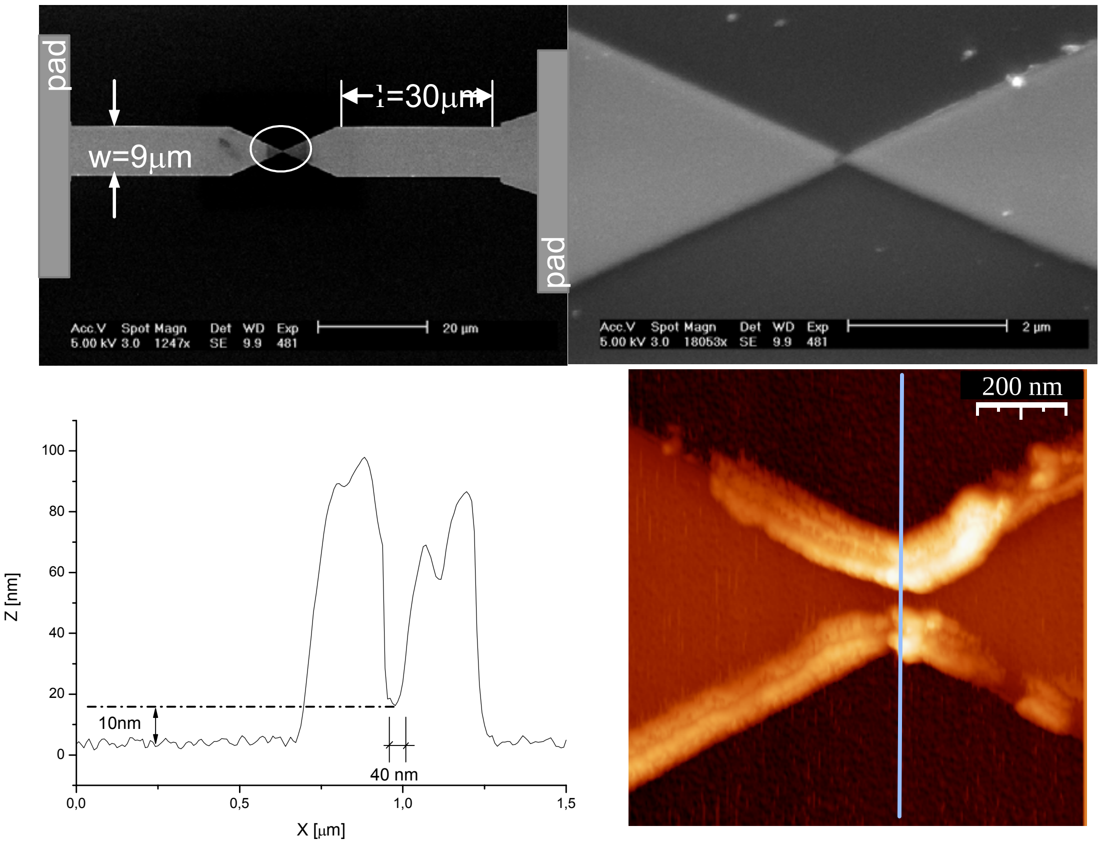
TALK FOR BENASQUE 2009

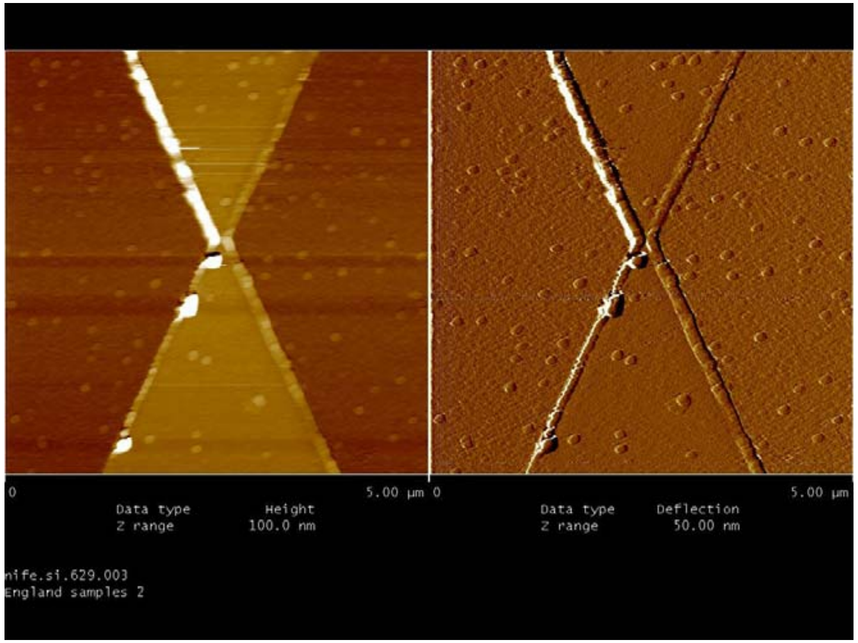
- **ELECTROSTATIC FIELD MICROSCOPY (EFM).**
- **DETERMINATION OF CONDUCTIVITY AND CHARGES AT BULK/SURFACES.**
- **Application to metal nanostructures**
- **Electrical currents**
- **APPLICATION TO GRAPHITE (A CONDUCTOR-INSULATING MATERIAL)**
- **STTUDY OF ELECTRICAL POTENTIAL FLUCTUATIONS IN SiO_2**
- **CONCLUSIONS**

COLLABORATION WITH Zan Yang and P. Esquinazi

An example of EFM in Metals

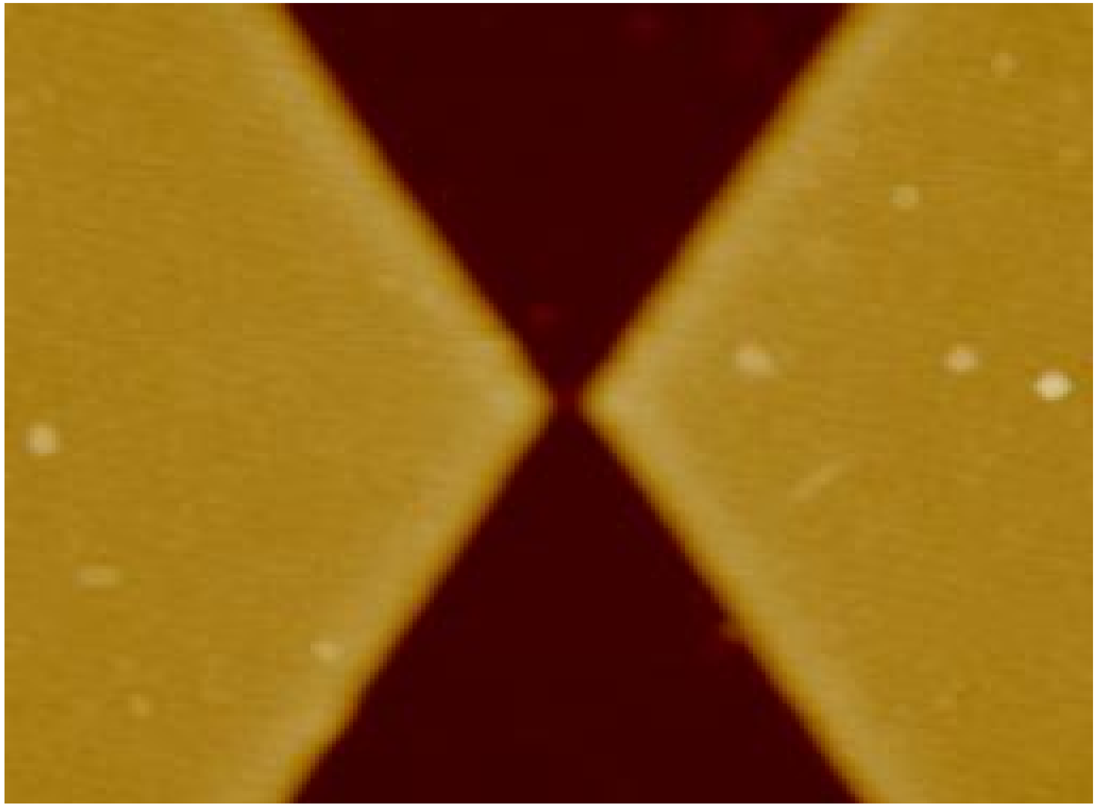


AFM characterization of nanocontacts



Low- and middle resolution views of the Contact #2

CONTINUOUS FILM HERE NO LIFT-OFF WAS DONE IN ORDER TO MEASURE ρ(resist.)



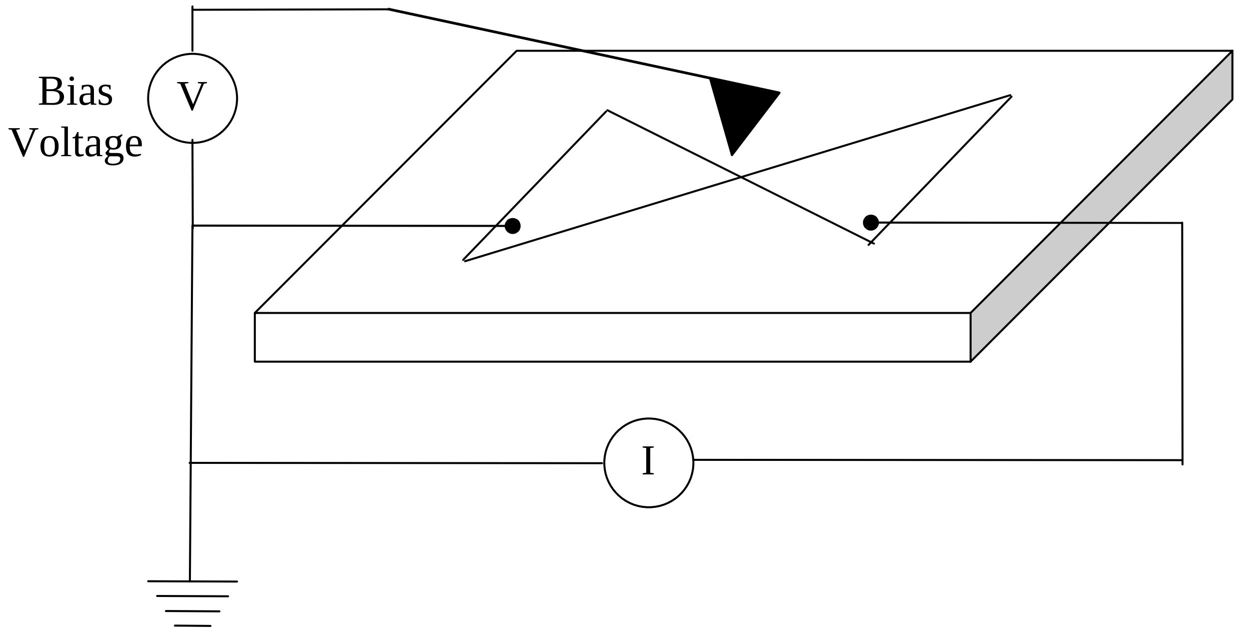


Diagram of the electrostatic force microscopic measurement.

Theory(EFM with current)

$$E=\frac{1}{2}CU^2=\frac{1}{2}C[(U_{apply}-U_{contact}-U_{current})+U_1\sin(\omega t)]^2$$

$$F=\frac{\partial E}{\partial z}=\frac{1}{2}\frac{\partial C}{\partial z}U^2 \qquad C=\frac{\alpha}{z}$$

$$F_z^{'}=\frac{\partial F}{\partial z}=\frac{\partial^2 E}{\partial^2 z}=\frac{1}{2}\frac{\partial^2 C}{\partial^2 z}U^2$$

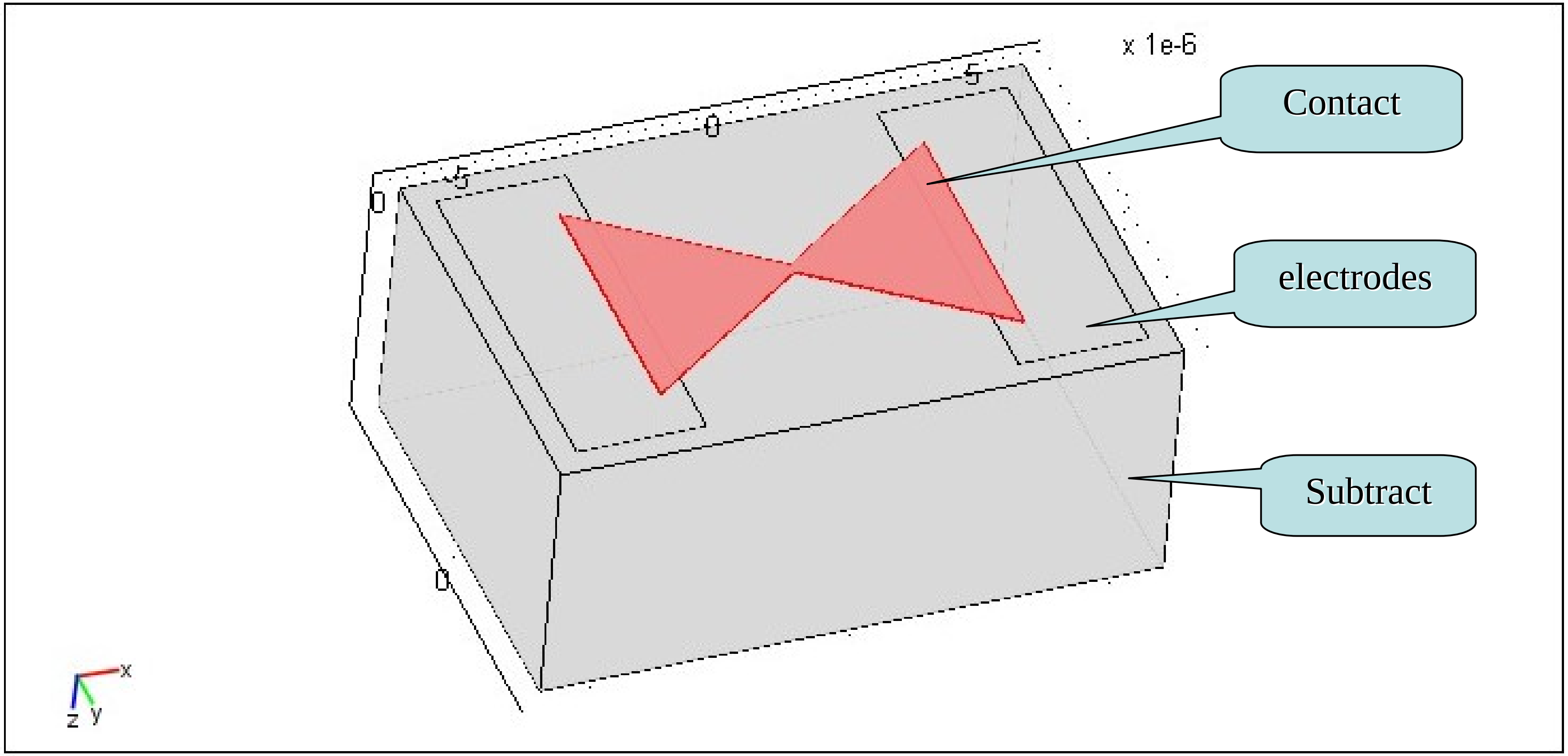
$$Mag\sin\propto F_z^{'}=\frac{\alpha}{z^3}(U_{apply}-U_{contact}-U_{current})^2$$

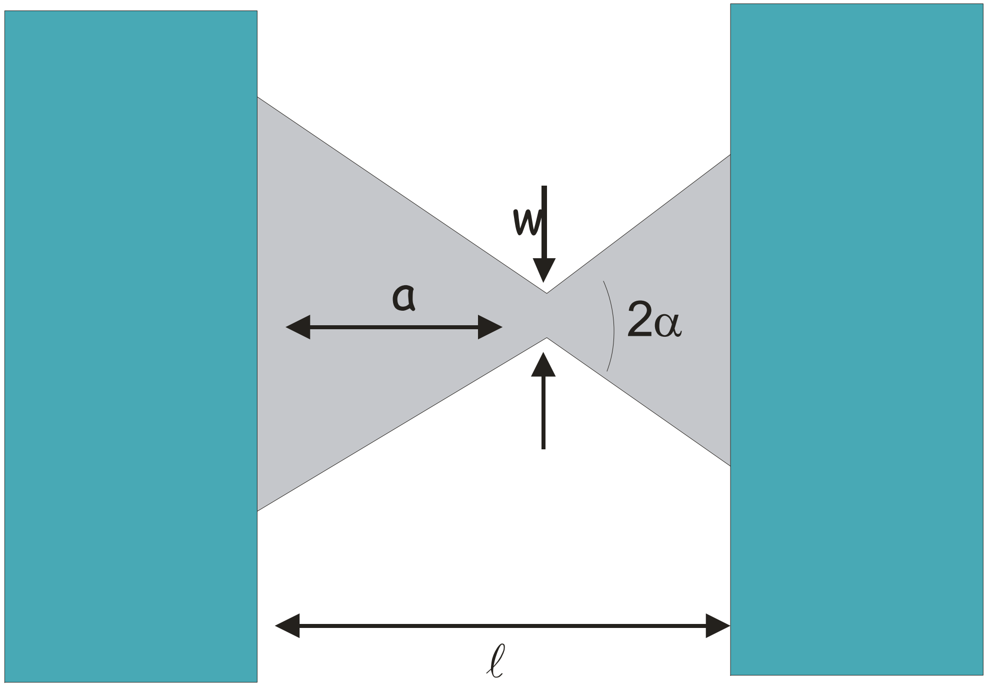
$$U_{contact}+U_{current}=U_{apply}-\beta\cdot Mag\sin^{1/2}\cdot z^{3/2}$$

Kelvin method:

$$F_z(\omega)=-[(U_{apply}-U_{contact}-U_{current})U_1\sin(\omega t)]\frac{\partial C}{\partial z}$$

Calculation Model

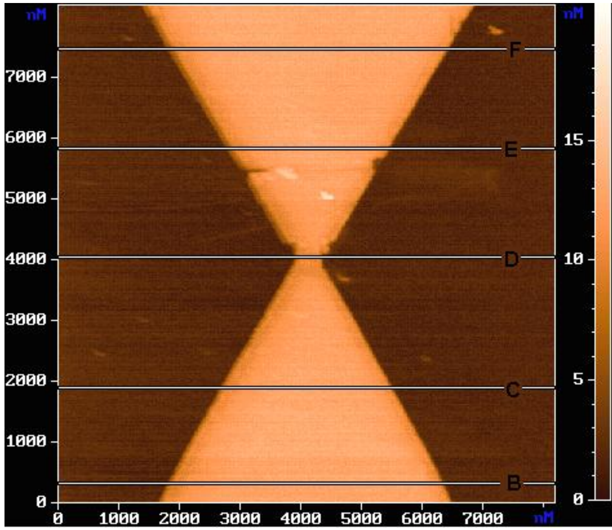


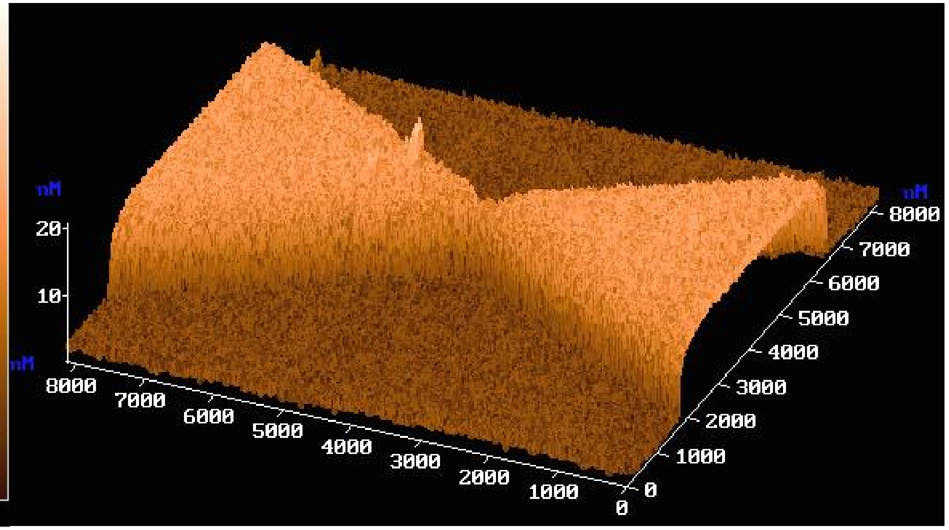


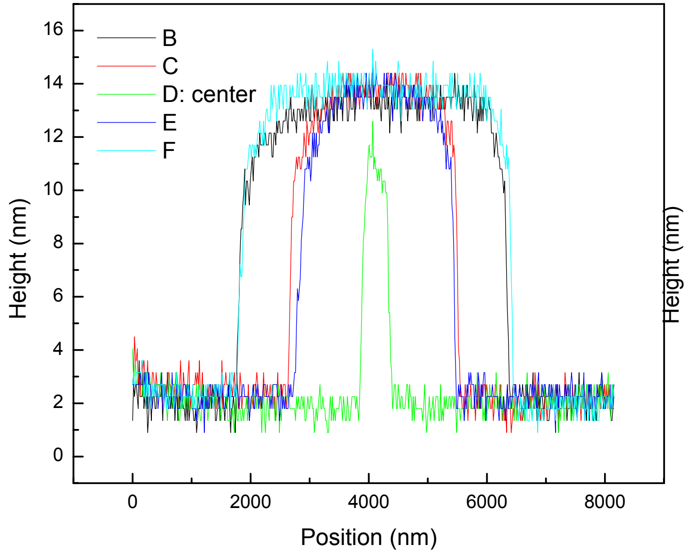
$$R = \frac{\rho}{2t\tan\alpha}\left[\ln\left(\frac{(l-a)\tan\alpha + w/2}{w/2}\right) + \ln\left(\frac{a\tan\alpha + w/2}{w/2}\right)\right]$$

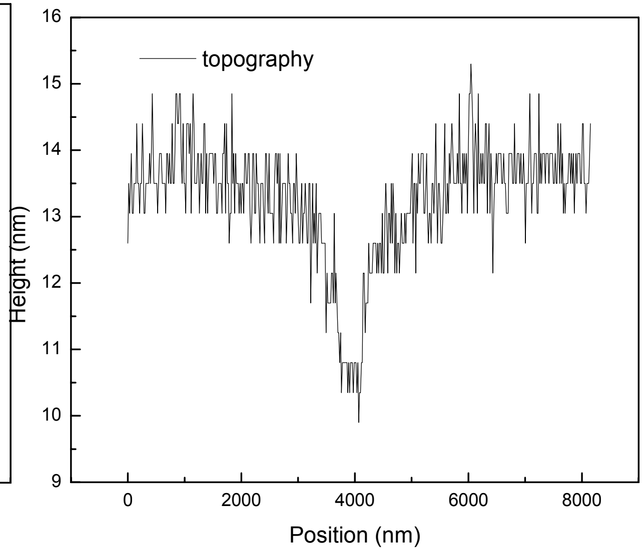
$$R = \frac{\rho}{t}\left[\frac{L}{W} + \frac{1}{\tan\alpha}\ln\left(\frac{l\tan\alpha + w/2}{w/2}\right)\right]$$

$$R(x)=\begin{cases} \dfrac{\rho}{2\cdot tg\dfrac{\varphi}{2}}\ln\left|\dfrac{\dfrac{a}{2\cdot tg\dfrac{\varphi}{2}}+b}{\dfrac{a}{2\cdot tg\dfrac{\varphi}{2}}-x}\right| & (when \qquad x\le 0) \\ R(0)+\dfrac{\rho}{2\cdot tg\dfrac{\varphi}{2}}\ln\left|\dfrac{\dfrac{a}{2\cdot tg\dfrac{\varphi}{2}}+x}{\dfrac{a}{2\cdot tg\dfrac{\varphi}{2}}}\right| & (when \qquad x>0) \end{cases}$$

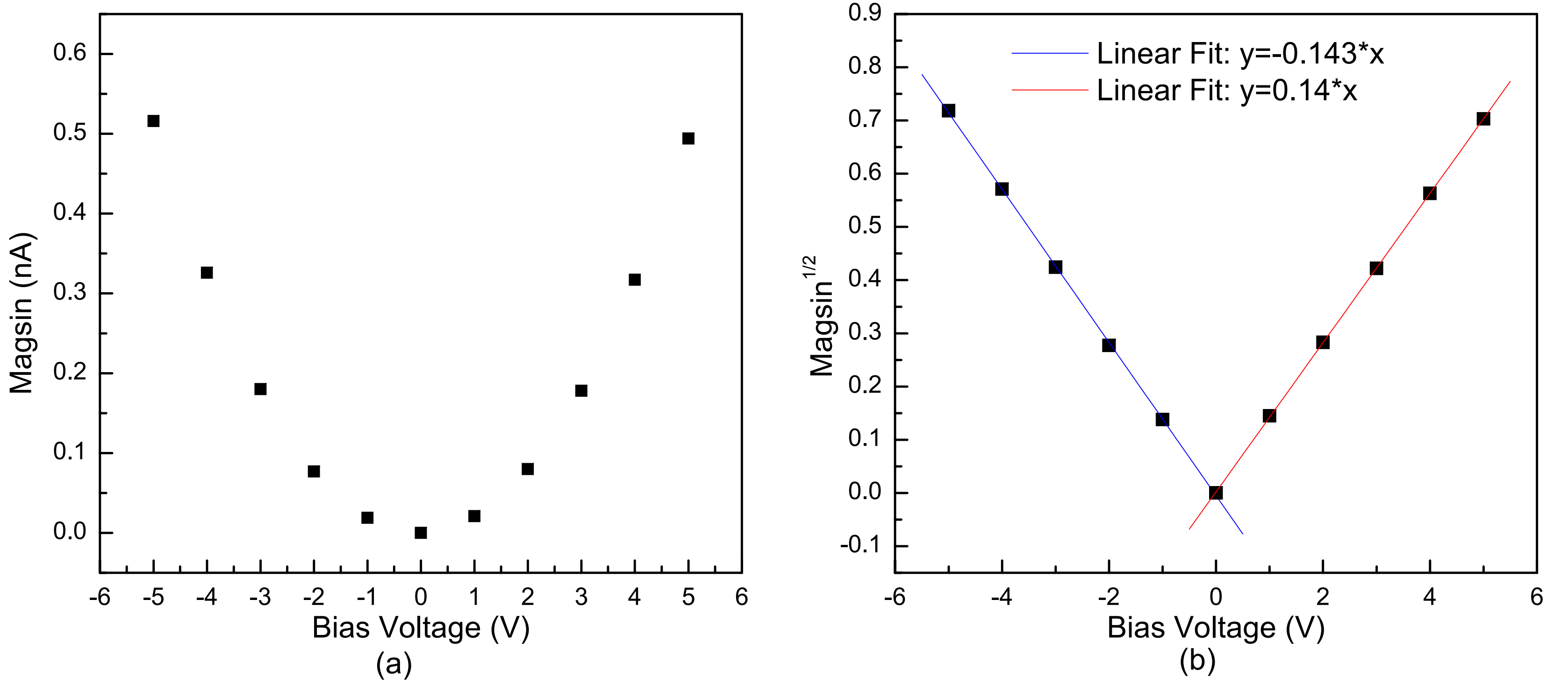




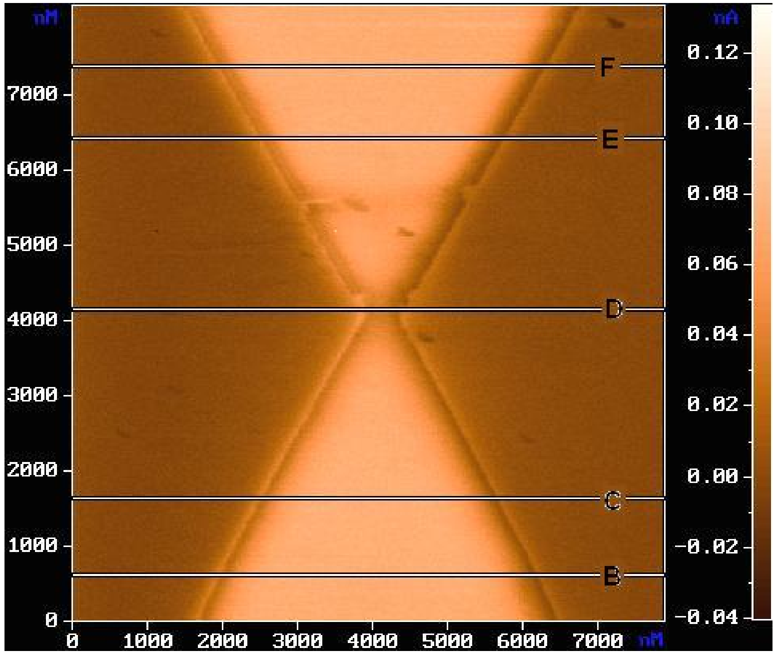


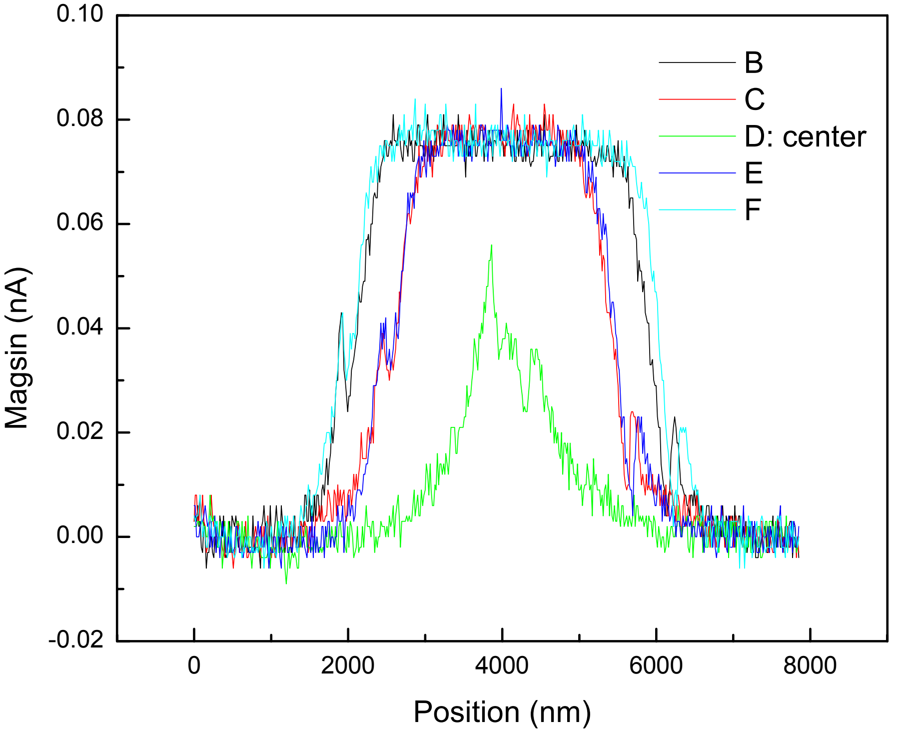


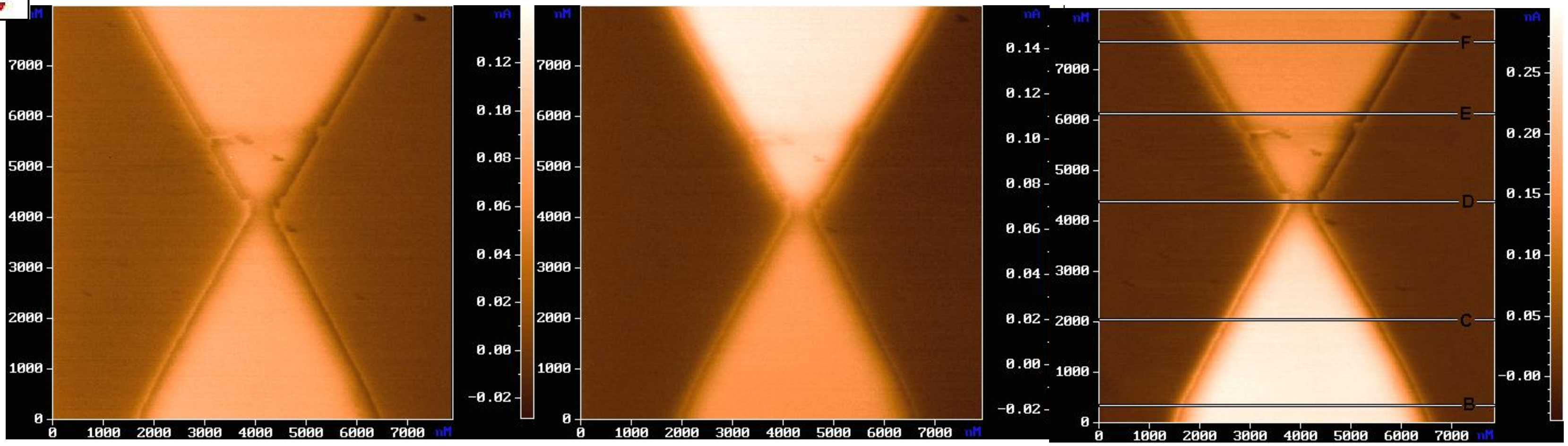
Topography (AFM) of the nanoconstriction show the width is 200nm, the thickness of the film is 13nm. The vertical cross-line(right) in the middle of the constriction indicate the film is about 3nm thinner in the constriction because of the fabrication.



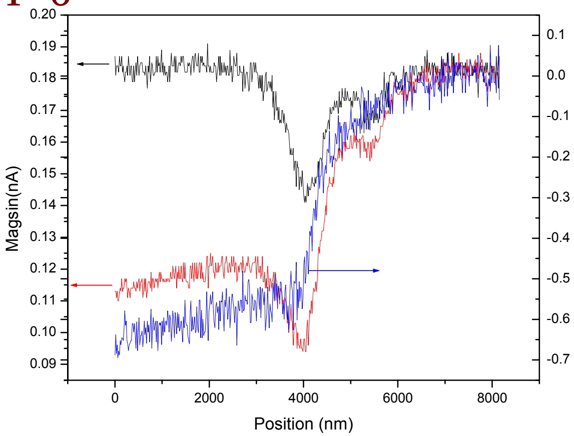
Quadratic dependence of the electrostatic force signal (“Magsin”) on bias voltage on the tip. (b) is the root of square of (a), which shows linear relationship.

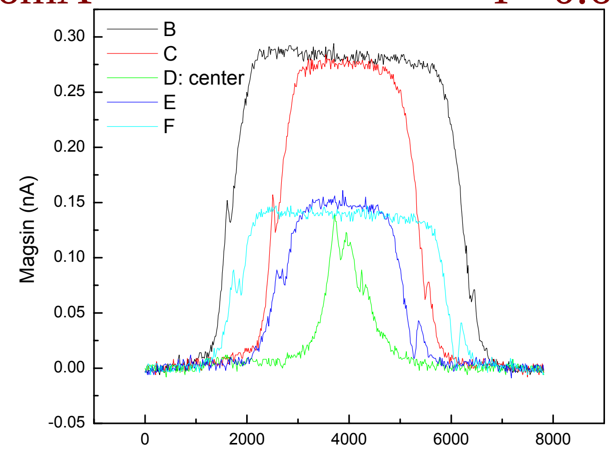

nM
7000
6000
5000
4000
3000
2000
1000
0
0 1000 2000 3000 4000 5000 6000 7000 nM
F
E
D
C
B
nA
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04


Magsin (nA)
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
0 2000 4000 6000 8000
Position (nm)
B
C
D: center
E
F

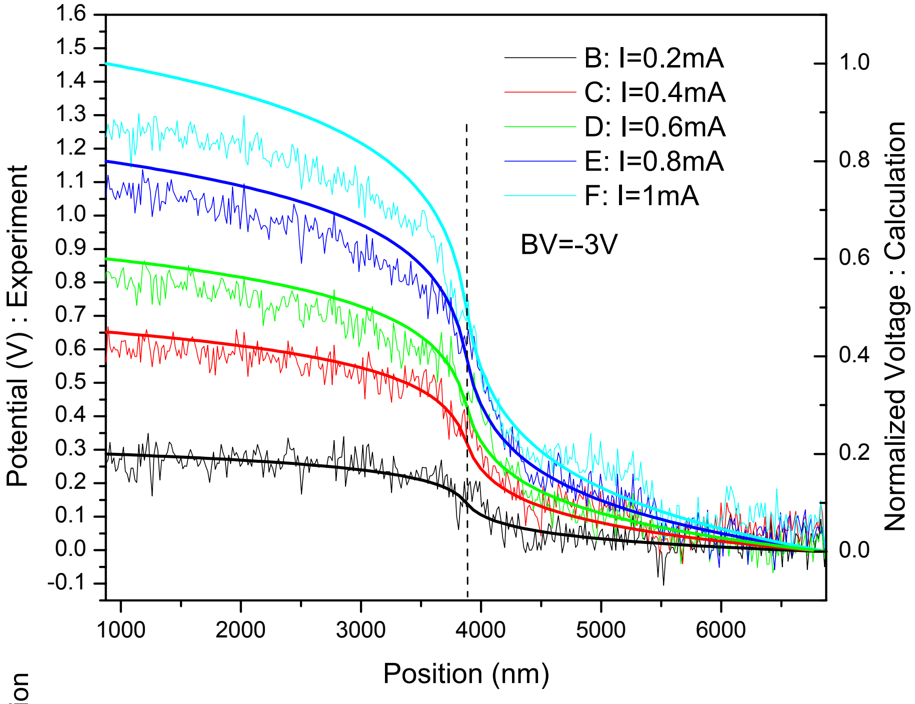


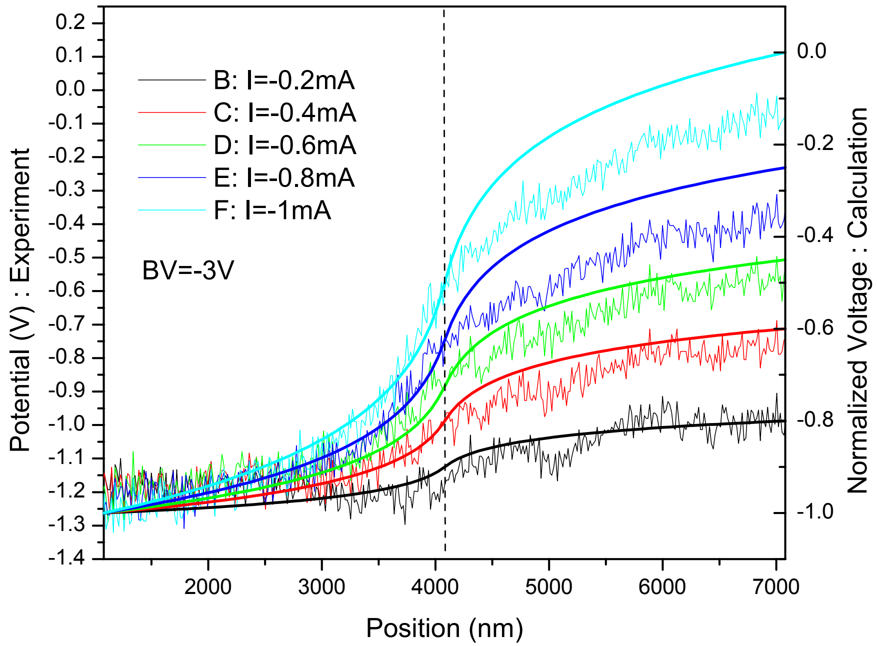
I=0 I=0.6mA I=-0.6mA





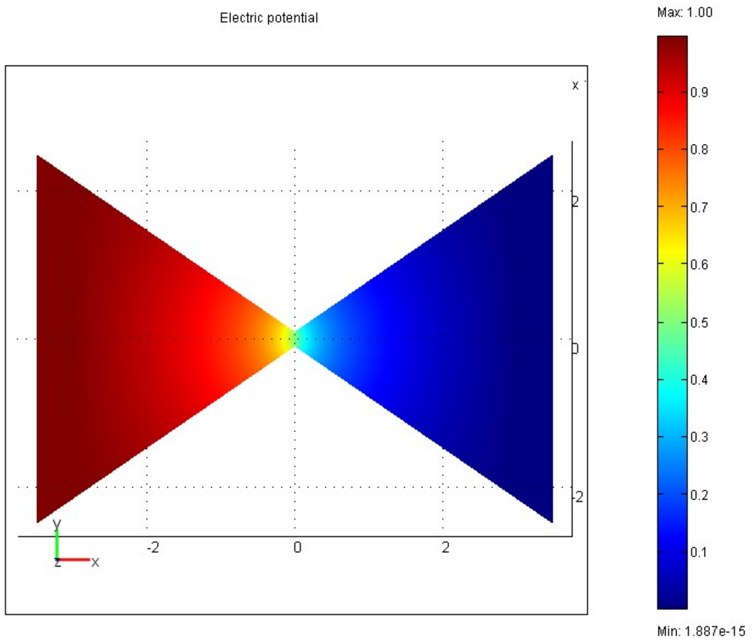
Electrostatic force microscopy (EFM) are measured without passing current (topleft), with 0.6mA current (topright) and with –0.6mA current (downdleft). Without current, the EFM signal has a dip within the constriction, the dip are still there when current passes and will be removed when we calculate the potential drop from the EFM signal.

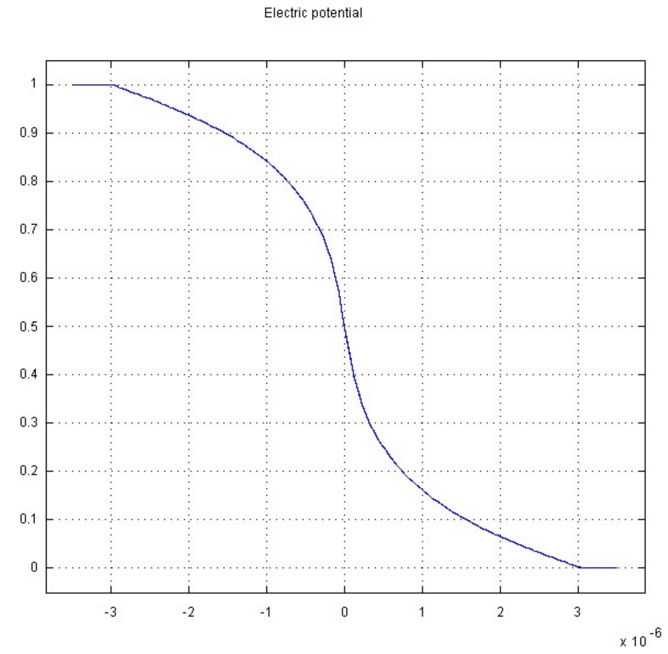




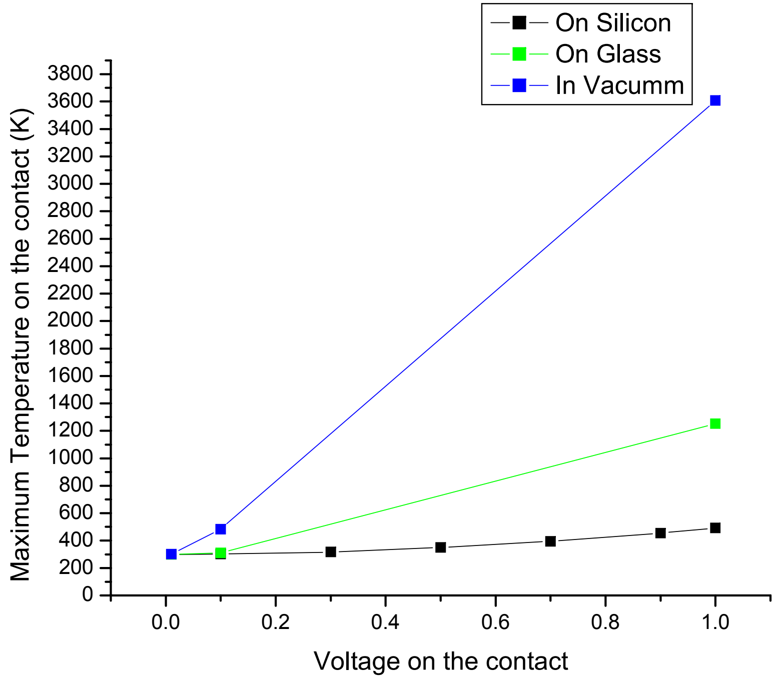
When the polarity of the bias voltage on the tip is reversed, similar potential drops across the constriction are also measured in the condition of different passing current.

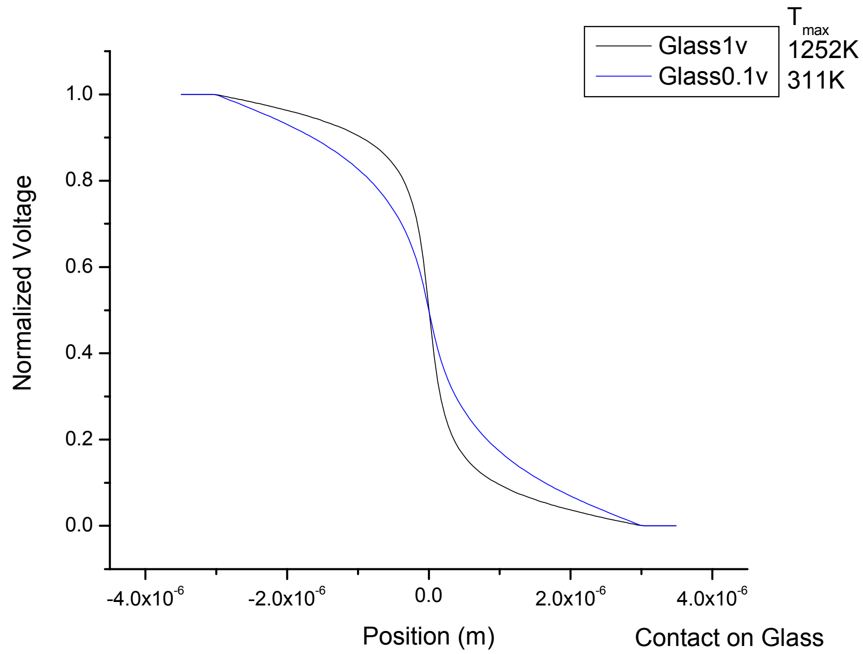
Potential drop along contact



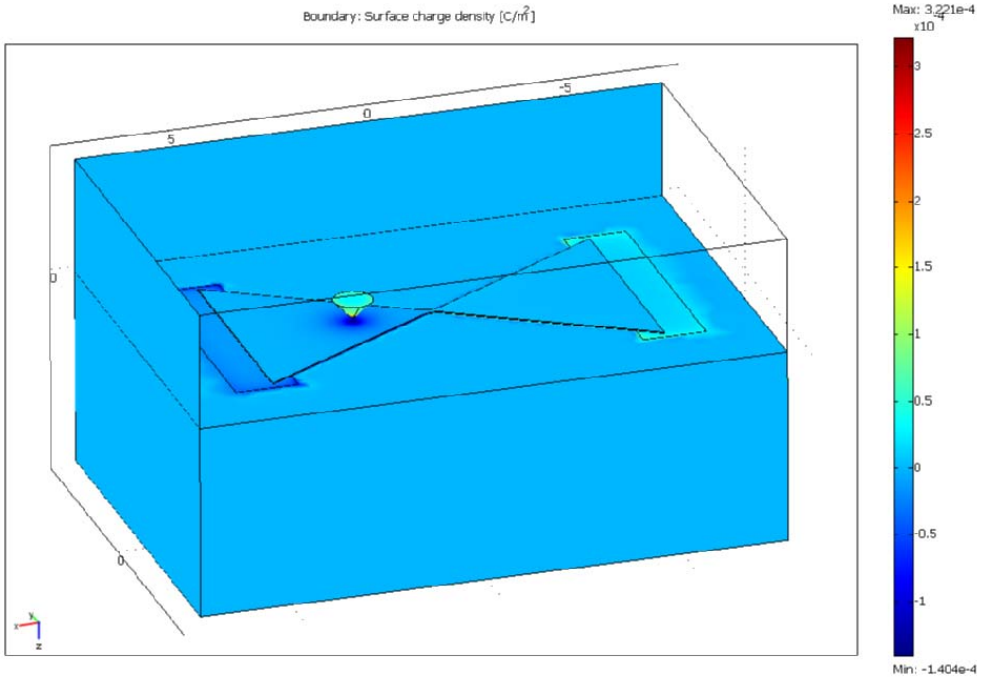


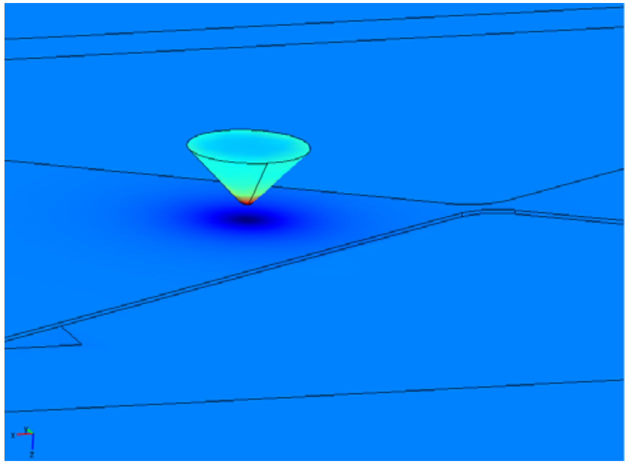
Temperature effect on resistivity

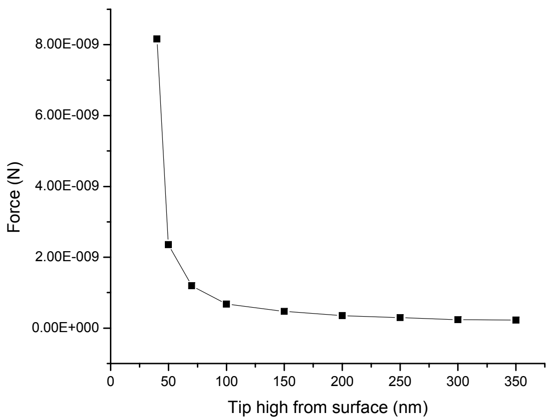




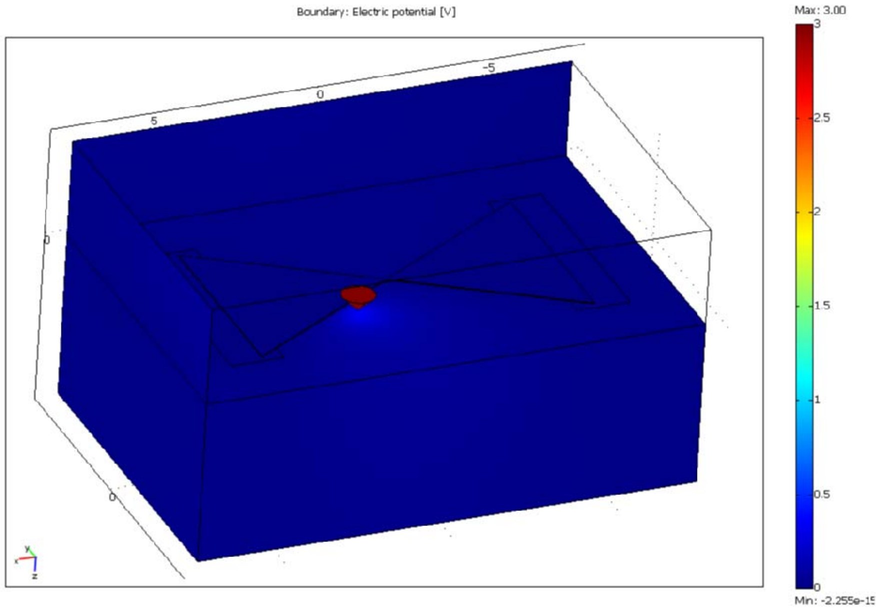
Measuring Surface Potential with AFM

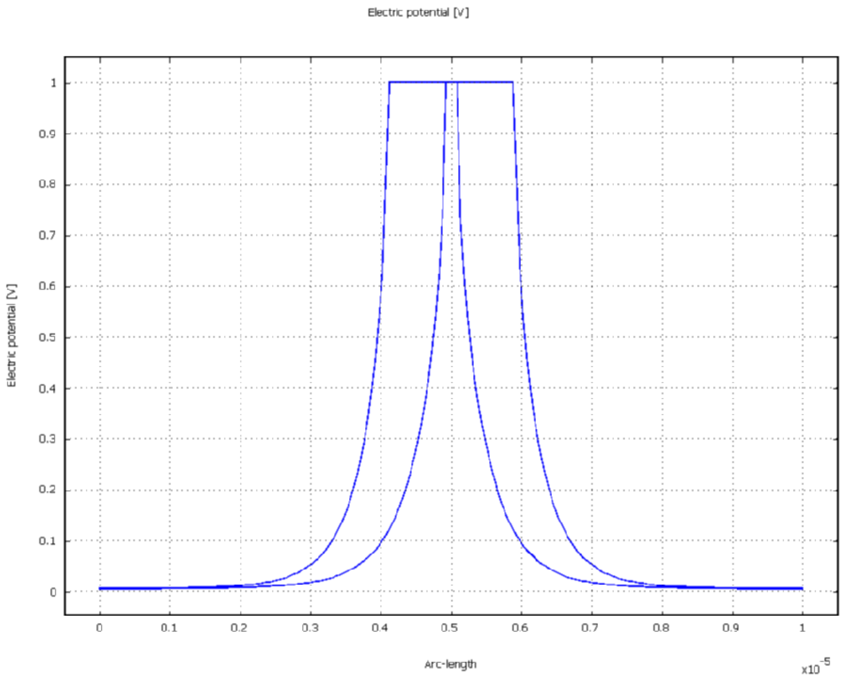






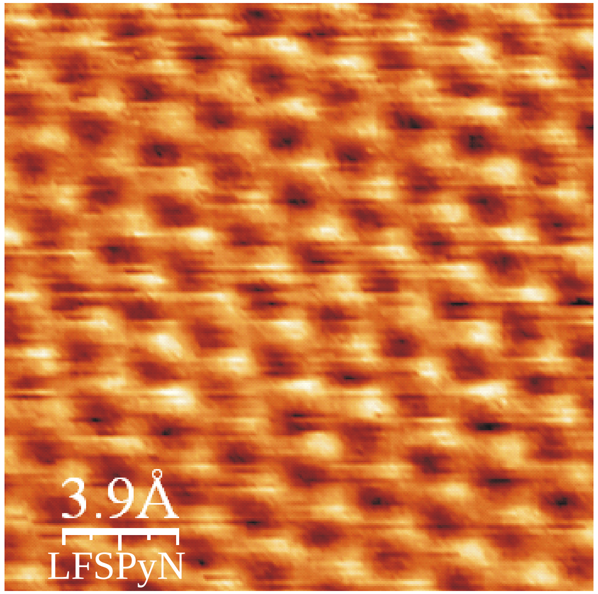
Measuring Surface Potential with EFM

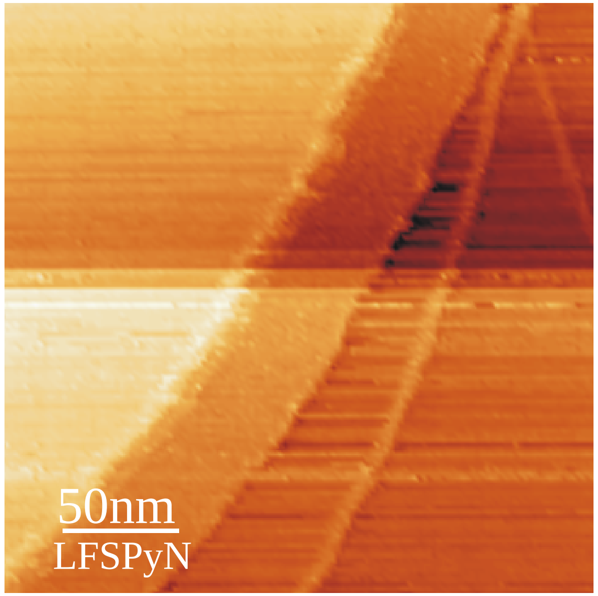


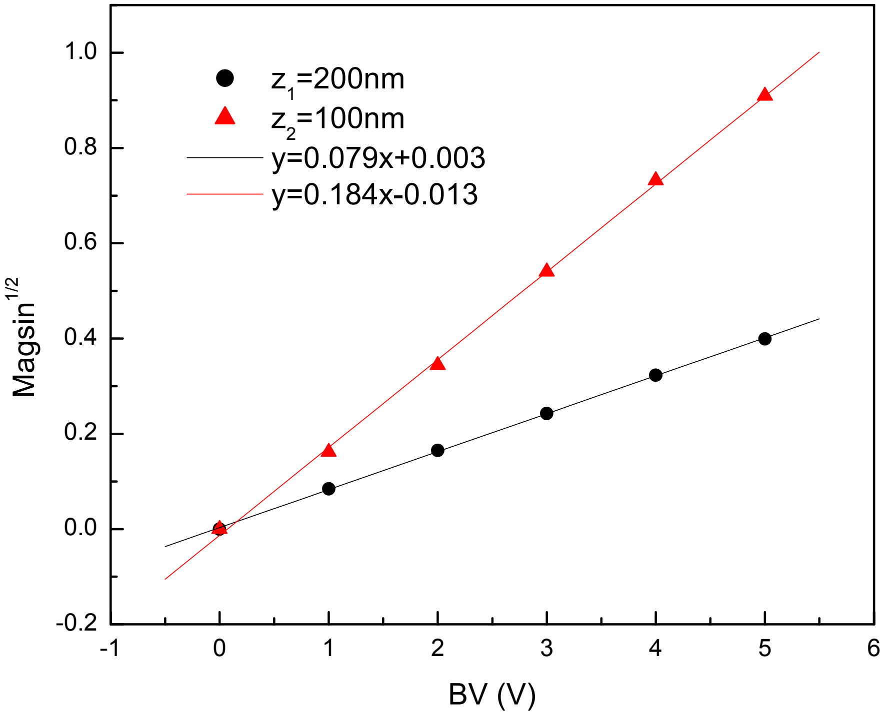


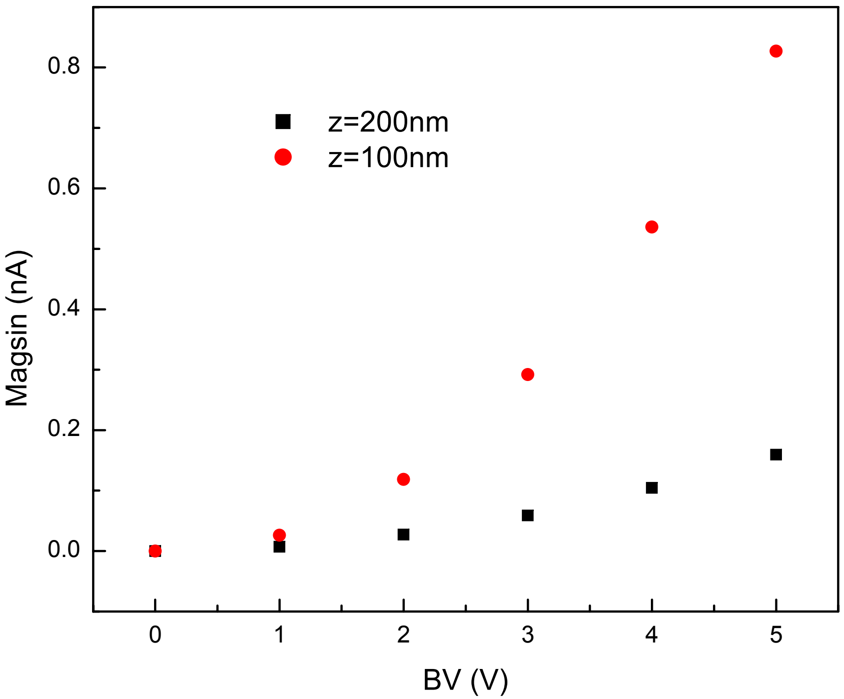
Lateral potential measurements

Graphite









$$\frac{\beta_2}{\beta_1} = \frac{0.184}{0.079} = 2.33$$

$$\approx \left(\frac{z_2}{z_1}\right)^{-3/2} = 2.83$$

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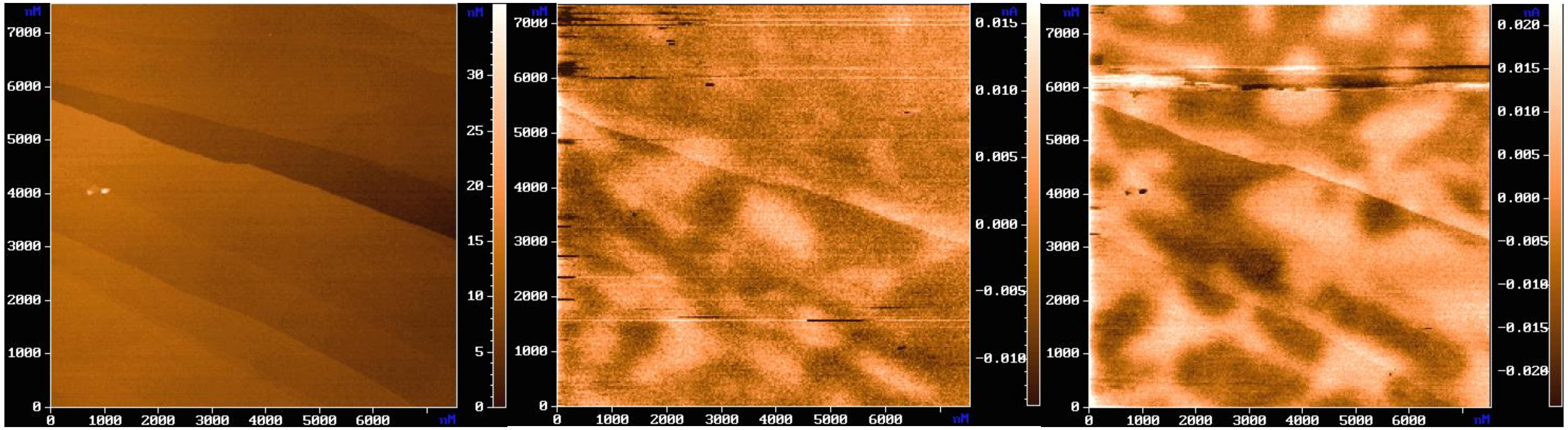

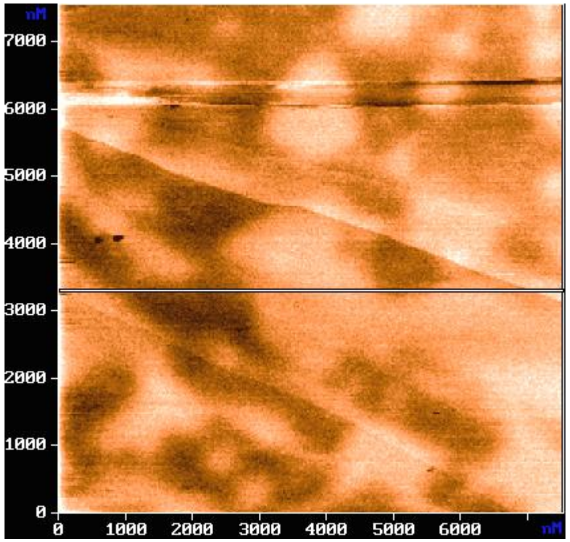

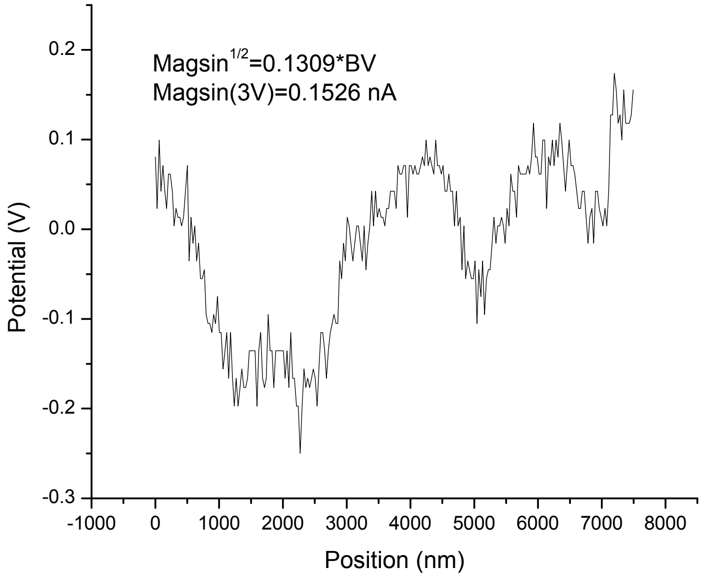

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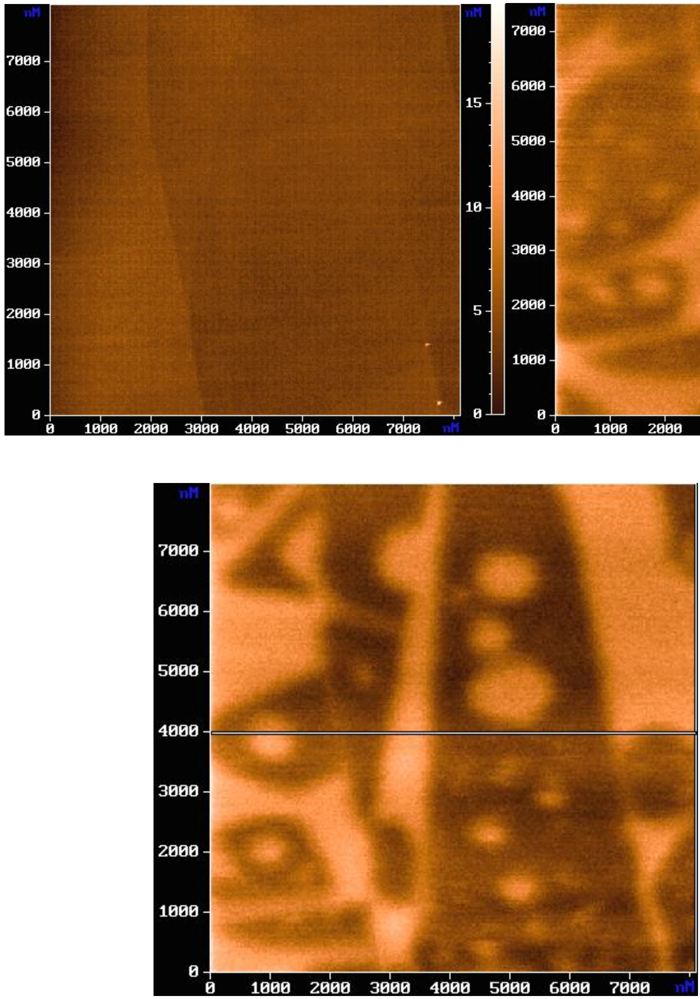
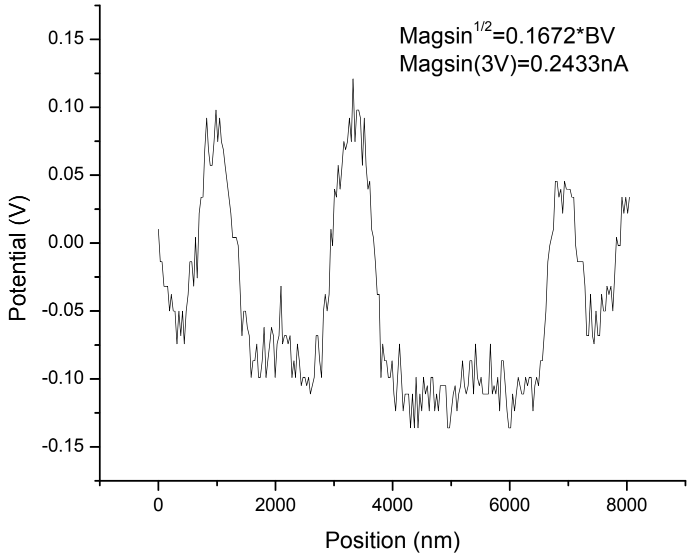
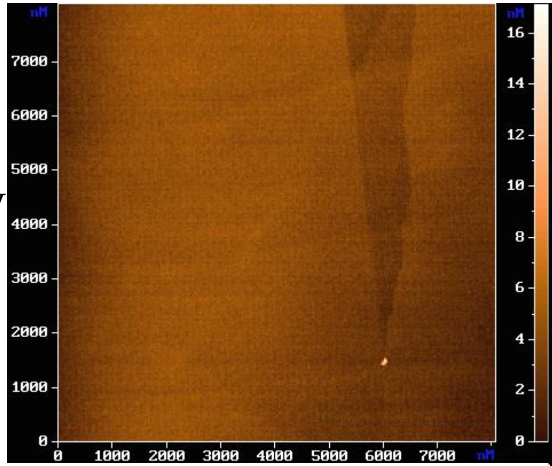
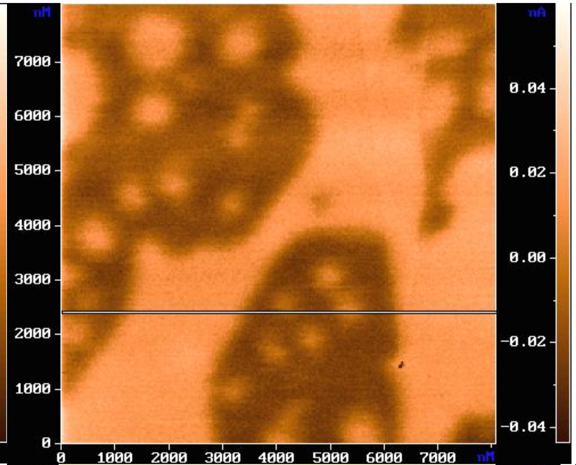


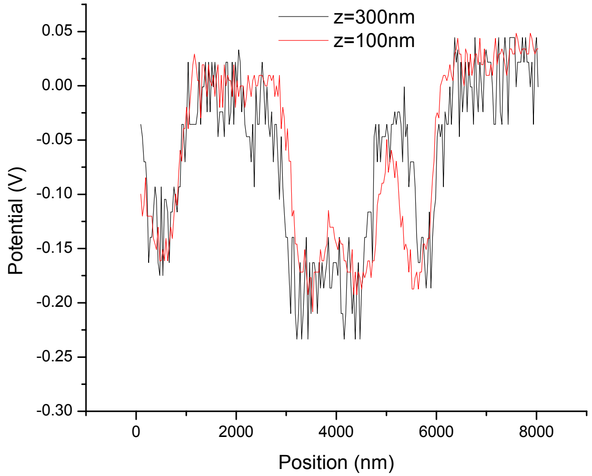


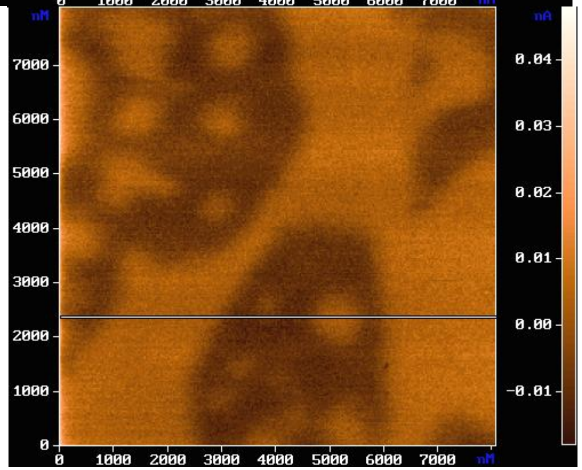
Topography



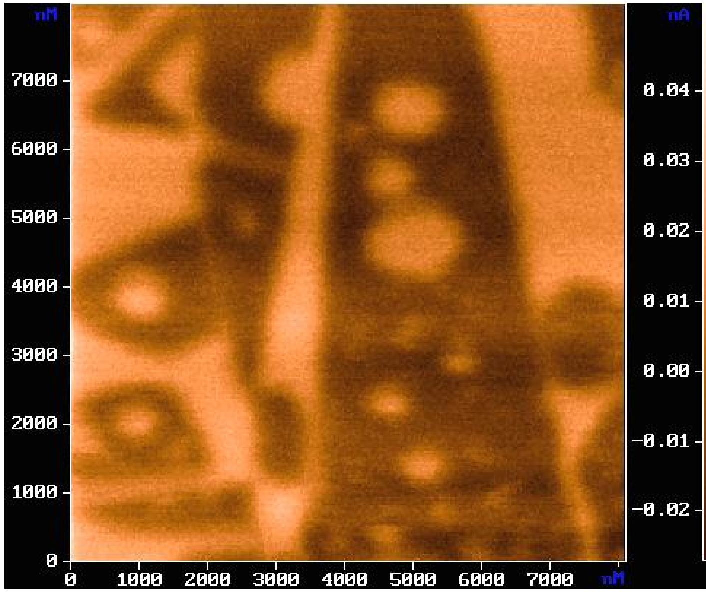


Z=100nm

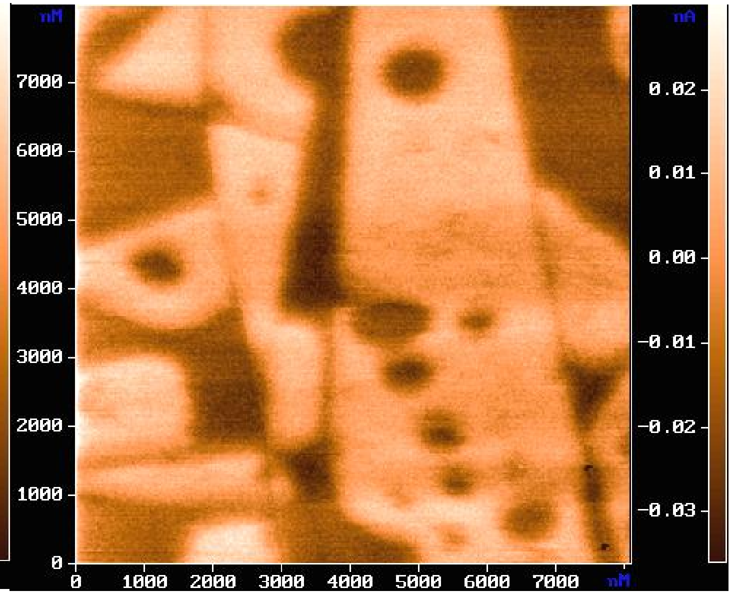




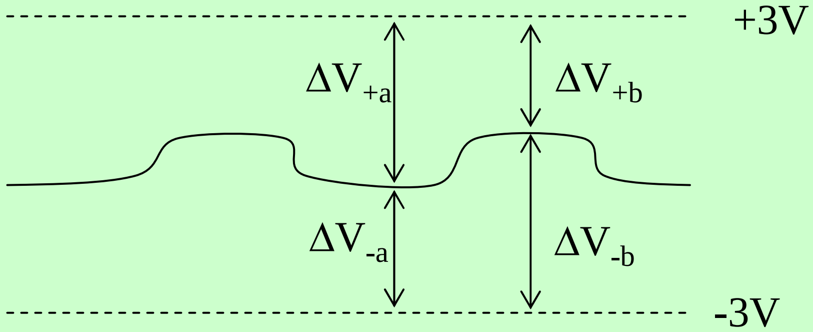
Z=200nm



BV= +3V



BV= -3V



If $\Delta V_{+a} > \Delta V_{+b}$

Then $\Delta V_{-a} < \Delta V_{-b}$

TEH $Si0_2$ CASE: This sustain graphene layers

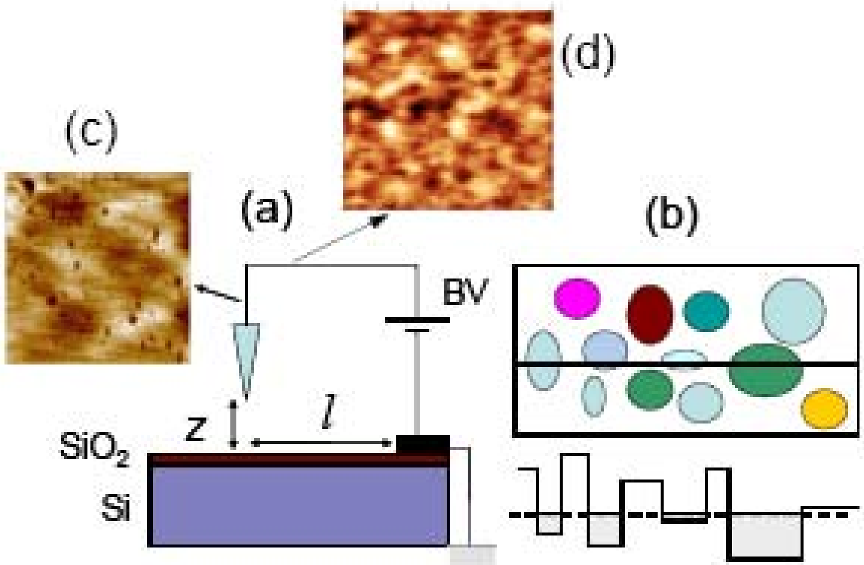
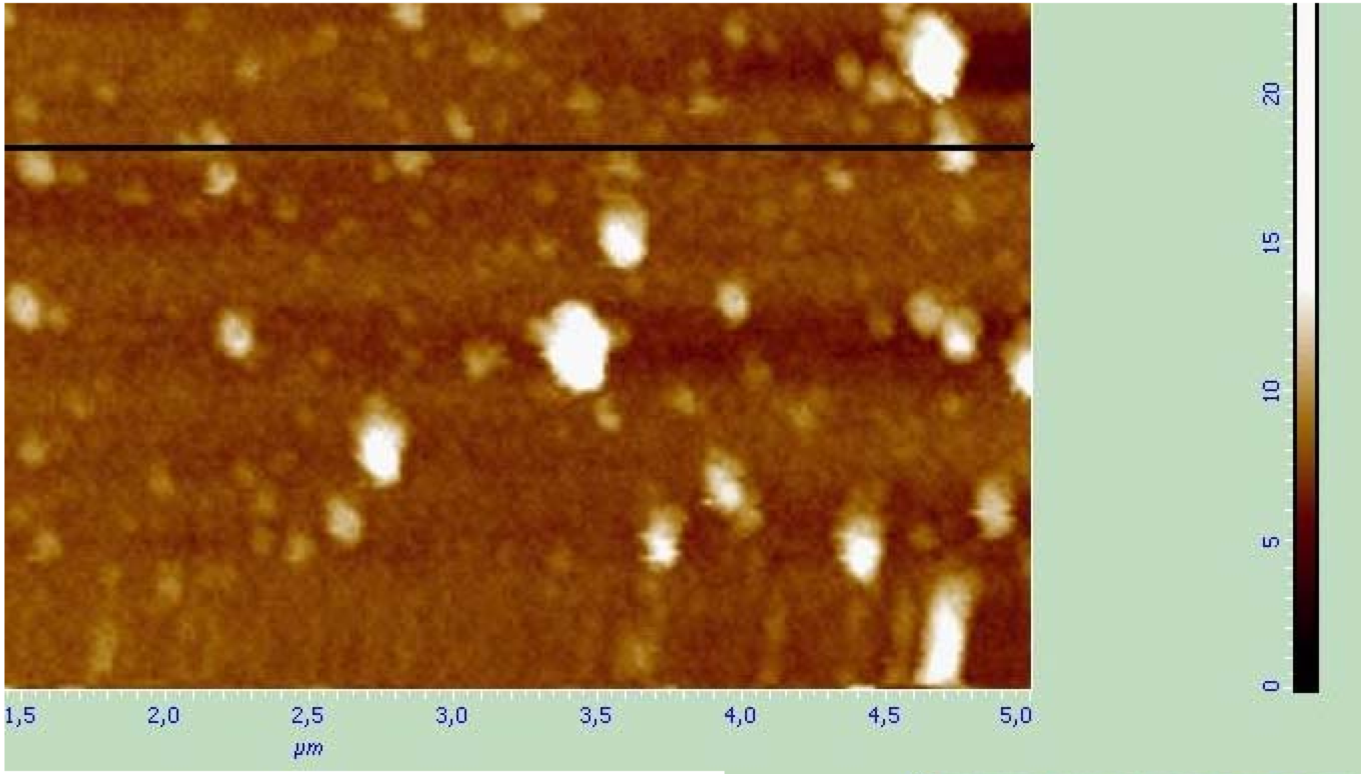
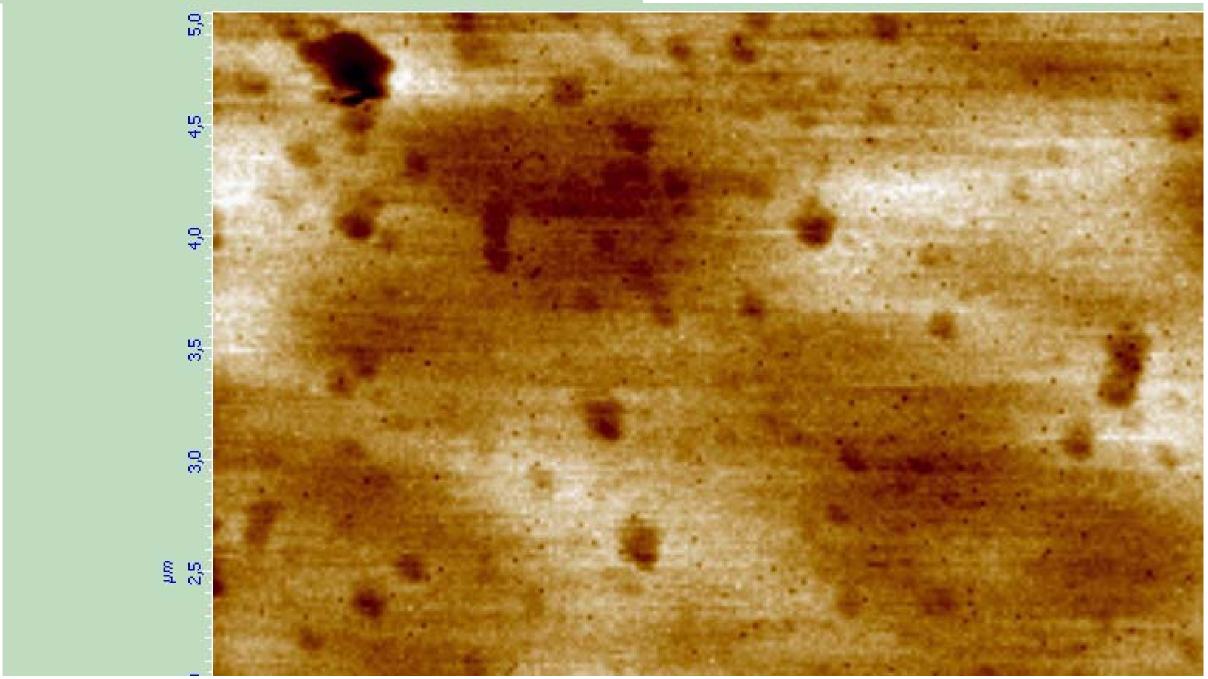


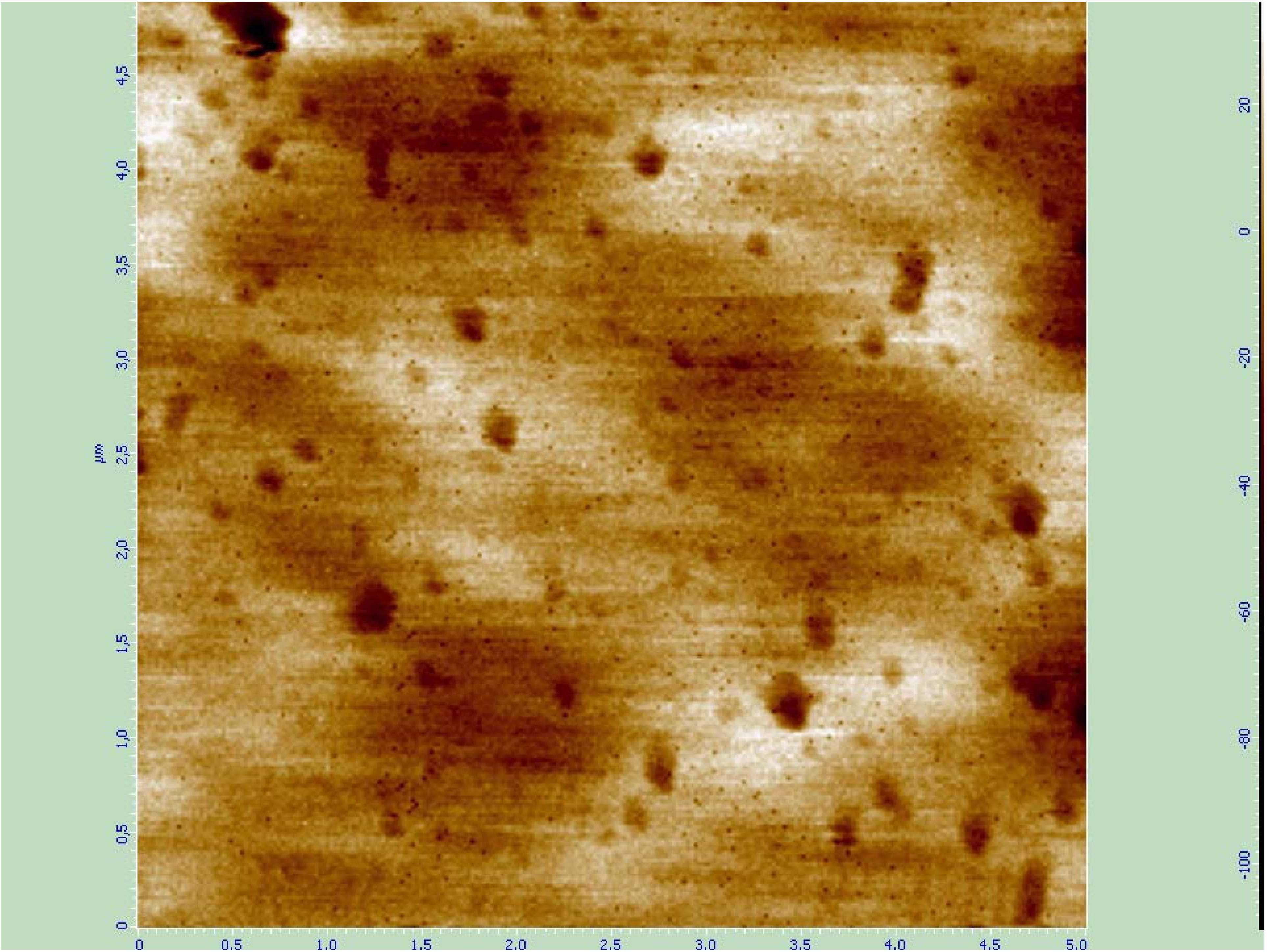
FIG. 1: (a) Sketch of the experimental arrangement. The distance z between tip and surface can be changed as well as the distance l to the mass contact. (b) Sketch of the potential distribution to which a graphene layer would be affected if it is attached to the surface. The scan line below represents a one dimensional potential with differently filled wells of graphene carriers. For simplicity only electron filled bands are depicted. The dashed line represents the Fermi energy of the graphene layer on top of the disordered potential surface. (c) EFM picture ($4 \times 4\ \mu m^2$) of a SiO_2 surface in a sample in which a resin rest (dark spots) were left. (d) EFM picture ($6 \times 6\ \mu m^2$) of a resin-free sample. These results were obtained with two different microscopes and different EFM tips. For both EFM pictures the potential gradients between light and dark broad areas (not spots) are $\lesssim 0.4$ V.



AFM

EFM




µm
0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
20
0
-20
-40
-60
-80
-100

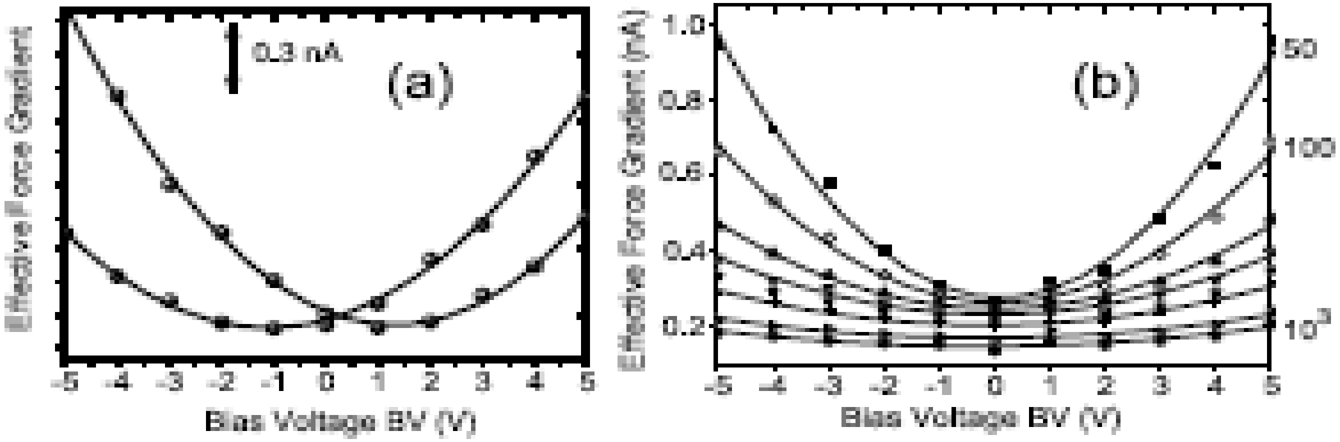


FIG. 2: Effective force gradient in nA vs. Bias Voltage $BV \propto U_{\mathrm{tip}}$. (a) Two curves obtained at a height of 100 nm between tip and surface at two different positions on the sample. (b) The same but at different heights in a position of the sample where the minima is at $BV \simeq 0$ V. The intermediate curves were taken at heights of 200, 300, 400, 500 and 800 nm. All the continuous lines are simple quadratic fits to the data in agreement with Eq. (1).

$$\frac{\partial^2 C}{\partial z^2} = \frac{A}{(z+\lambda)^b}\,, \qquad \frac{\partial F_z}{\partial z} = \frac{1}{2}\frac{\partial^2 C}{\partial z^2}[U_{\mathrm{tip}} - \Psi(x,y)]^2\,,$$

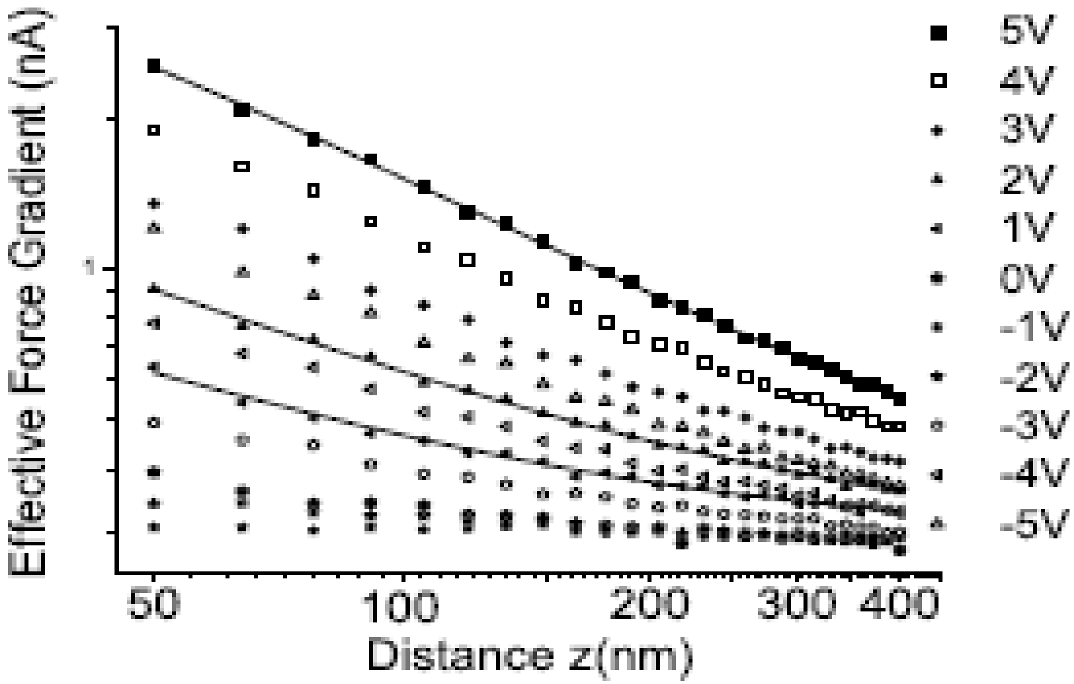


FIG. 3: Effective force gradient in nA vs. distance between tip and surface in nm taken at different constant applied voltages (see right list) in a "bright" region (see e.g. Fig. 1 or Fig. 4). The continuous lines are fit to the function given by Eq. (2) with the parameters $A = 380, 100, 56$ nA nm$^{1.2}$ (for the upper, middle and lower curves), $\lambda = 25 \pm 4$ nm and $b = 1.2$ for the three curves.

$$\frac{\partial^2 C}{\partial z^2} = \frac{A}{(z+\lambda)^b}, \qquad \frac{\partial F_z}{\partial z} = \frac{1}{2}\frac{\partial^2 C}{\partial z^2}[U_{\rm tip} - \Psi(x,y)]^2,$$

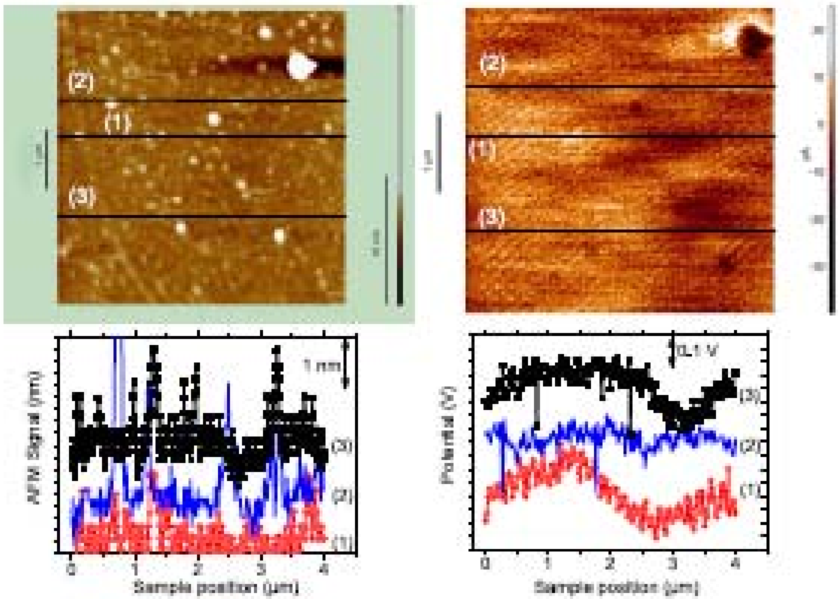


FIG. 4: Left: AFM pictures of the SiO_2 surface in a $5 \times 5\ \mu m^2$ area (the left bar indicates 1 μm). The pictures below shows the AFM signal at the three scan lines (1)-(3). Right: The corresponding EFM result at an area of $3.8 \times 3.8\ \mu m^2$ inside the area of (a) obtained at z = 200 nm and BV = 3 V. The lower picture shows the potential vs. sample position at the three scan lines. Note that the white spots in the AFM picture correspond to little resin rests that practically do not produce significant changes in the EFM signal with exception of the large ones as the one at the right upper corner.

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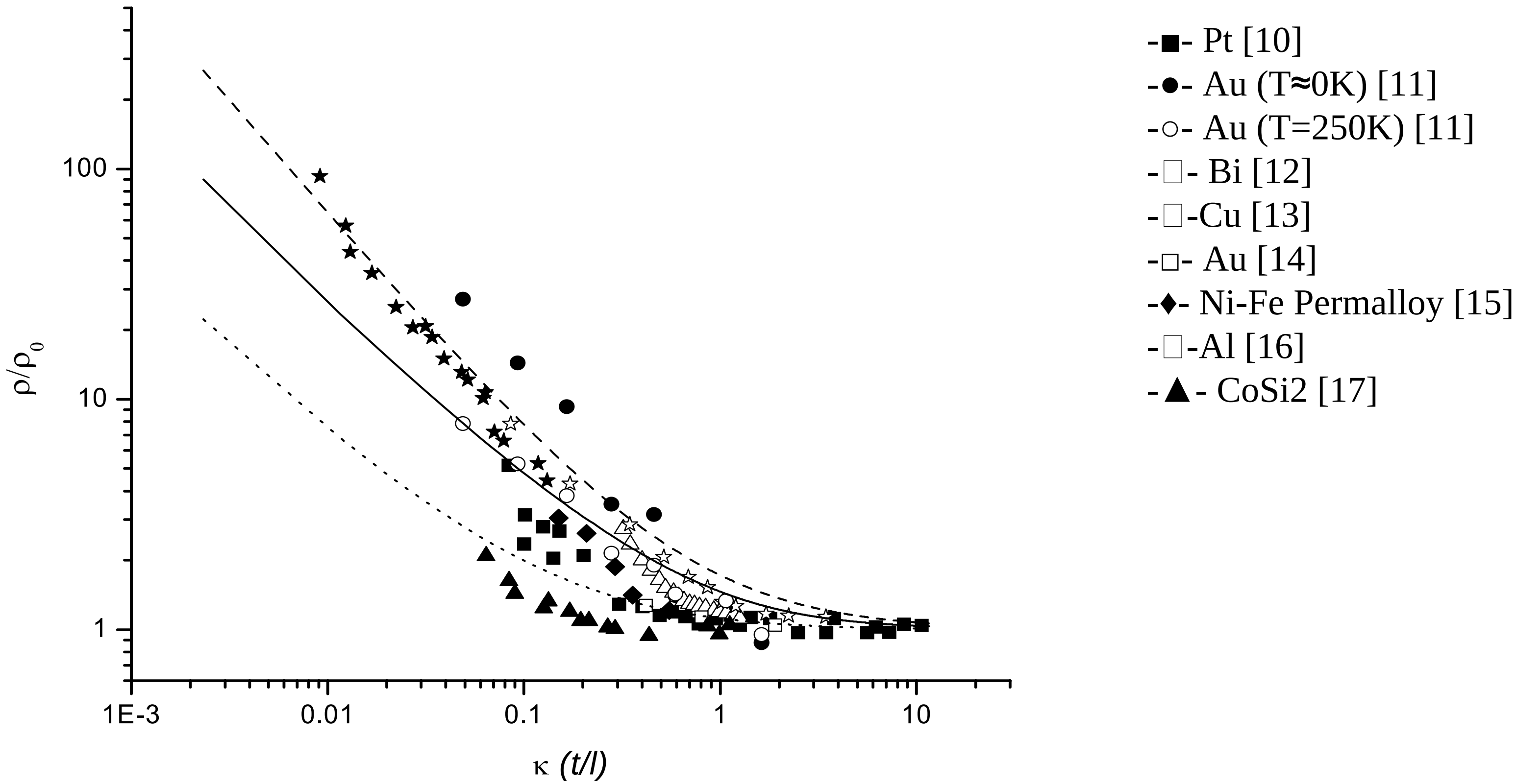
Conduction in Thin Films



A summed up of measured thin film’s resistivities vs thickness of several metals retrieved from corresponding references

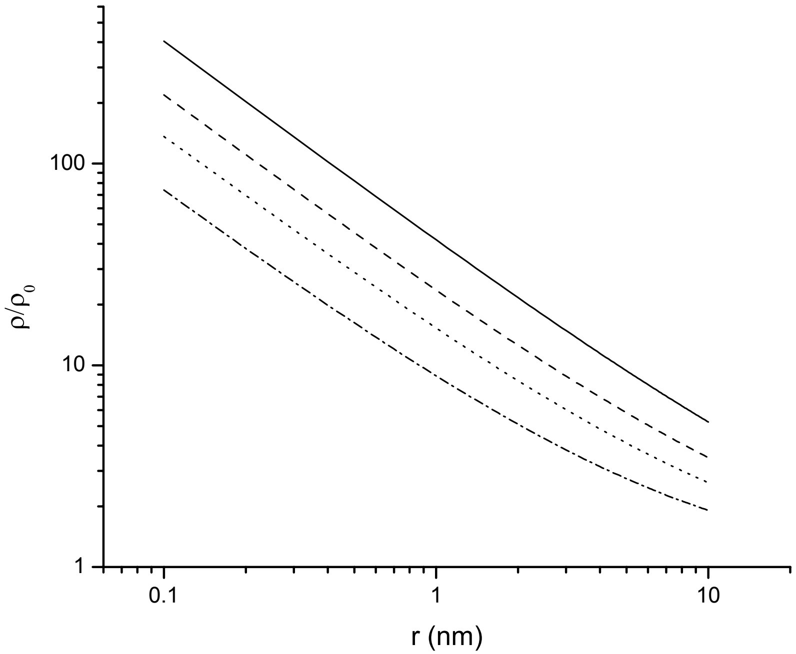
Conduction in Nanocontacts:Ohmic Calculations

$$S4(u) := \int_1^{\infty} e^{-u \cdot t} \cdot \left(t^2 - 1\right)^{\frac{1}{2}} \cdot t^{-4}\, dt$$

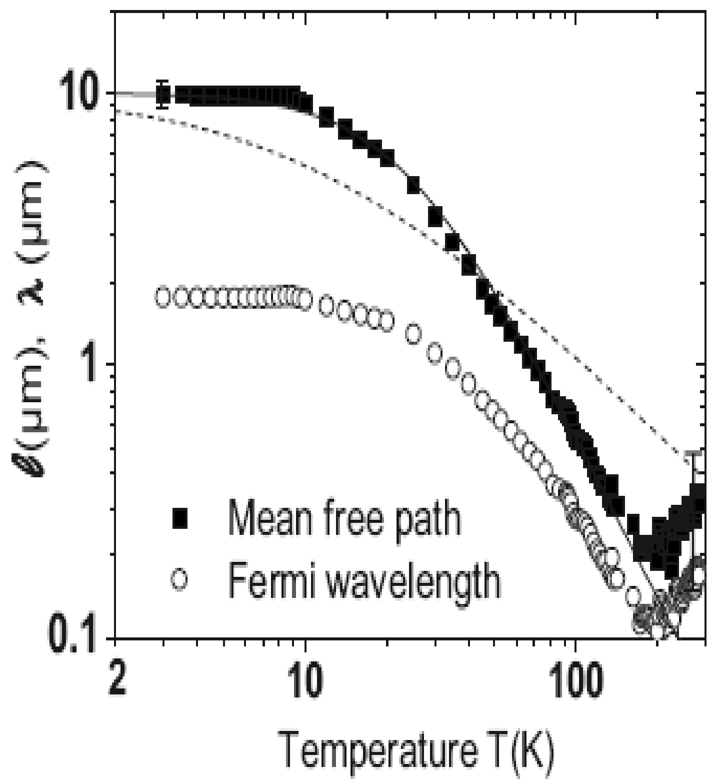
$$\psi(k) := \left[\frac{1}{k} - \frac{12}{\pi \cdot k} \cdot \int_0^1 \left(1 - t^2\right)^{\frac{1}{2}} \cdot S4(k \cdot t)\, dt \right]^{-1}$$

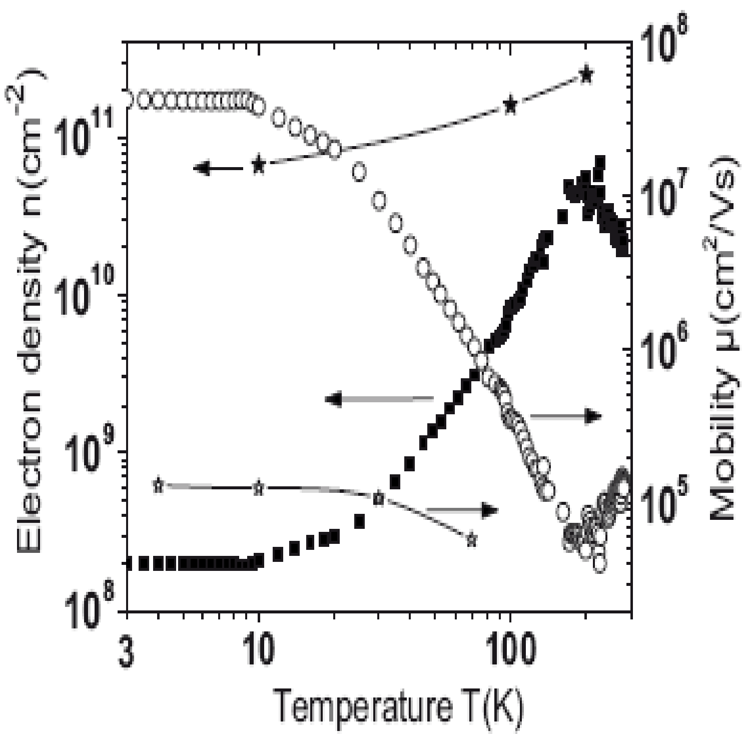
$$\sigma(k) := \frac{k}{\psi(k)}$$

$$\rho2(r,p,m) := \rho0 \cdot \left[(1-p)^2 \cdot \sum_{n=1}^{m} n \cdot p^{n-1} \cdot \sigma\left(n \cdot \frac{r}{\lambda}\right) \right]^{-1}$$



The resistivities for different *p* values as a function of the wire radius, based on the analysis from the theory of Dingle [7], see also Ref.5. The solid line, dashed line, the dotted line and the dash-dotted line represent for *p*=0, 0.3, 0.5 and 0.7 respectively.





$$\mu = (e/h)\lambda(T)\ell(T).$$

Graphite data PRB 2008 (N.G and P.E)

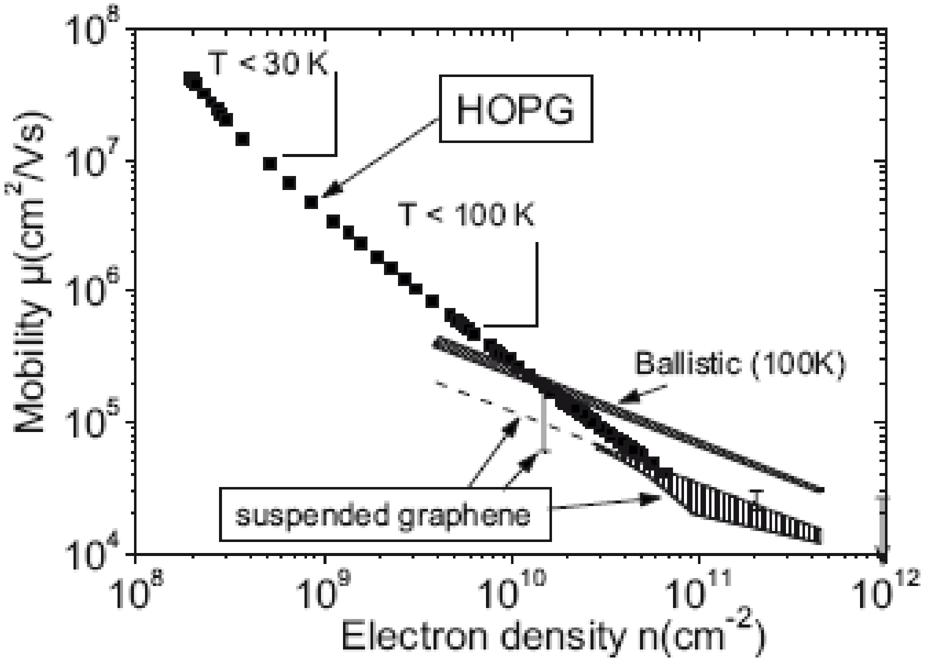
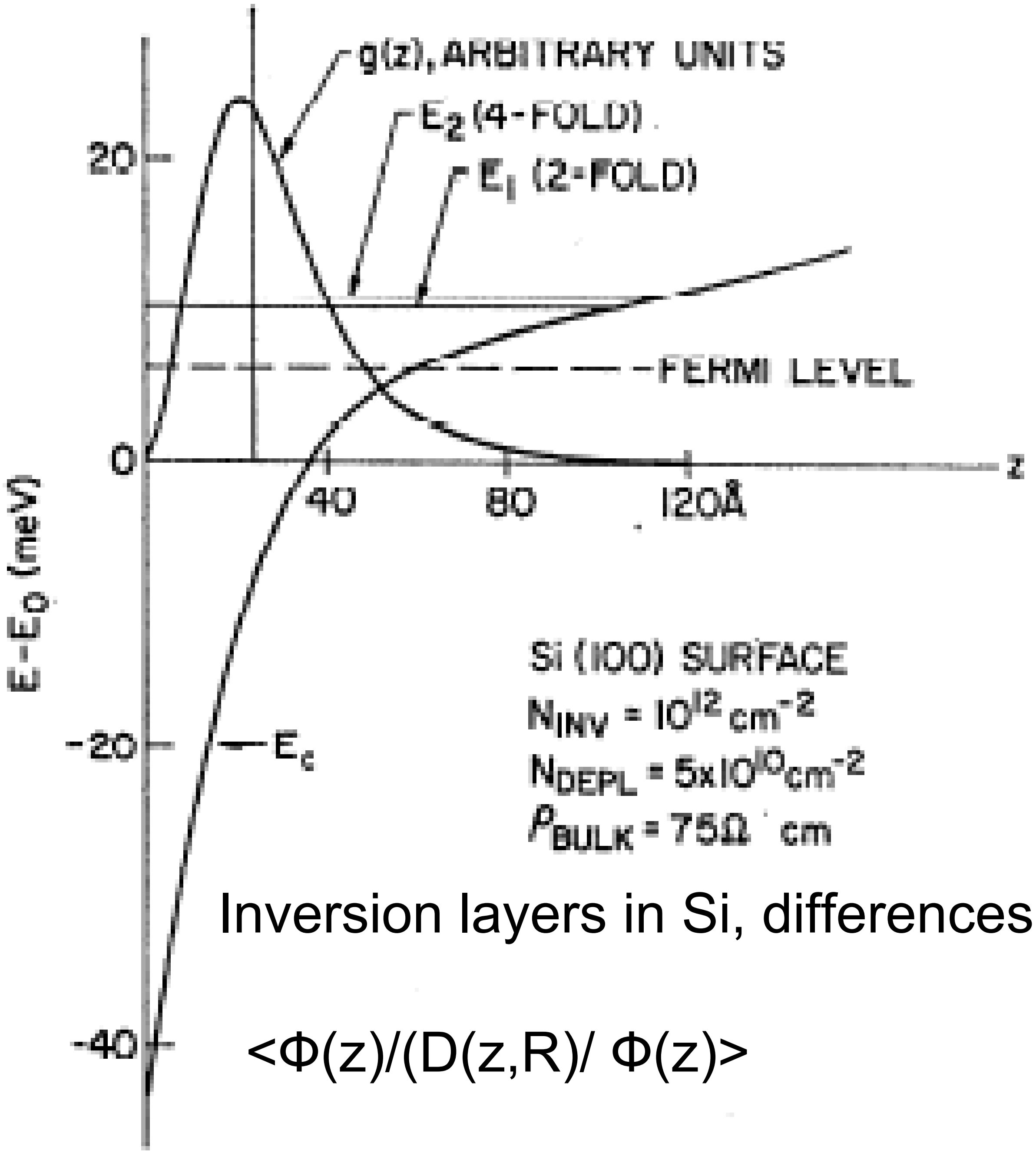


FIG. 8. Mobility vs carrier density obtained for HOPG [our data, (■)]. Note that the carrier density in our case changes with temperature that is why two temperature regions are depicted in the figure as a guide. The shadowed region called "ballistic" is obtained from the ballistic model prediction at 100 K from Ref. 19. The suspended graphene data are obtained from Ref. 19 (shadowed area and dashed line) for temperatures between 20 and 300 K and from Ref. 18 (vertical error bars) at 5 K.

18) Bolotin et al, SSC 2008

19) Skachko; Barker and Andrei, arXiv:0802.2933



Inversion layers in Si, differences with C

<Φ(z)/(D(z,R)/ Φ(z)>