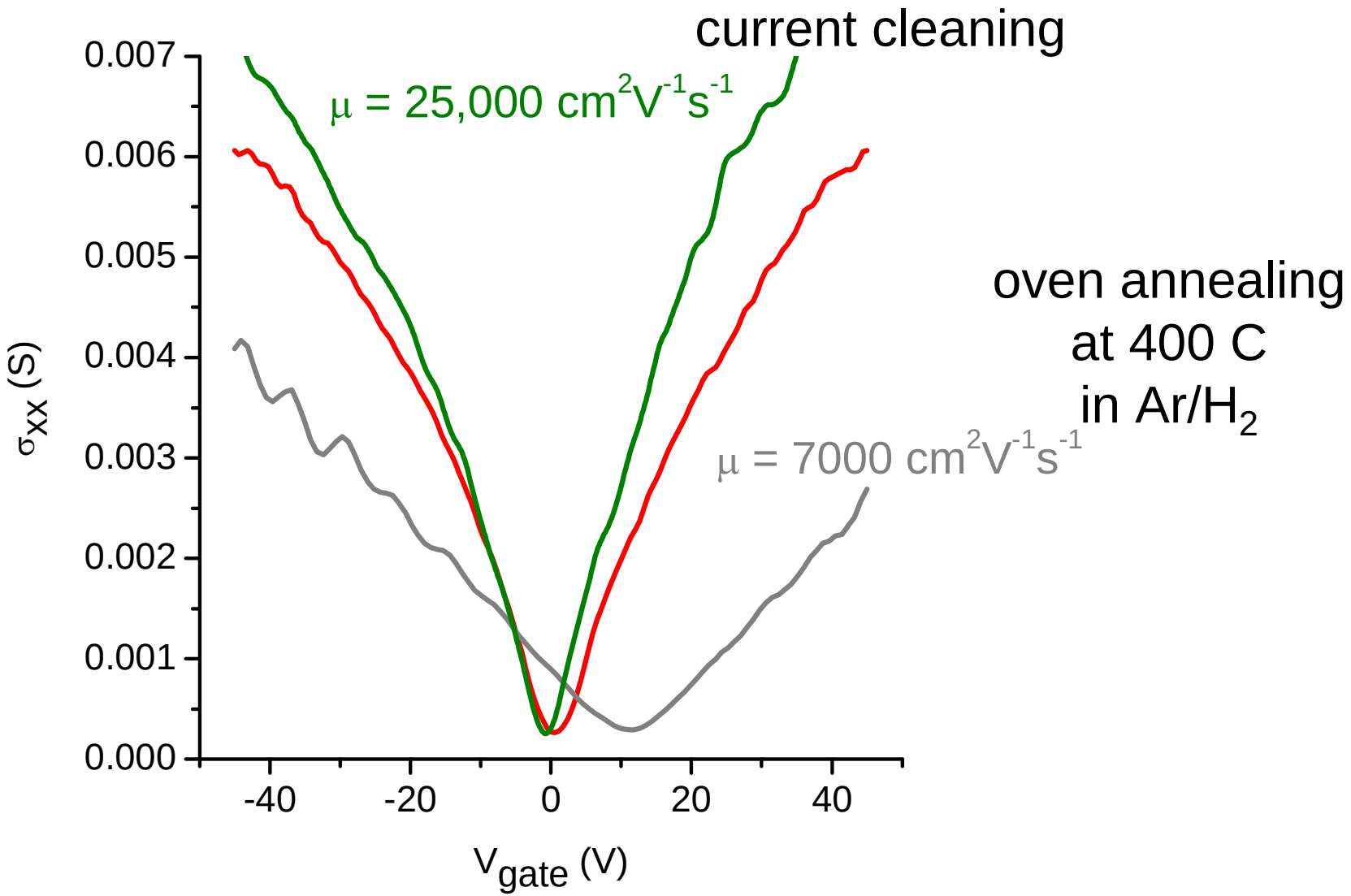
Another possible cleaning mechanism: *electro-migration*



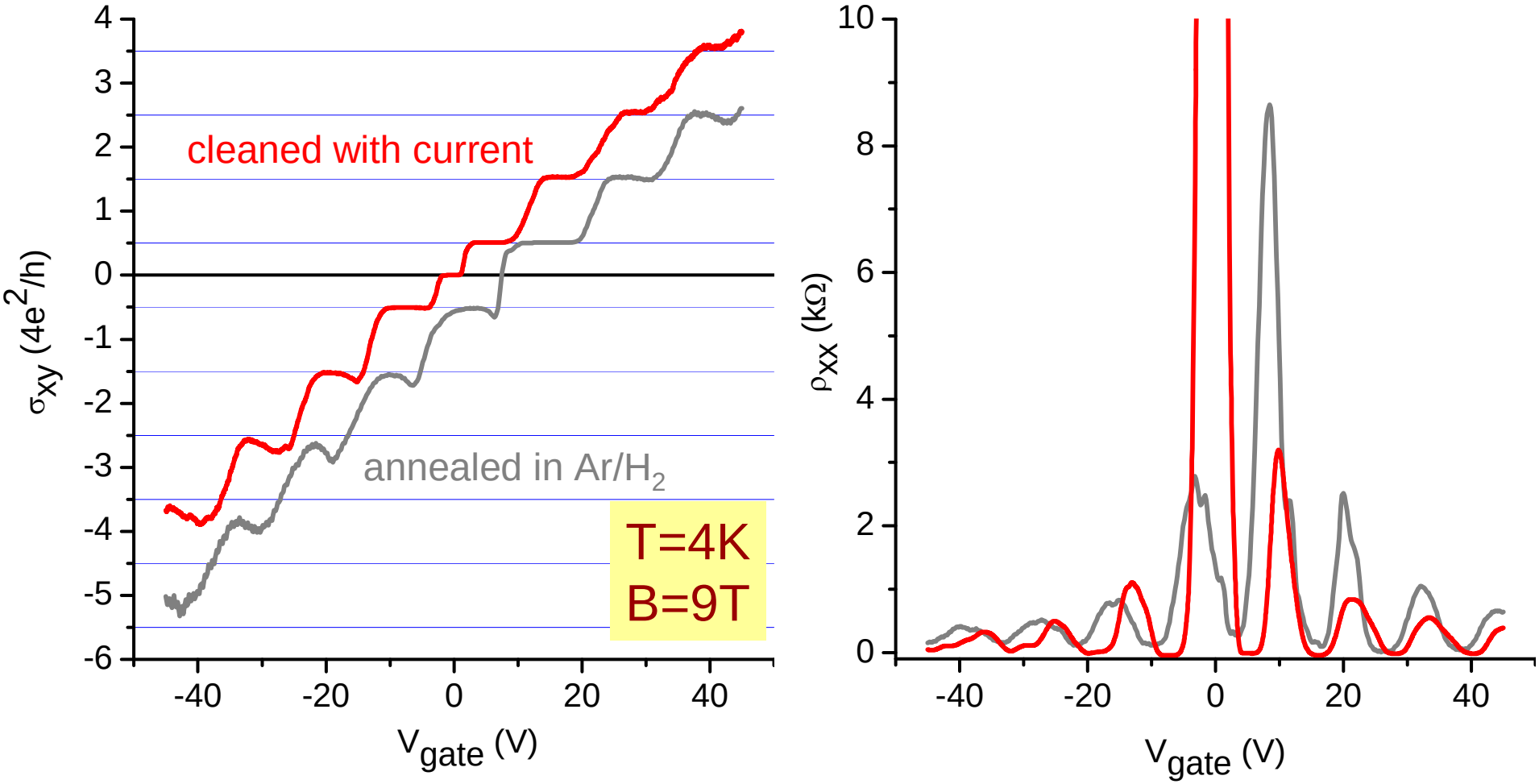
Influence on doping **and** mobility



Influence on doping **and** mobility



A. Barreiro, et al., work in progress



ν=0 plateau: high quality samples

- Y. Zhang, Z. Jiang, J. P. Small, M. S. Purewal, Y.-W. Tan, M. Fazlollahi, J. D. Chudow, J. A. Jaszczak, H. L. Stormer, and P. Kim, **PRL 96, 136806 (2006).**
- D. A. Abanin, K. S. Novoselov, U. Zeitler, P. A. Lee, A. K. Geim, and L. S. Levitov, **PRL 98, 196806 (2007).**
- Z. Jiang, Y. Zhang, H. L. Stormer, and P. Kim, **PRL 99, 106802 (2007).**

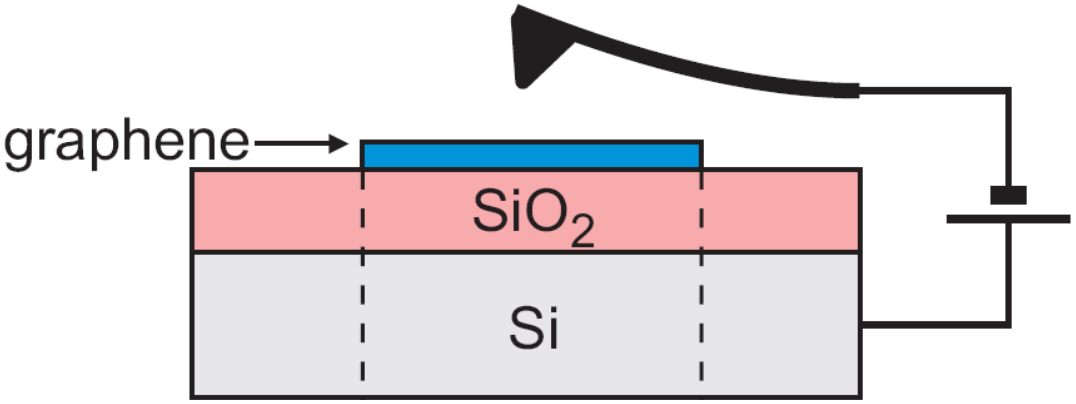
Conclusion

1) Electrostatic Force Microscopy: water sticks to graphene

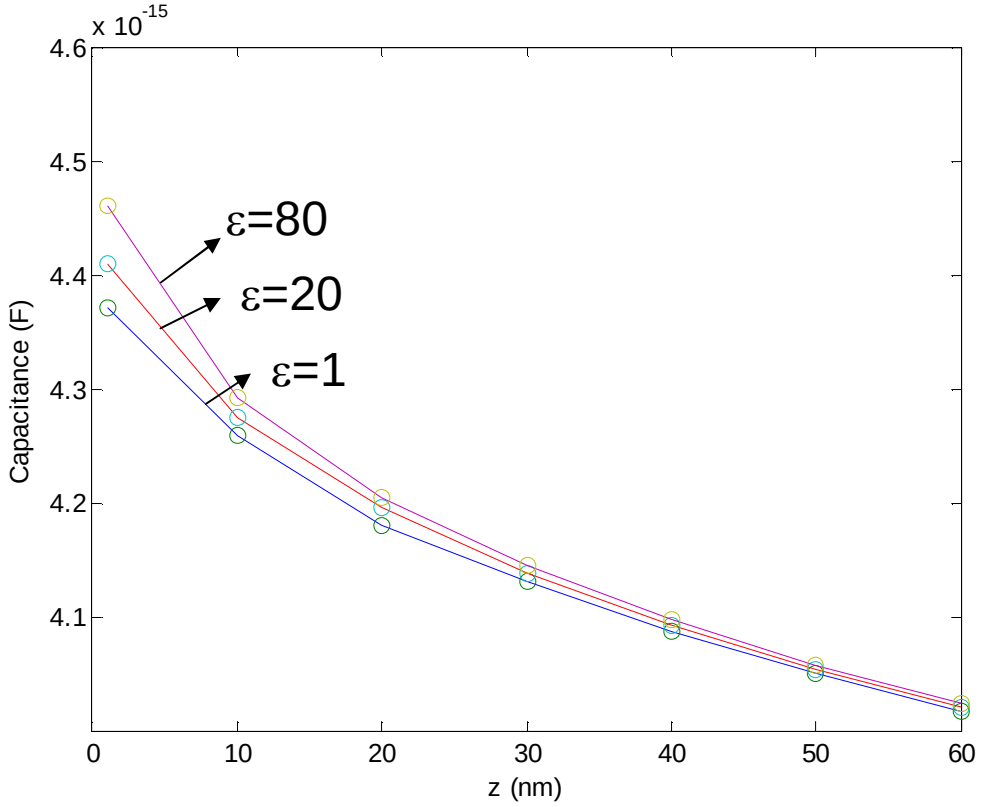
J. Moser, A. Verdaguer, D. Jiménez, A. Barreiro, and A. Bachtold
Appl. Phys. Lett. 92, 123507 (2008)

2) Current-induced cleaning technique: lowers extrinsic doping, improves mobility even for samples in contact with substrate

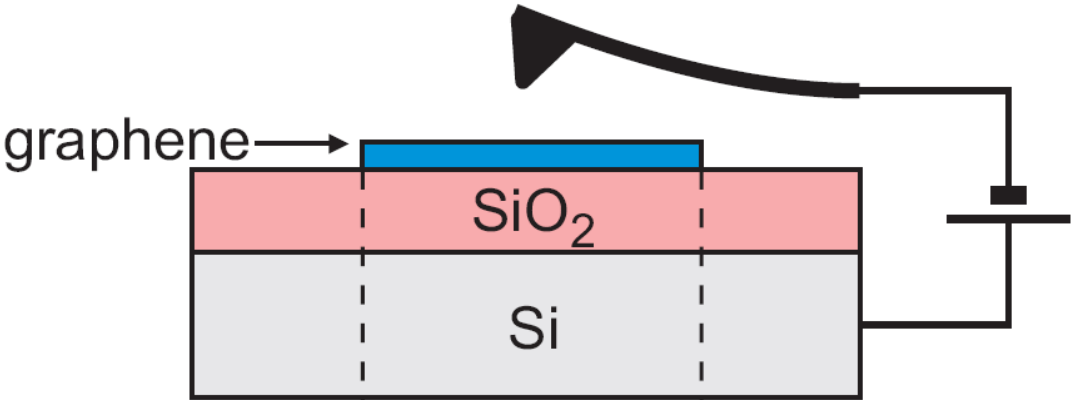
J. Moser, A. Barreiro, and A. Bachtold
Appl. Phys. Lett. 91, 163513 (2007)

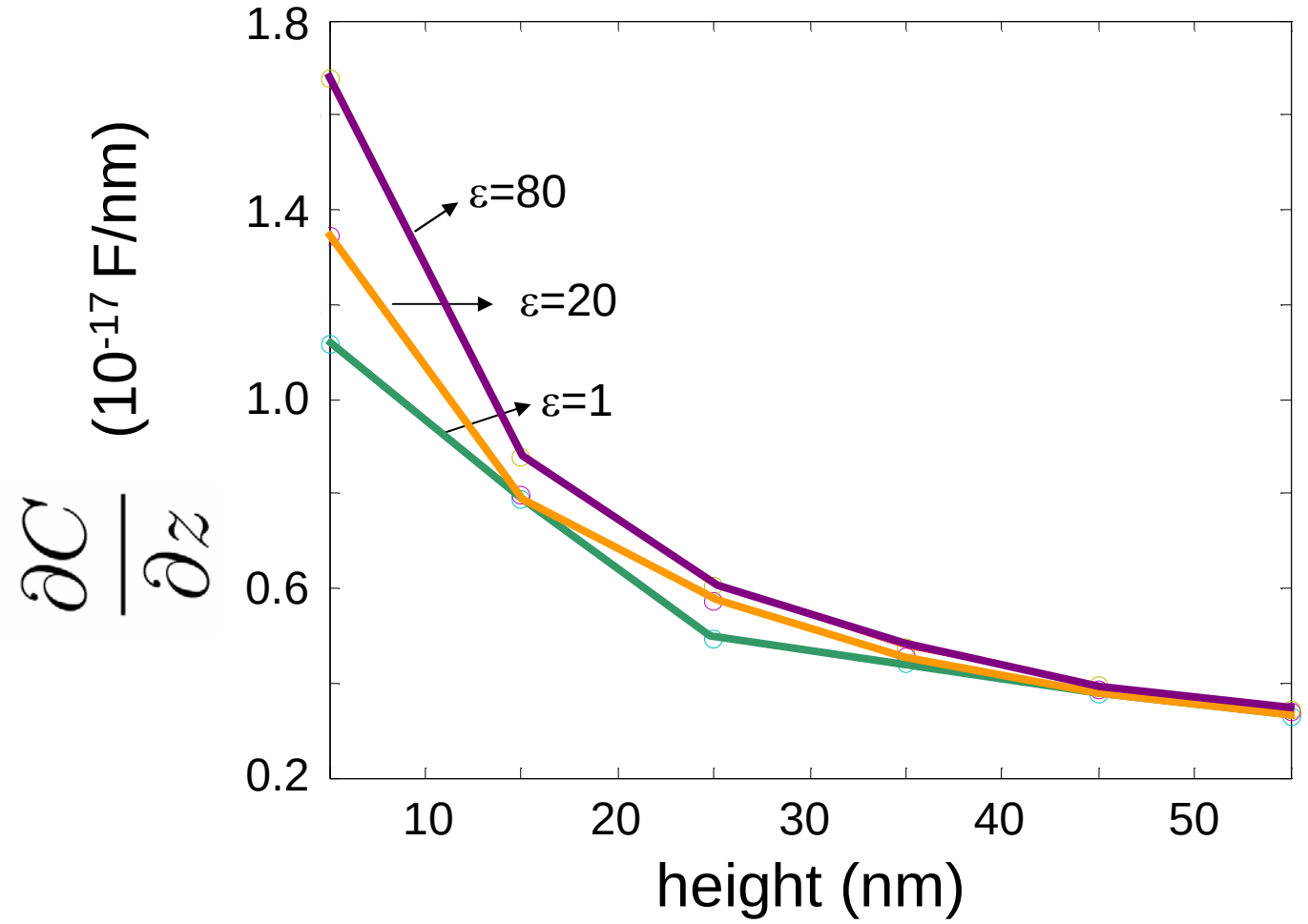

graphene
SiO_2
Si

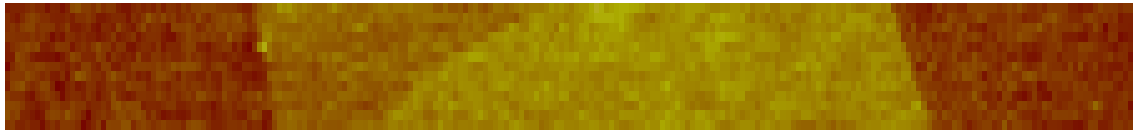
1 nm layer

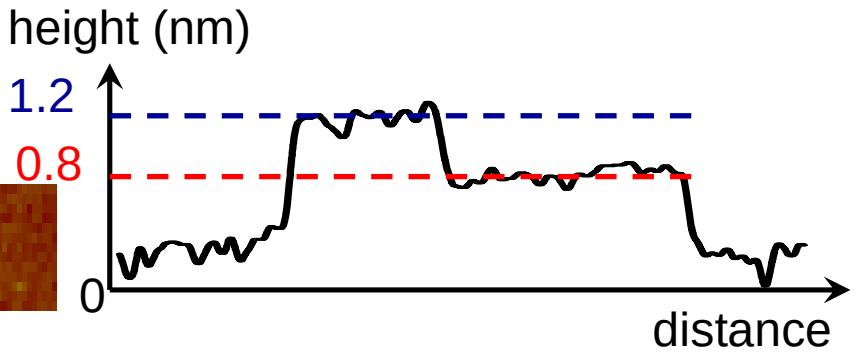

x 10^-15
4.6
4.5
4.4
4.3
4.2
4.1
Capacitance (F)
ε=80
ε=20
ε=1
0
10
20
30
40
50
60
z (nm)

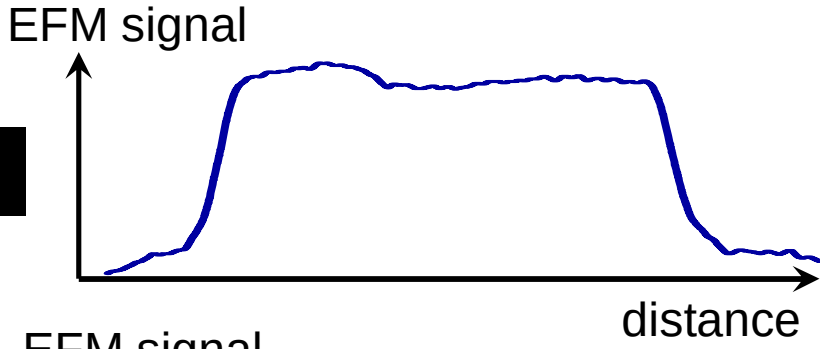
Solving Poisson's equation

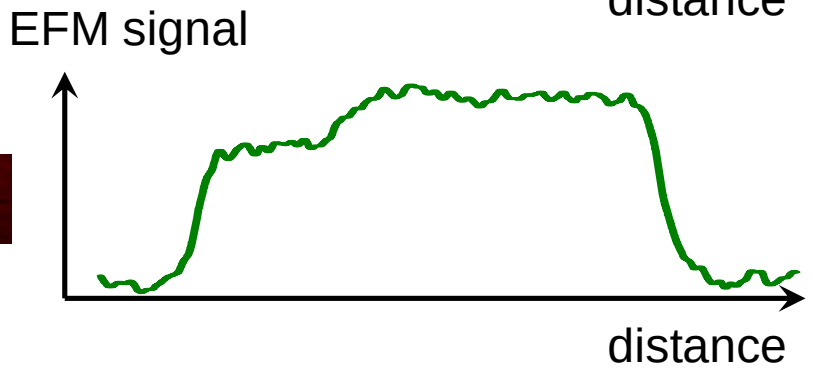


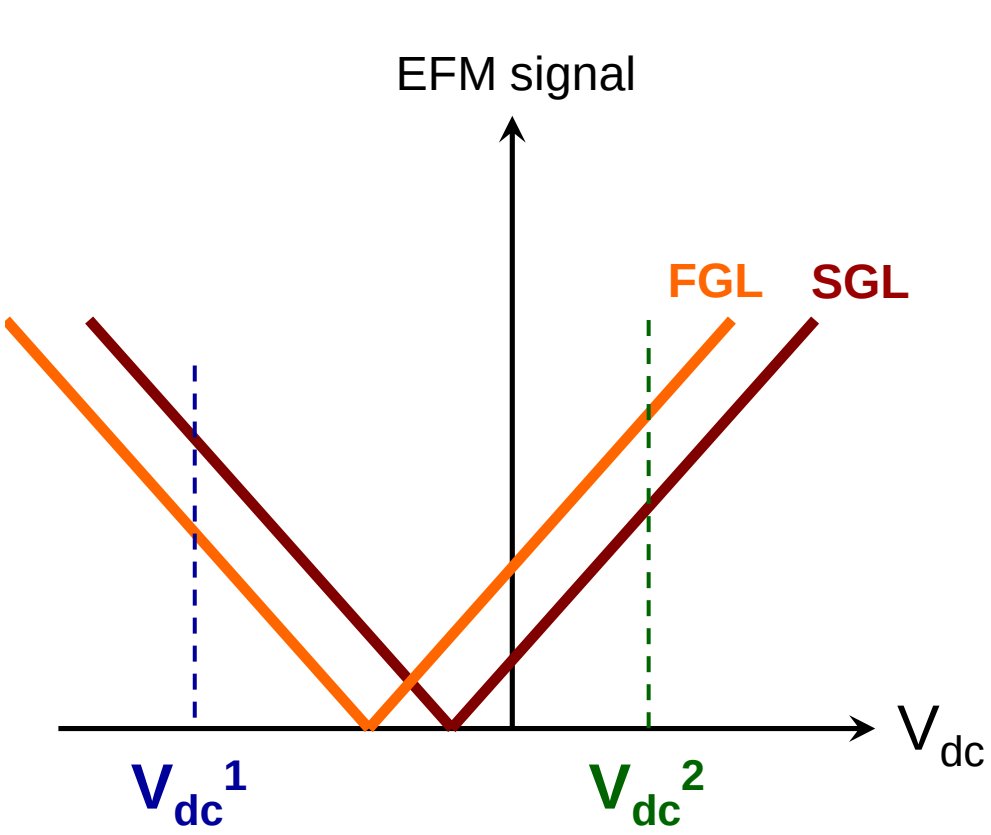


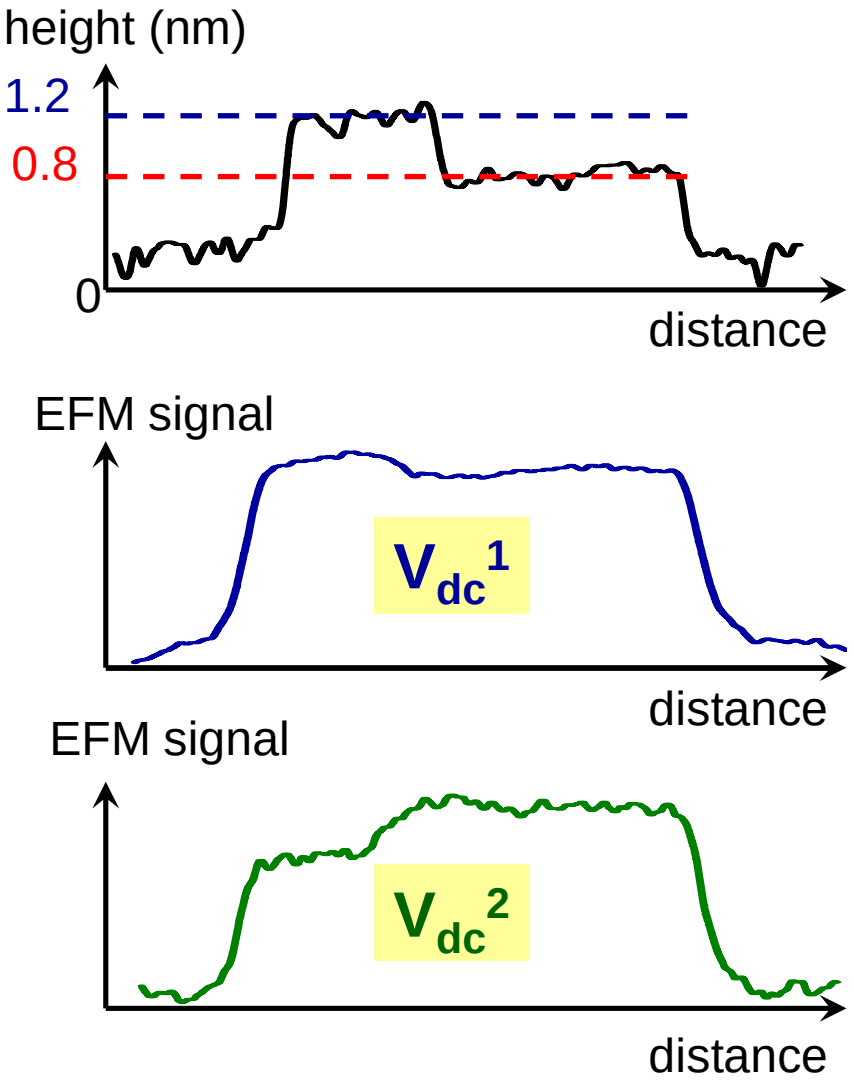



height (nm)
1.2
0.8
0
distance


EFM signal
distance


EFM signal
distance


EFM signal
FGL
SGL
V_{dc}
V_{dc}^1
V_{dc}^2


height (nm)
1.2
0.8
0
distance
EFM signal
V_{dc}^1
distance
EFM signal
V_{dc}^2
distance