G-COE PICE International Symposium and IEEE EDS Minicolloquium on Advanced Hybrid Nano Devices (IS-AHND), Tokyo, 4-5 October 2011

Silicon nanowires for advanced sensing:
Electrical and electromechanical characteristics and functionalisation technology

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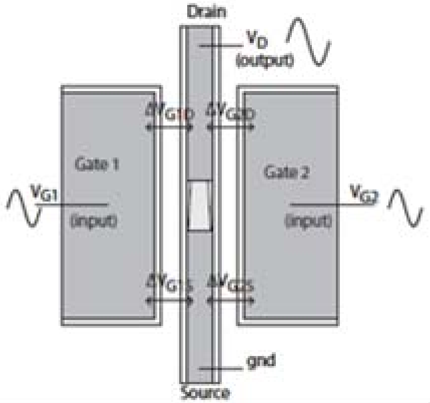
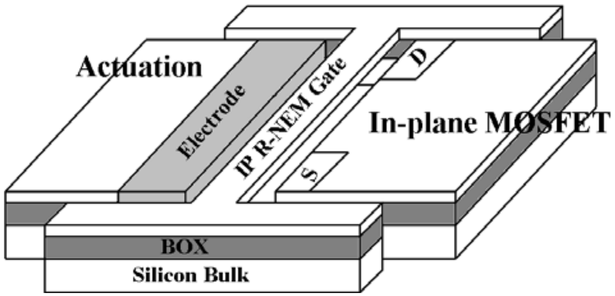
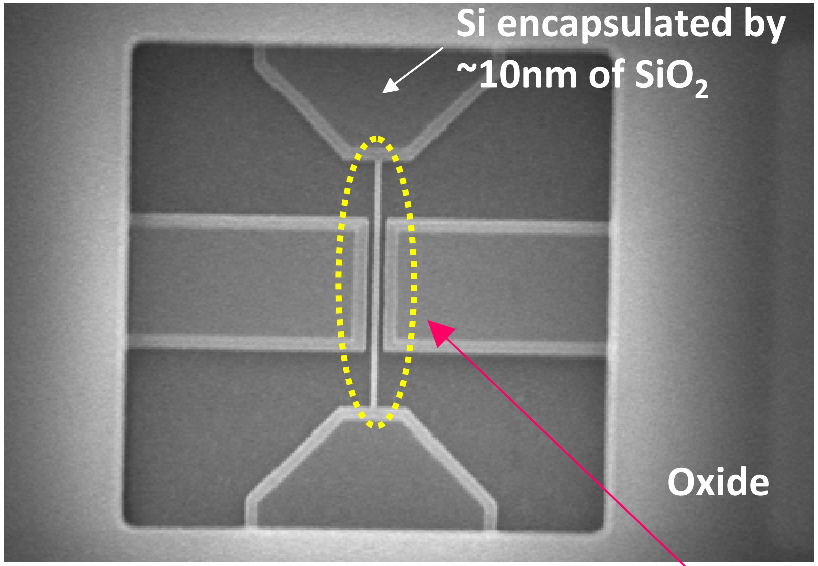
NEMSIC sensor devices

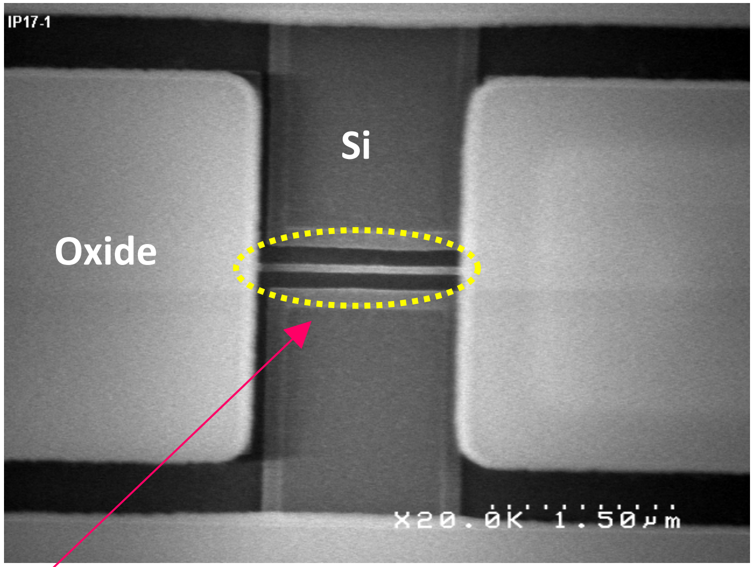


Vibrating **Body** FET
Vibrating Junctionless FET



In-plane Resonant Suspended **Gate** FET



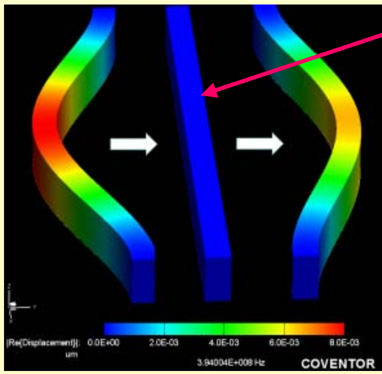


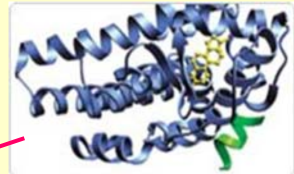
A suspended SiNW as a sensor head

NEMSIC detection principle

Resonance-based sensing – Mass detection

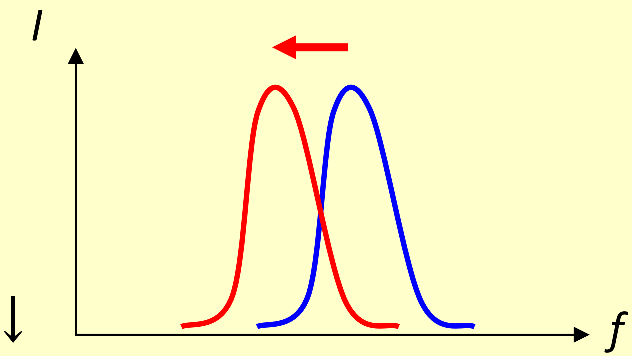
Vibrating
suspended SiNW





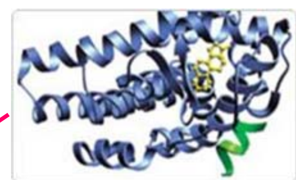
$$f_r = \frac{1}{2\pi}\sqrt{\frac{k_b}{m_b}}$$

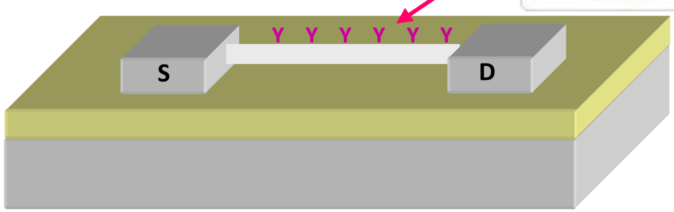
Mass ↑, Frequency ↓

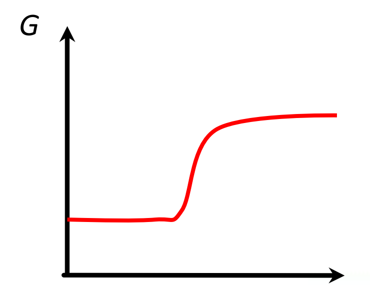


cf. conventional principle:

Conduction-based sensing – Charge detection







Outline

- **Development of selective surface functionalization techniques for SiNWs**
- **SiNW electrical characteristics and the impact of suspension and surface functionalization**
- **Design and fabrication of in-plane resonant suspended gate FETs (IP-RSGFETs)**
- **Summary**

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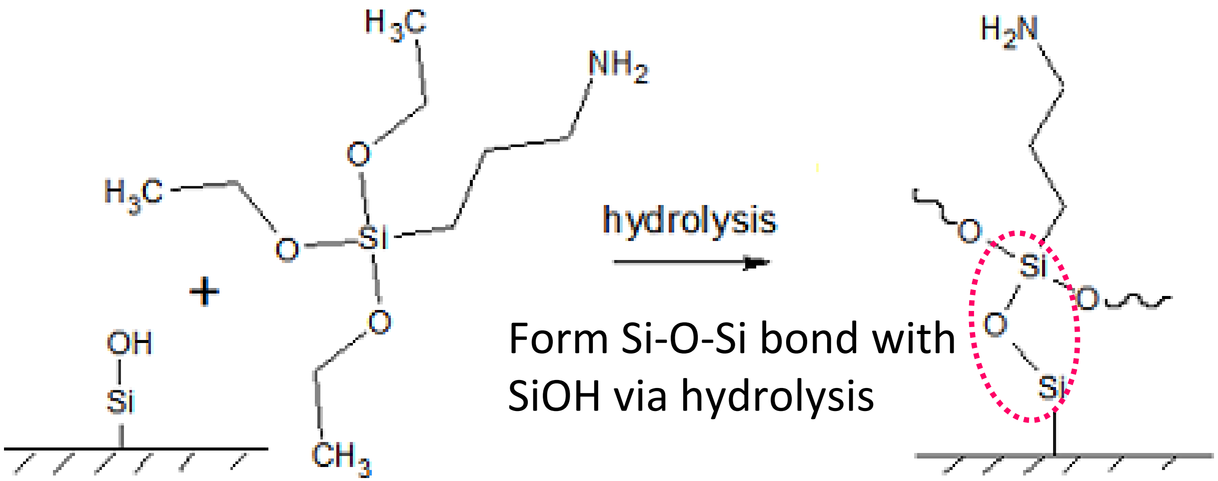
Bio-functionalization using NH_2-SAM on SiO_2

NH_2-SAM deposition on SiO_2

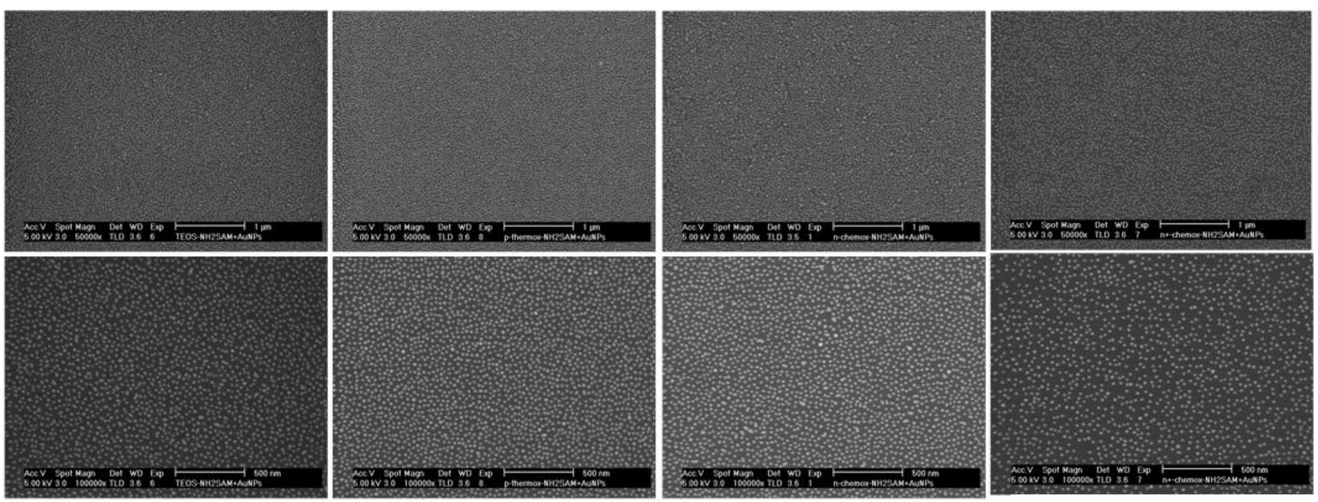


APTS (Amino-propyltrimethoxysilane)

Sample	**C.A** (degrees)
Cleaned SiO_2	< 10
NH_2-SAM 15min	52.1 (reported as monolayer CA)
30min	54.9
45min	58.3
1h	60.1

BOFORE

AFTER



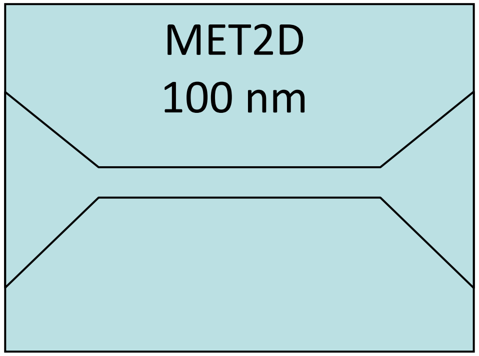
TEOS oxide | p-type thermally grown oxide | n-type native oxide | n-doped chemical oxide

Works for all different types of SiO2

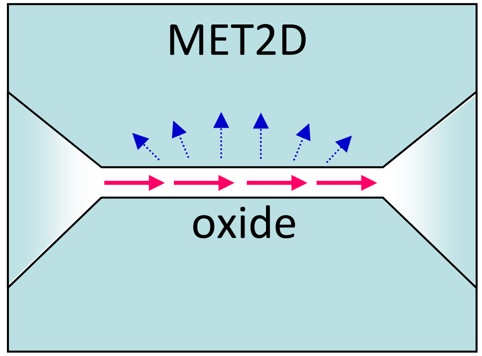
S. Armini *et al.*, MRS Symposium on Functional Materials and Nanostructures for Chemical and Biochemical Sensing (2010)

Selective functionalization of SiNW surface

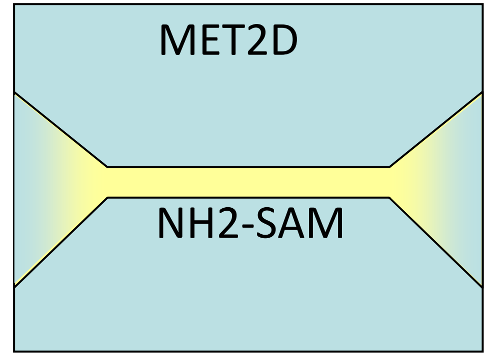
① Joule heating method



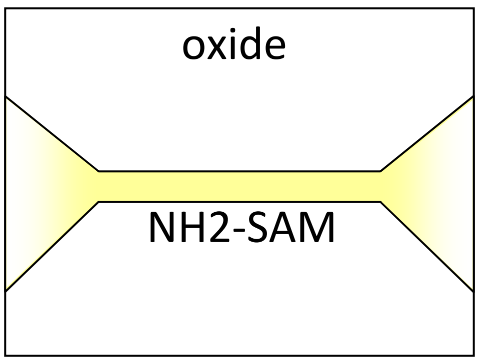
Resist spincoating



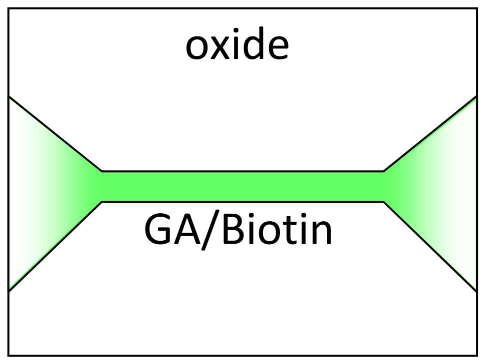
Ablation via Joule heating



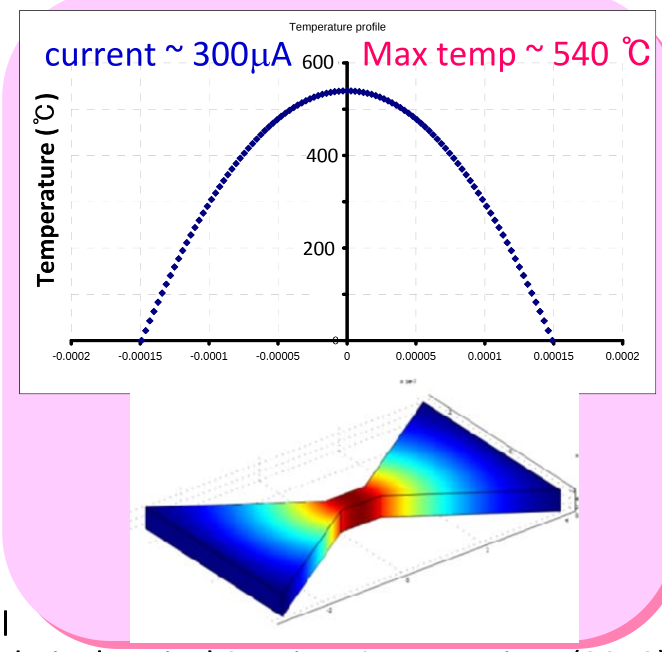
SAM coating



Resist removal



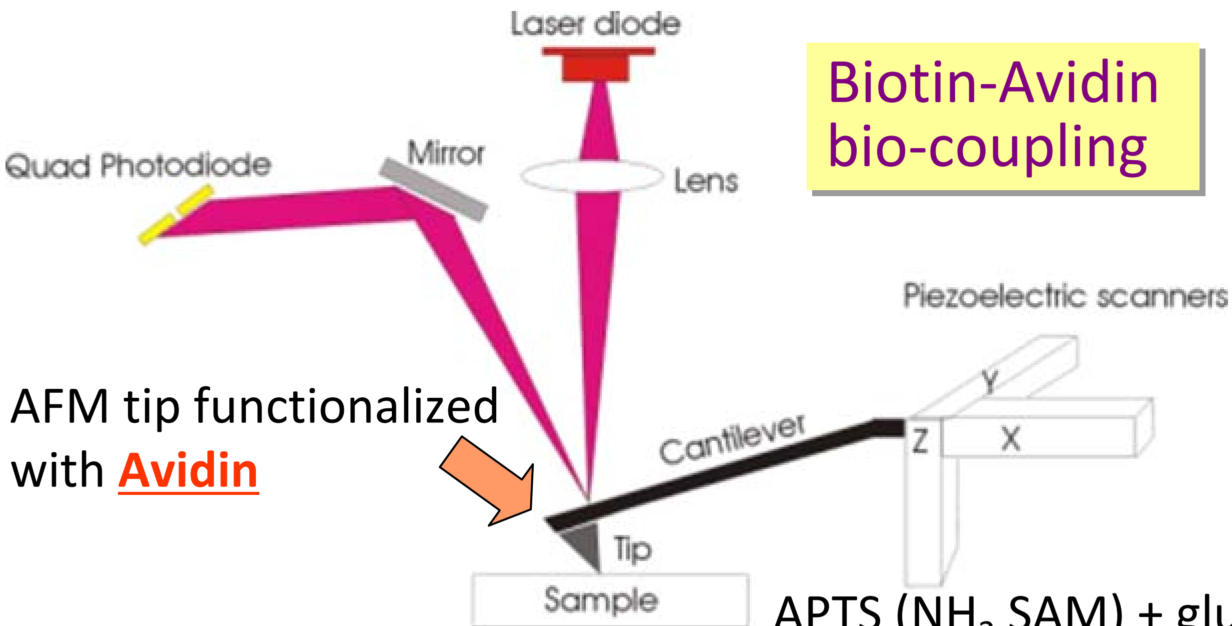
Biofunctionalization



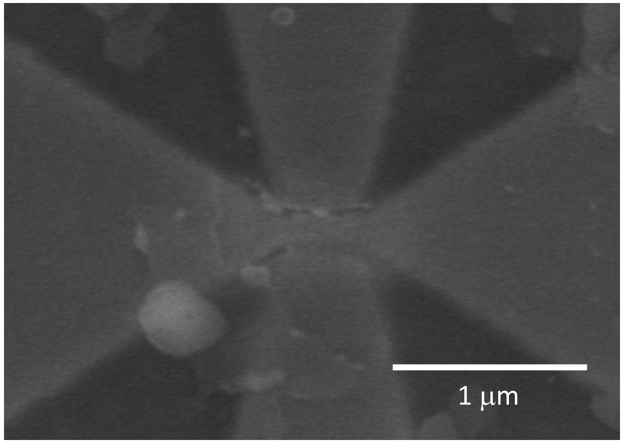
S. Armini *et al.*, MRS Symposium on Functional Materials and Nanostructures for Chemical and Biochemical Sensing, San Francisco (2010)

AFM-based testing of selective functionalization

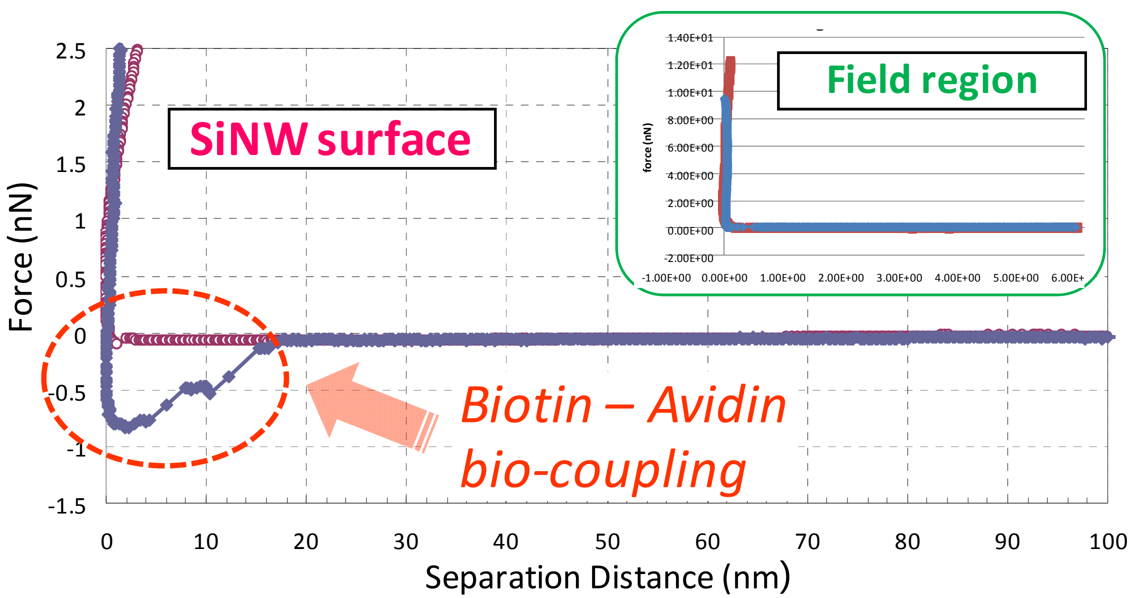
Biotin-Avidin bio-coupling

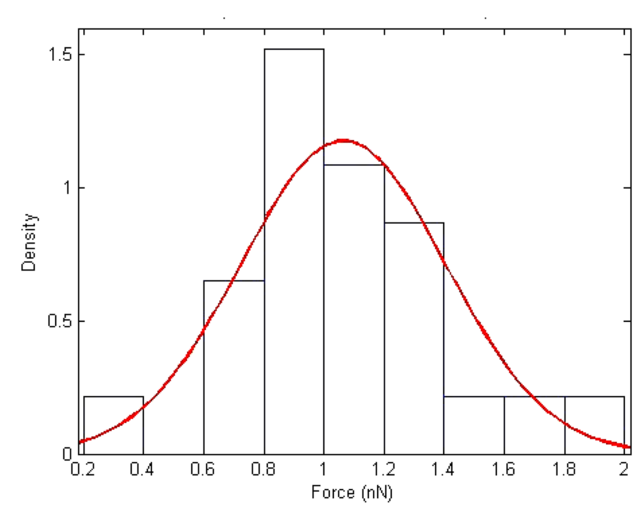


AFM tip functionalized with **Avidin**



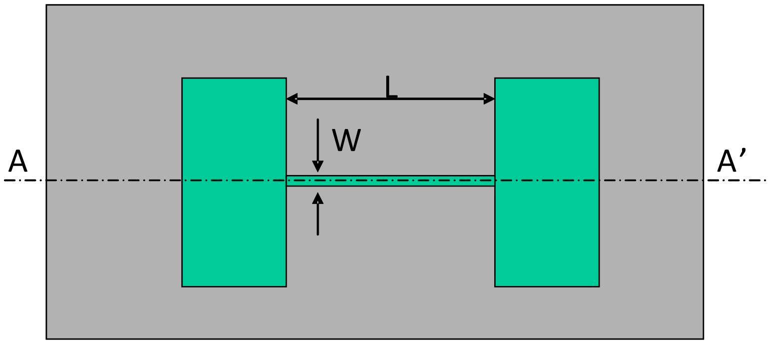
APTS (NH_2 SAM) + glutaraldehyde (GA) + **Biotin**



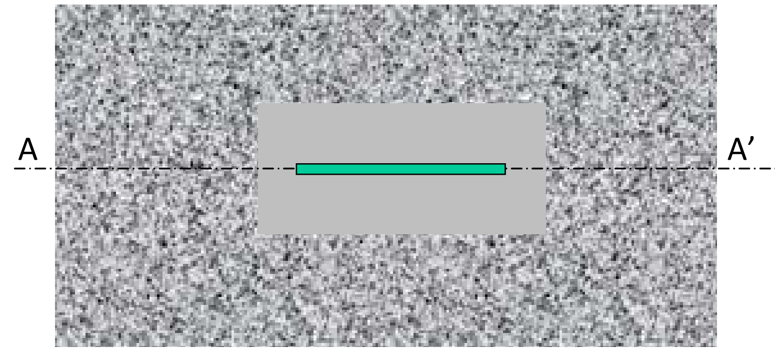


Selective functionalization of SiNW surface

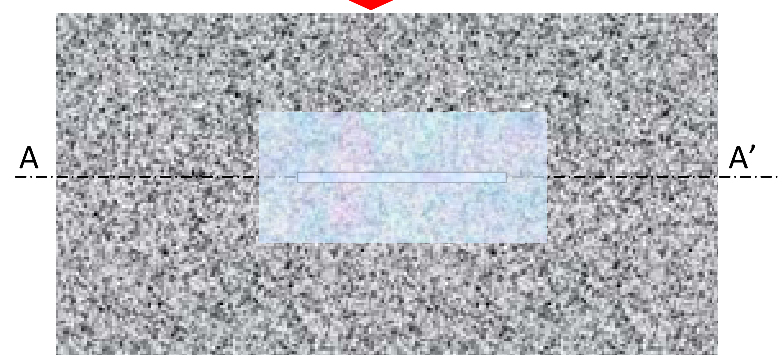
② E-beam lithography appriach



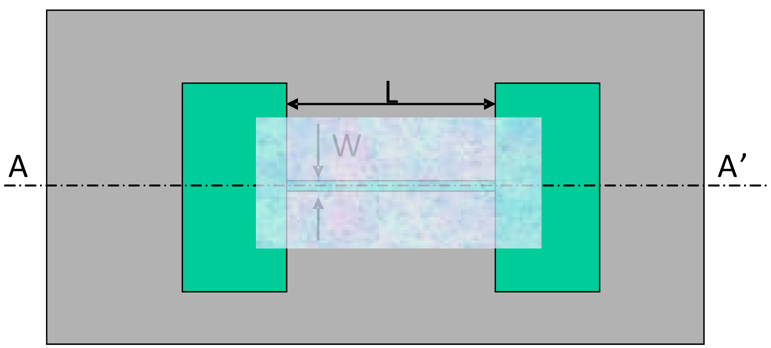
Spin coating develop 100 nm resist MET-2D



E-beam lithography resist opening



Short clean + NH_2-SAM deposition

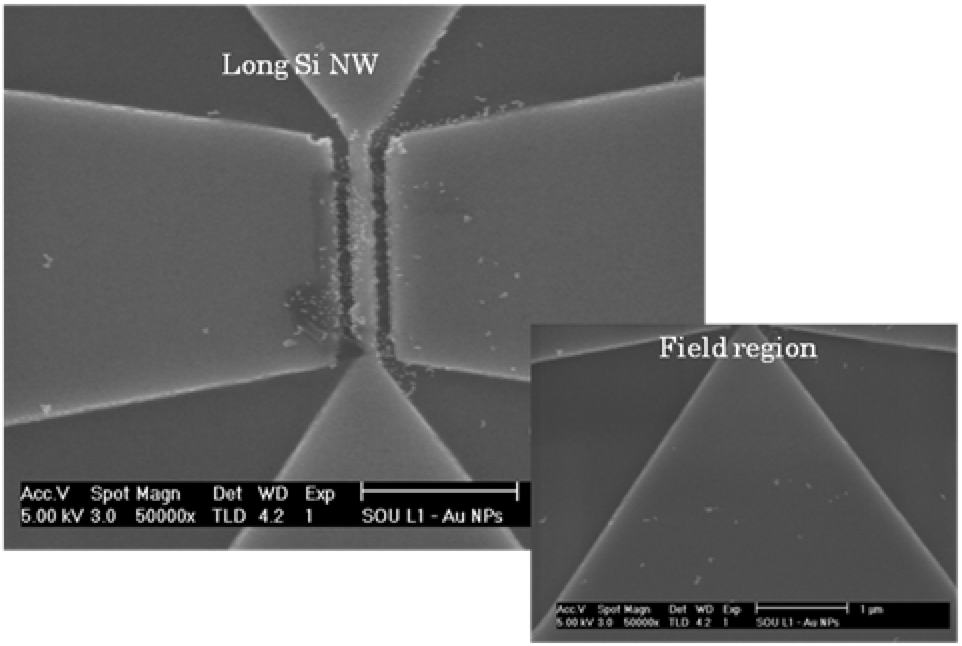


Selective resist removal

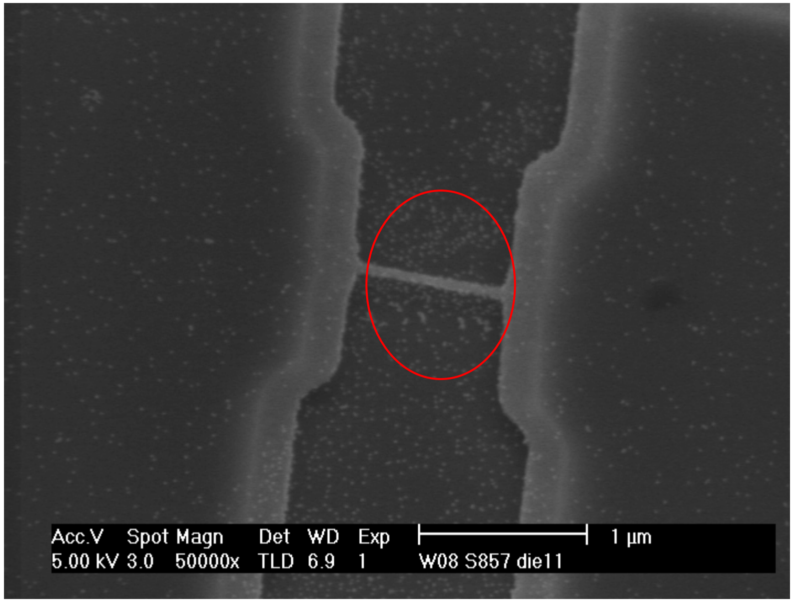
S. Armini *et al.*, MRS Symposium on Functional Materials and Nanostructures for Chemical and Biochemical Sensing (2010)

Testing of selective functionalization with AuNPs

Nonsuspended SiNW



Suspended SiNW



- ✓ Only SiNW region decorated by Au NPs (15 nm)
- ✓ Suspended Si NWs survived the spin coating of the polymer resist, ebeam lithography, resist removal in acetone and functionalization in toluene

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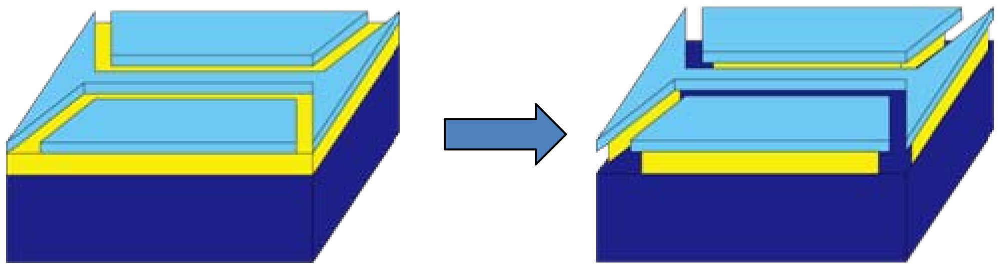
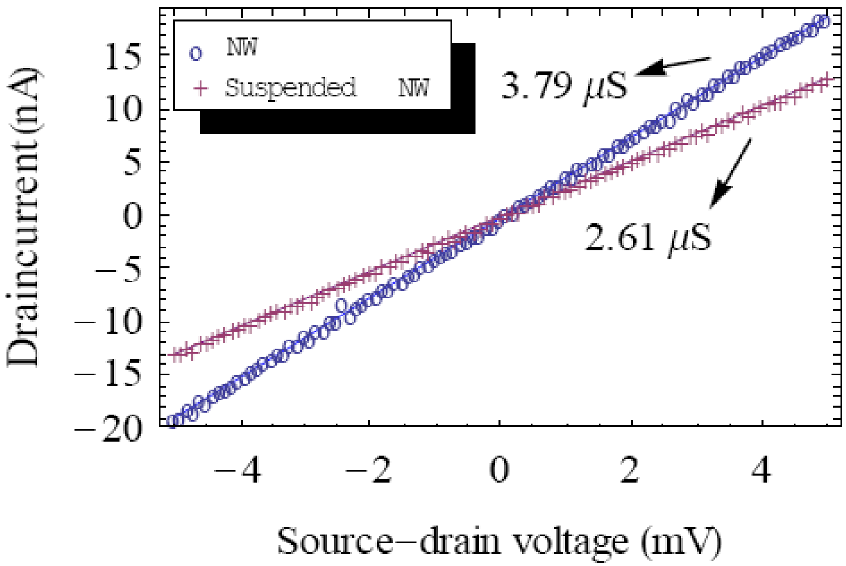
Impact of SiNW suspension

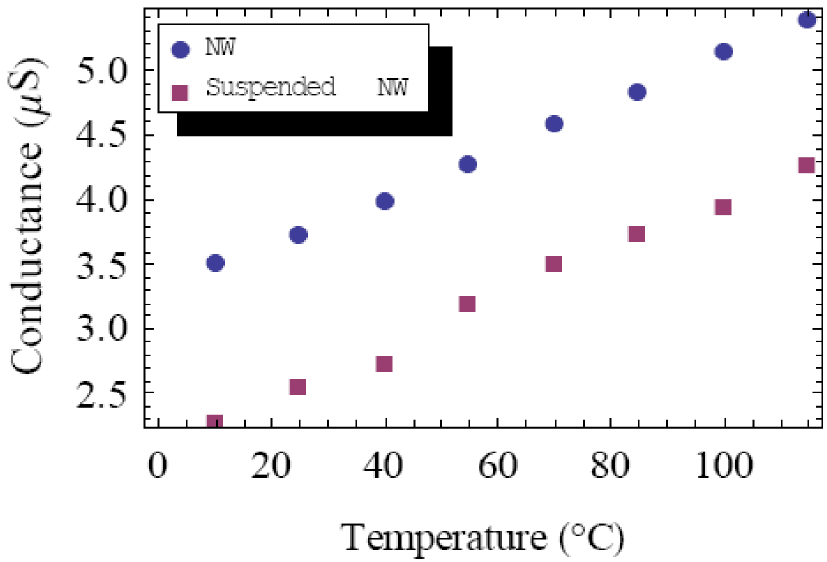


SOI N_D = 2 x 10^{19} cm^{-3}
SOI thickness t_{SOI} = 53 nm
SiNW length L = 0.5 - 2.0 μm
SiNW width W = 100 nm

I-V characteristics



T dependence of *G*

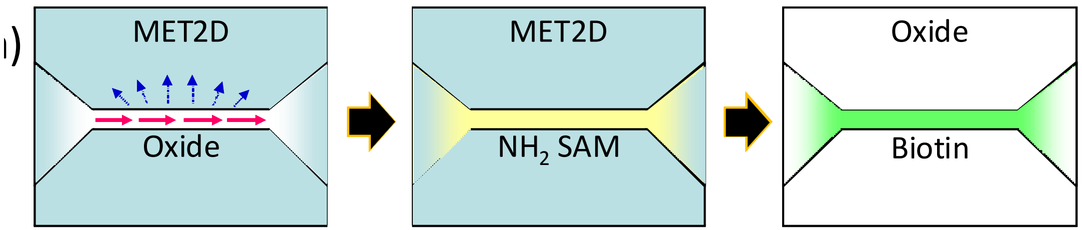


- Conductance decreases after suspension
- Conductance increases with increasing temperature

M. A. Ghiass *et al.*, Microelectronic Engineering **88**. pp. 1753-1756 (2011)

Impact of bio-functionalisation

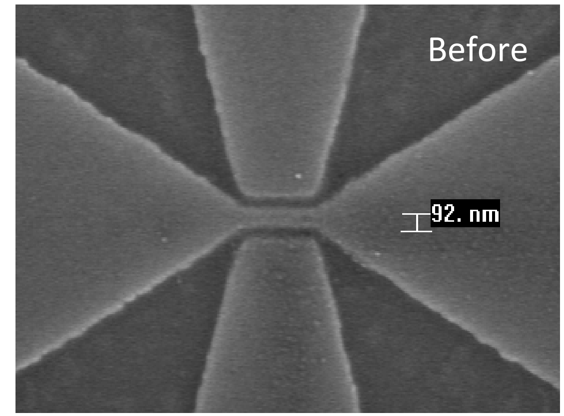
- Comparison between before and after bio-functionalisation

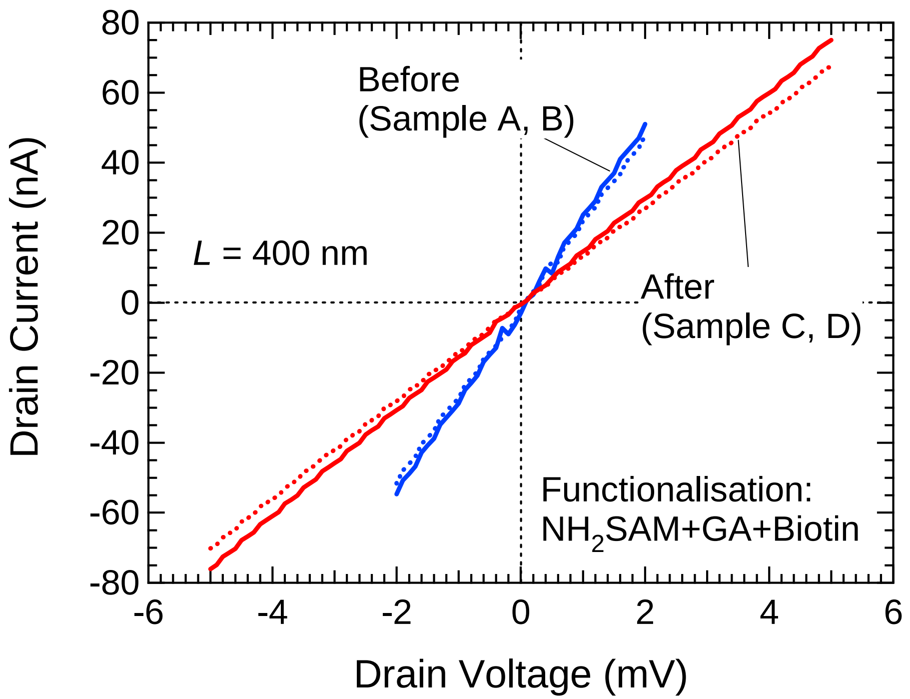


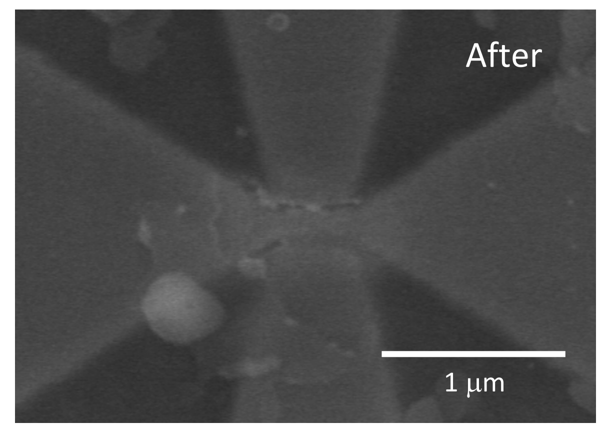
Ablation of deposited MET2D by Joule heating

NH_2 SAM coating

Resist removal followed by GA/Biotin functionalisation







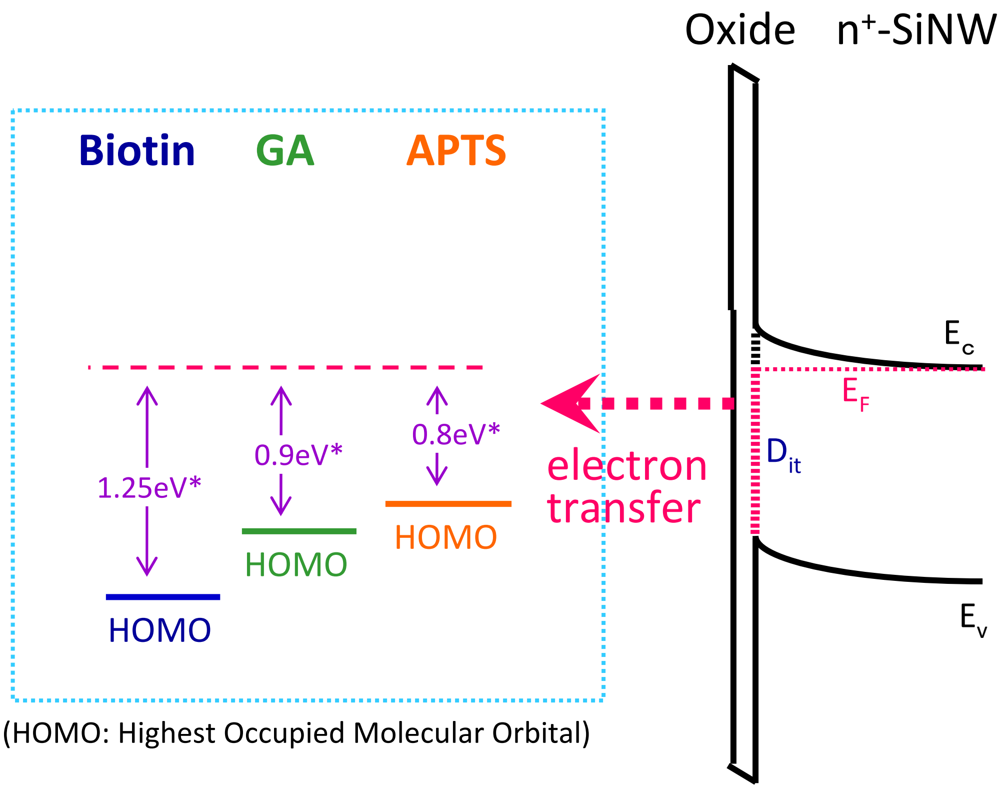
Conductance reduction after functionalisation

M. A. Ghiass *et al.*, Microelectronic Engineering **88**. pp. 1753-1756 (2011)

Possible charge transfer mechanism

SAM layers

Silicon nanowire



(HOMO: Highest Occupied Molecular Orbital)

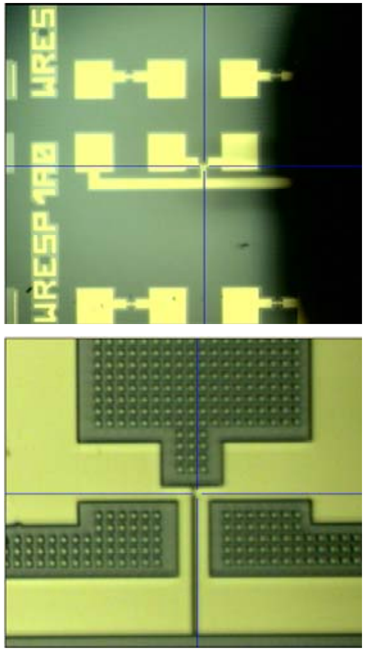
Electron transfer expected from SiNW to surface molecular layers results in conductance reduction

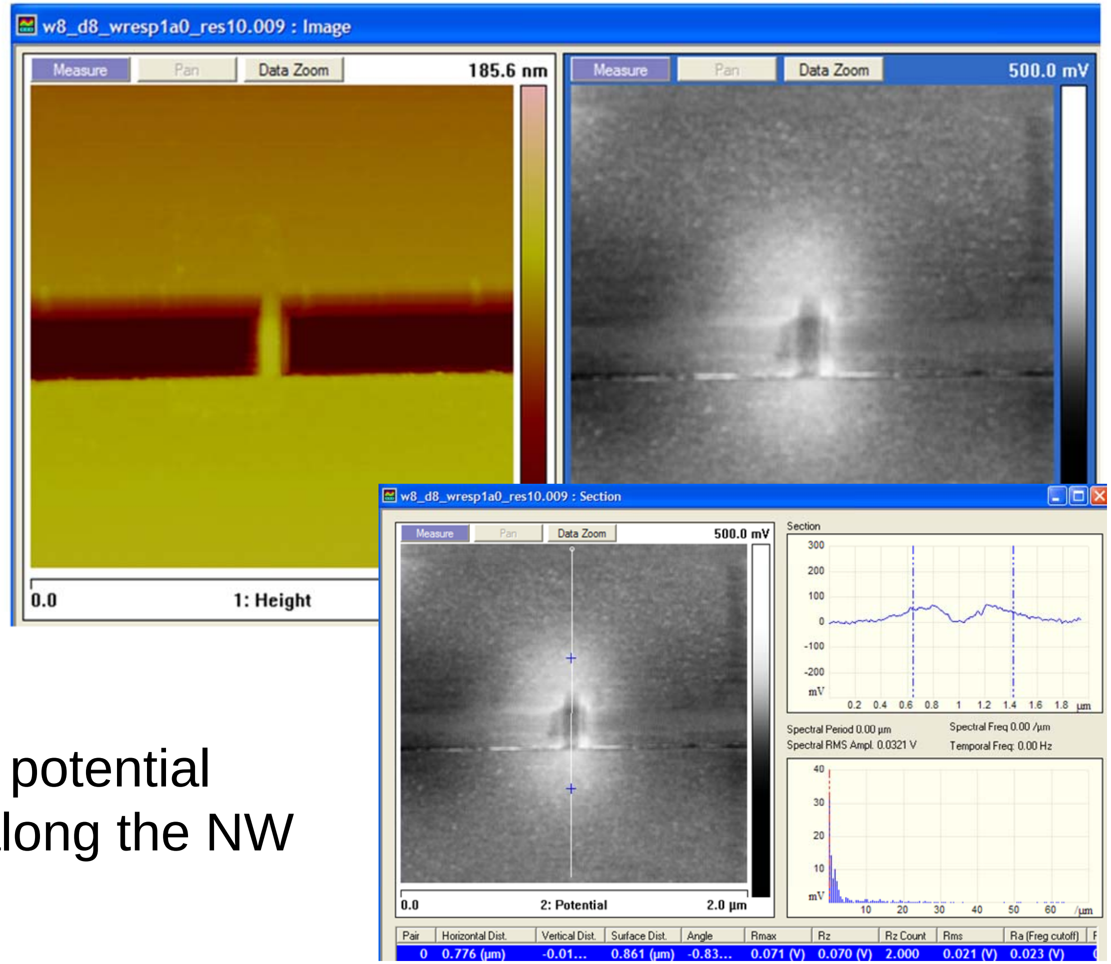
*All HOMO energies of organic molecules were estimated the KFM results reported in D. M. Taylor et al., ‘Characterization of chemisorbed monolayers by surface potential measurements’, J. Phys. D: Appl. Phys. 24, 1443 (1991)

Surface potential distribution

Topography

Surface potential



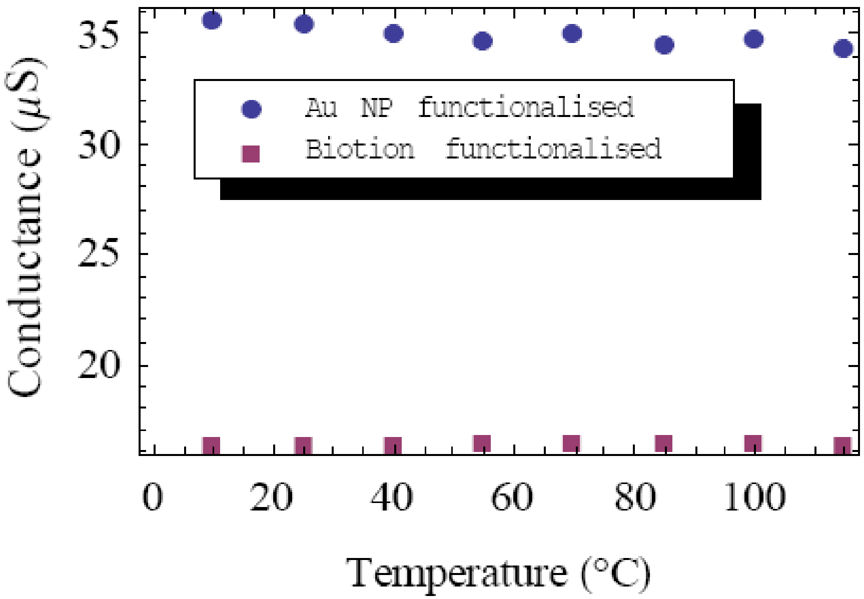


Surface potential profile along the NW

Surface potential shift in the cloudy rectangular area corresponds to the NH2 SAM selective functionalization.

Temperature dependence of conductance

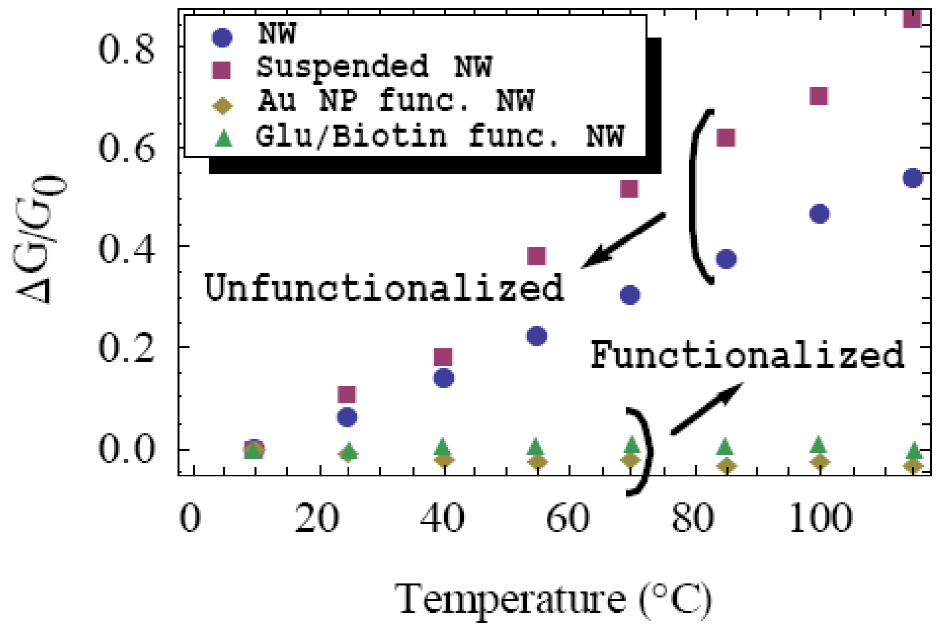
Conductance G vs T



Normalised conductance difference

$\Delta G/G_0 = (G-G_0)/G_0$ vs T

G_0: Conductance at T = 10 °C



After functionalisation

- $\Delta G/G_0$ is virtually temperature independent
- Regardless of the difference in functionalisation methods

➡ Advantageous for real sensing applications

M. A. Ghiass *et al*., Microelectronic Engineering **88**. pp. 1753-1756 (2011)

SiNW LF noise spectra for advanced sensing scheme

Conduction noise in Si NW

conductance + LNF spectra

advanced sensing scheme

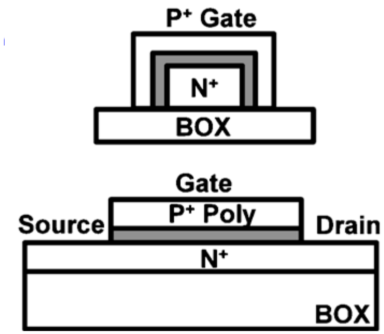
Low frequency noise measurements

✓To investigate the oxide/interface traps

✓To explore a new sensing scheme using noise spectra beyond conductance detection

LF noise in Junctionless Transistor

Jang *et al.* Appl. Phys. Lett. **98**, 133502 (2011).



Hooge mobility fluctuation (HMF)

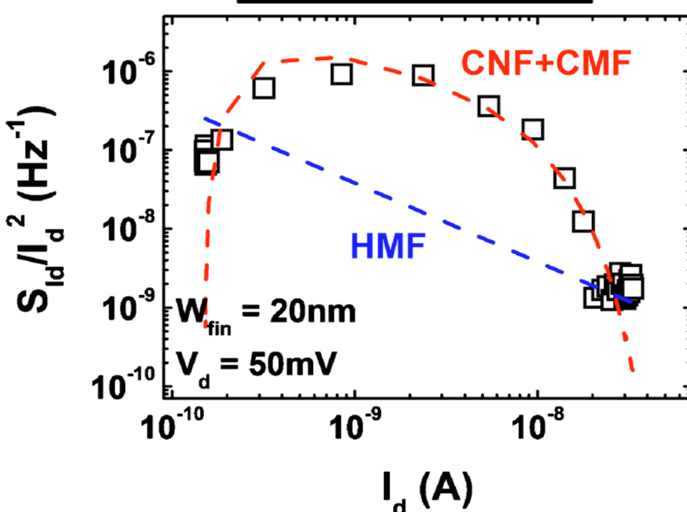
—— Expected in bulk conduction

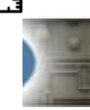
$$\frac{S_{Id}}{I_d^{\beta}} = \frac{\alpha_H}{N_c}\frac{1}{f^{\gamma}} = \frac{q\alpha_H \mu_{bulk} V_d}{f^{\gamma} I_d L^2}$$

Carrier number fluctuation correlated with carrier mobility fluctuation (CNF+CMF)

—— Related to surface conduction

$$\frac{S_{Id}}{I_d^2} = S_{Vfb} \cdot \left(1 + \alpha_C \mu_{eff} C_{ox} \frac{I_d}{g_m}\right)^2 \cdot \left(\frac{g_m}{I_d}\right)^2$$

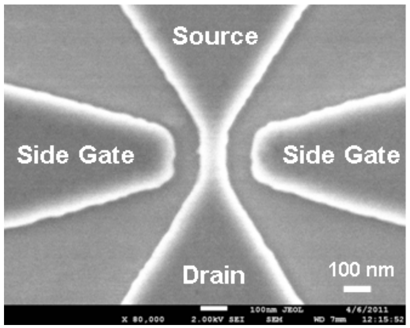




Results are rather consistent with CNF+CMF

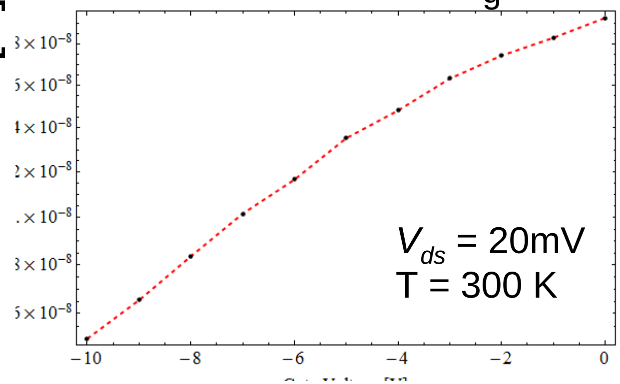
LF noise in non-suspended n-type SiNWs

Device structure



Conduction current vs V_g

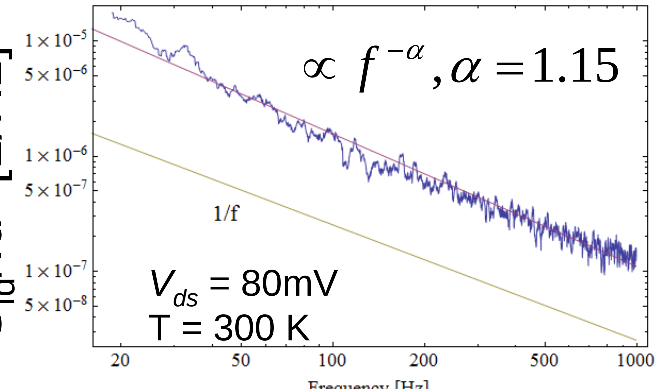
Drain current [A]



Side gate voltage [V]

Noise spectrum

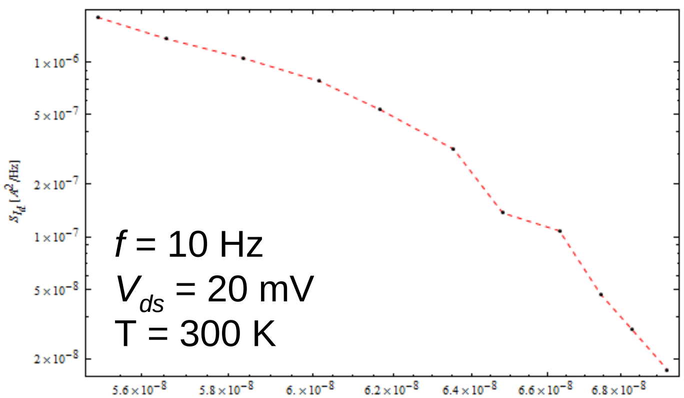
S_{Id}/Id^2 [1/Hz]



Frequency [Hz]

Noise intensity vs I_d

S_{Id}/Id^2 [1/Hz]



Drain current [A]

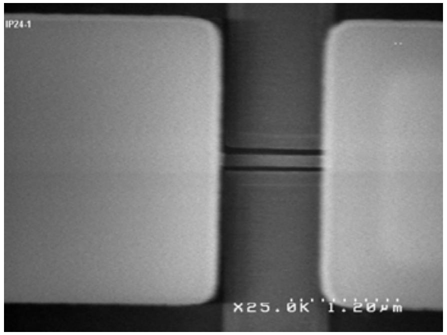
Noise intensity reduced with increasing drain current

- Indicating the result is related to mobility fluctuation but it is not clear whether this is with HMF or CNF+CMF
- Data should be taken by varying wider range of drain current

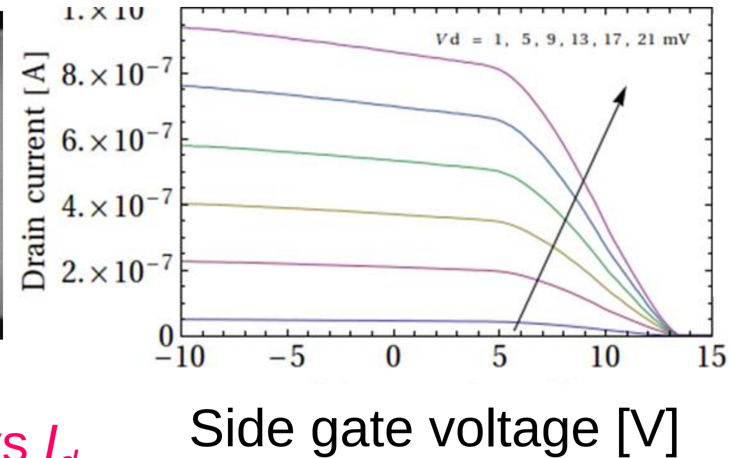
LF noise in suspended p-type SiNWs

(Preliminary)

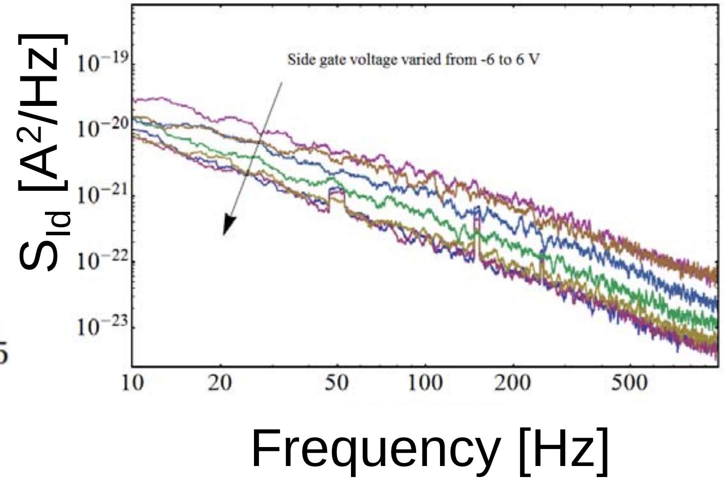
Device structure



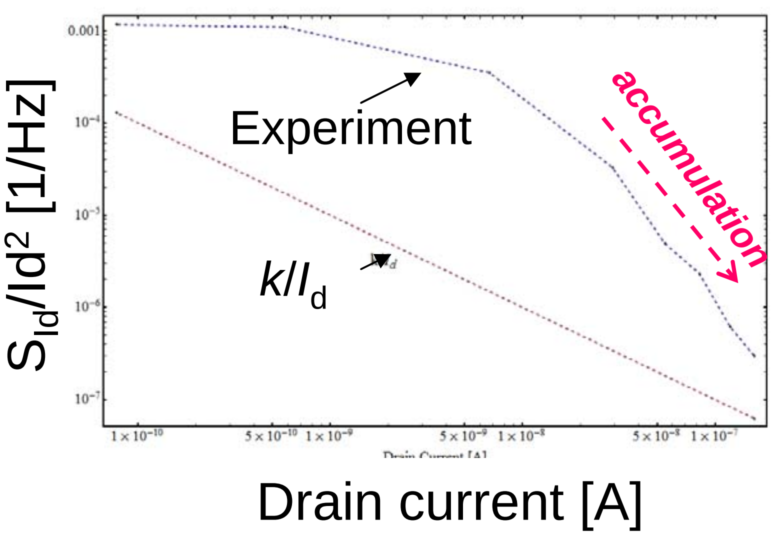
Conduction current vs V_g



Noise spectra



Noise intensity vs I_d



- I_d dependence of S_{Id}/I_d^2 is similar to the results of Jang et al's, i.e., (CNF+CMF)

- S_{Id}/I_d^2 in the ***accumulation region*** is governed by CNF at the surface and interface ⇒ may be used for advance sensing.

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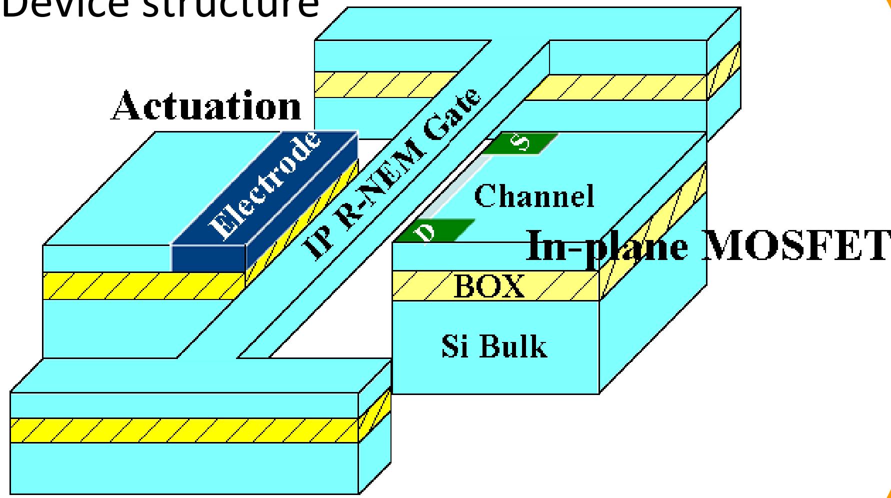
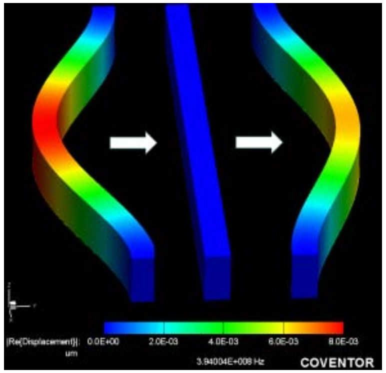
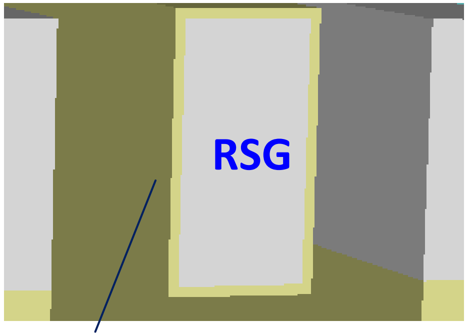
Design of IP-RSGFETs for mass detection

Device structure

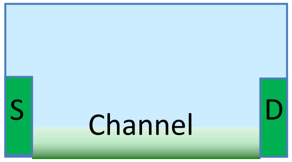


3D FEM analysis of RSG with surface layers using CoventorWare

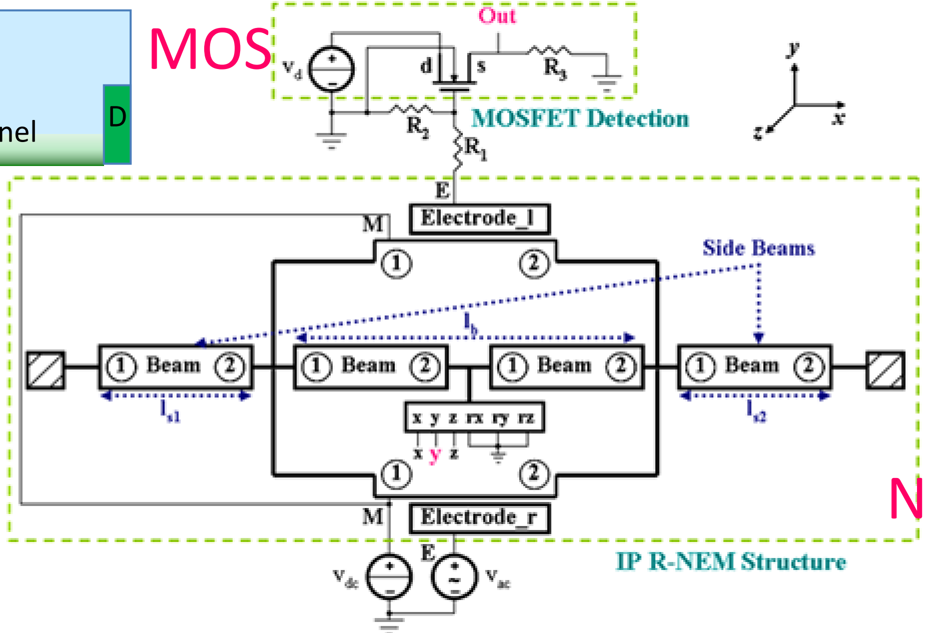




Surface functionalization & molecule adsorption /desorption

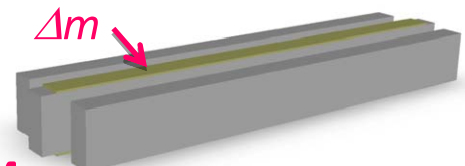


MOS

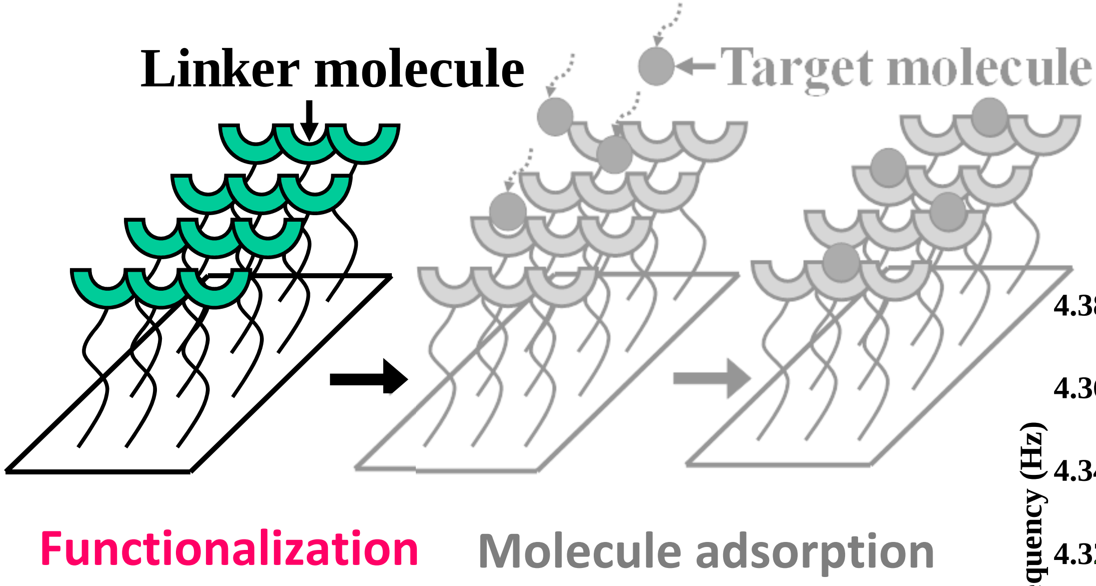


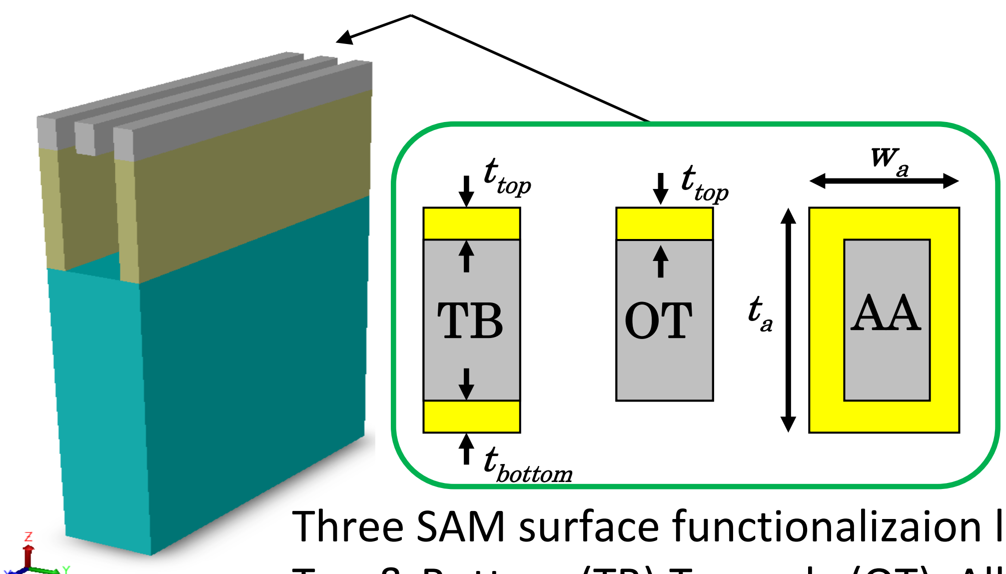
NEM

NEM-MOS hybrid circuit analysis using Architect

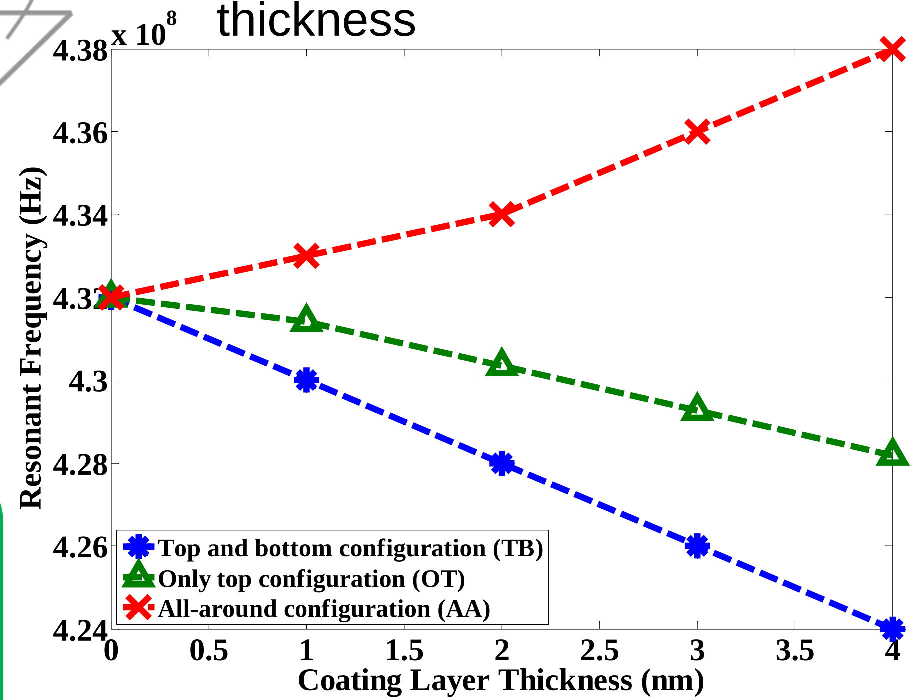


Surface layer modelling in 3D FEM analysis





Resonance frequency vs SAM surface functionalization layer thickness



RSG mass ↑ ➡ f_R ↓

RSG stiffness ↑ ➡ f_R ↑

Three SAM surface functionalizaion layer configuration:
Top & Bottom (TB),Top only (OT), All around (AA)

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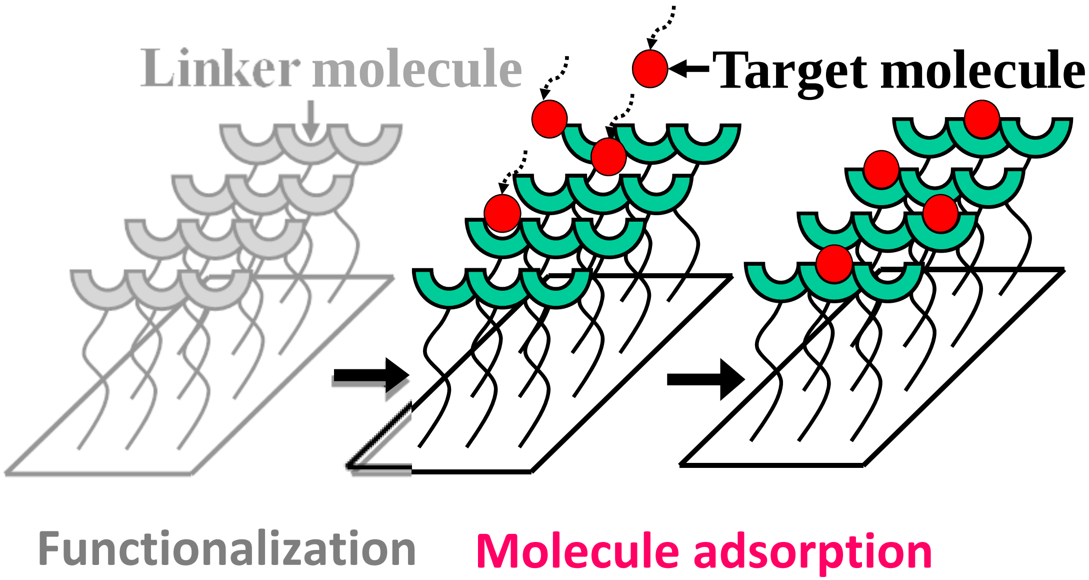
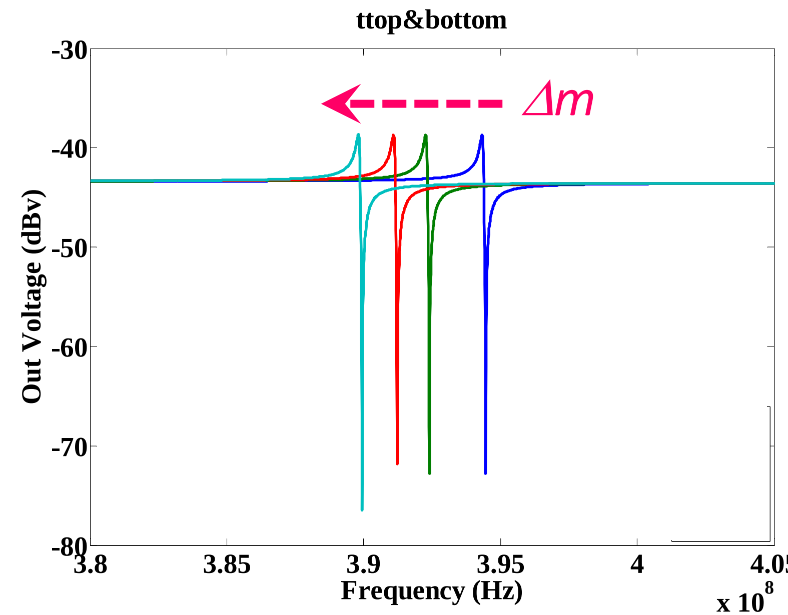
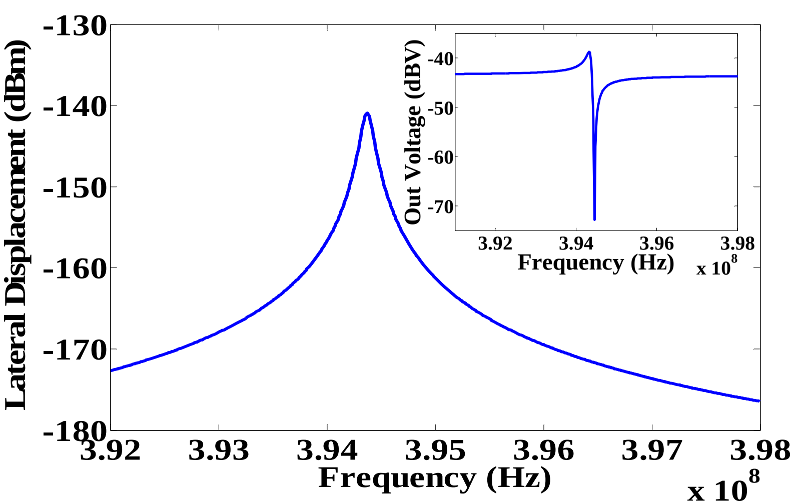
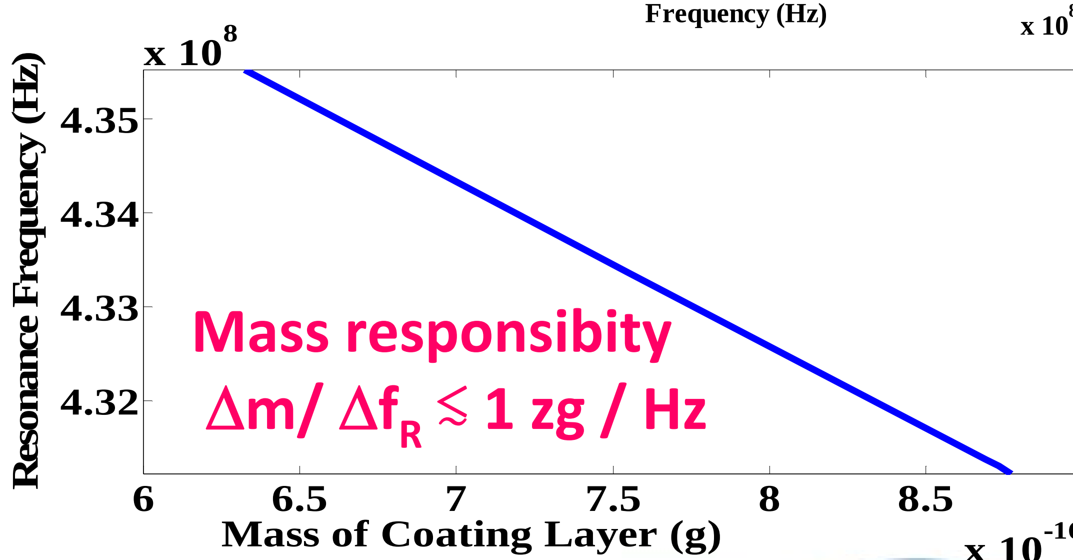
NEMS

Surface layer modelling in 3D FEM analysis









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RSG Q-factor design

Quality factor analysis & advanced RSG design

Numerical modelling of Q-factor

$$\frac{1}{Q_{total}} = \frac{1}{Q_{air}} + \frac{1}{Q_{anchor}} + \frac{1}{Q_{structural}}$$

Q_{air} : dissipation in air

Q_{anchor}: through the anchors

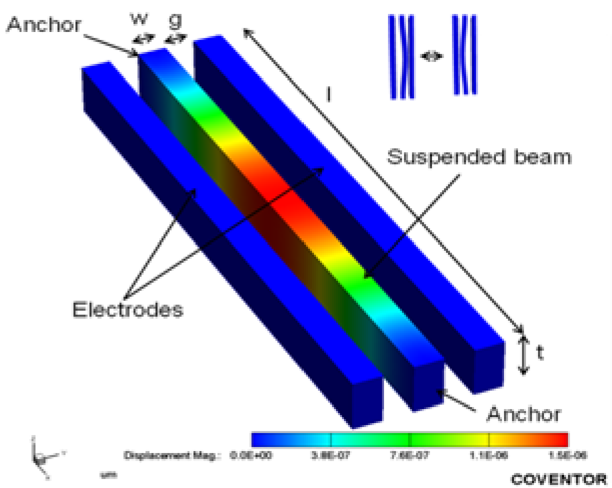
$Q_{\mathrm{structual}} = Q_{\mathrm{material}} + Q_{\mathrm{thermoelastic}}$

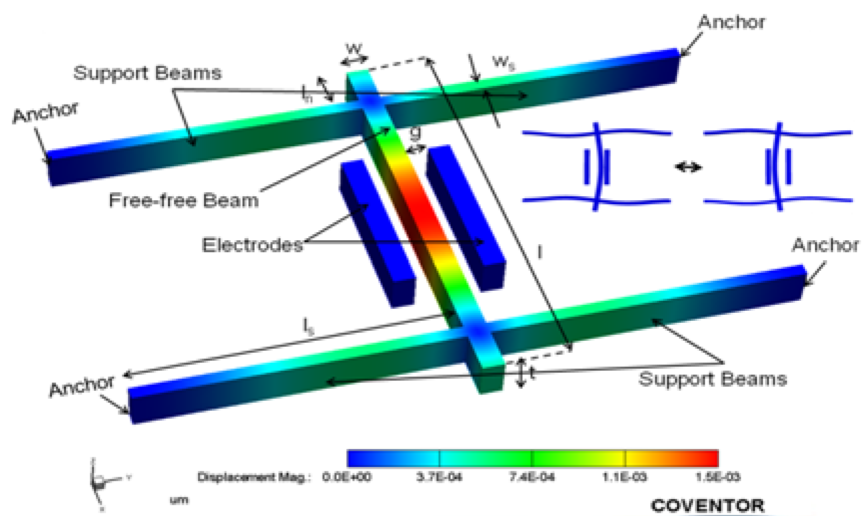
Q_{material}: material loss

$Q_{\mathrm{thermoelastic}}$: thermoelastic damping

Clamped-clamped RSG

Free-free RSG





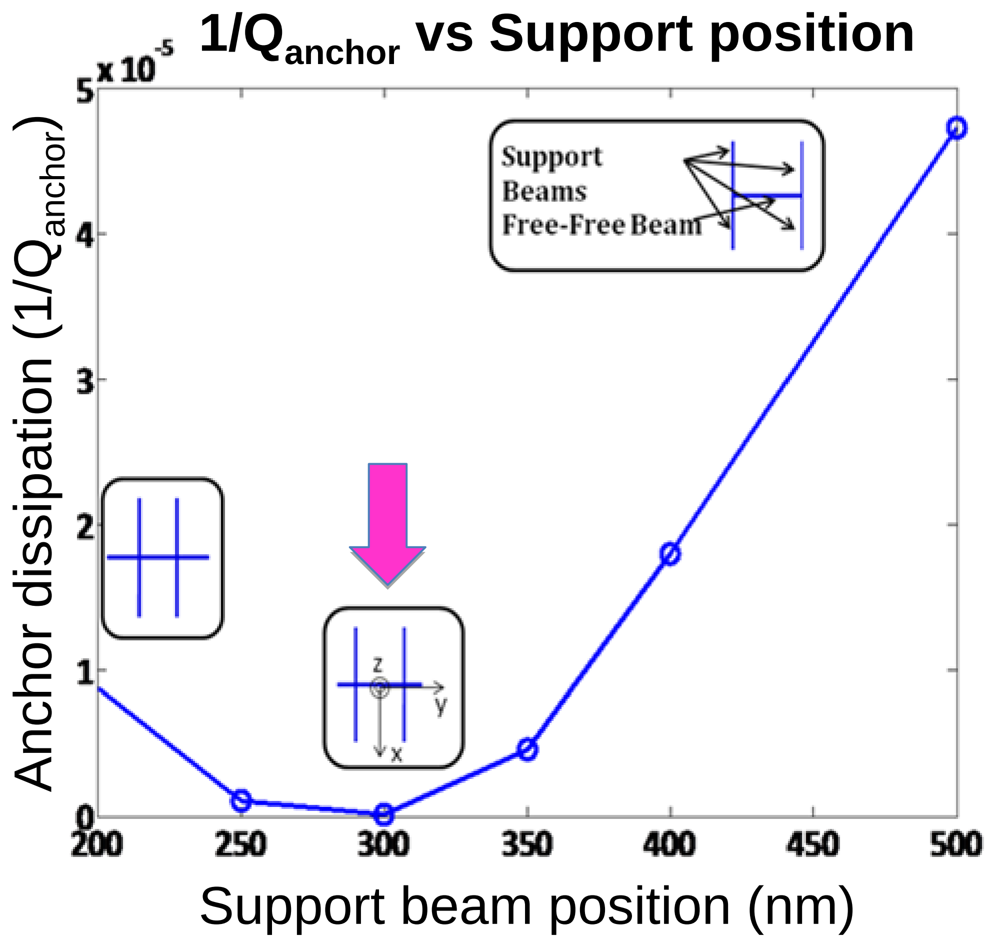
RSG Q-factor design

Clamped-clamped RSG

f_0=432.47 MHz b=3.724x10^{-12} (N.s)/m Mass sensitivity= 0.0544 zg/Hz
Q_{Air}=6245.97 $Q_{Thermoelastic}$=680632.73 Q_{Anchor}=3153.67 Q_{Total}=2089.15

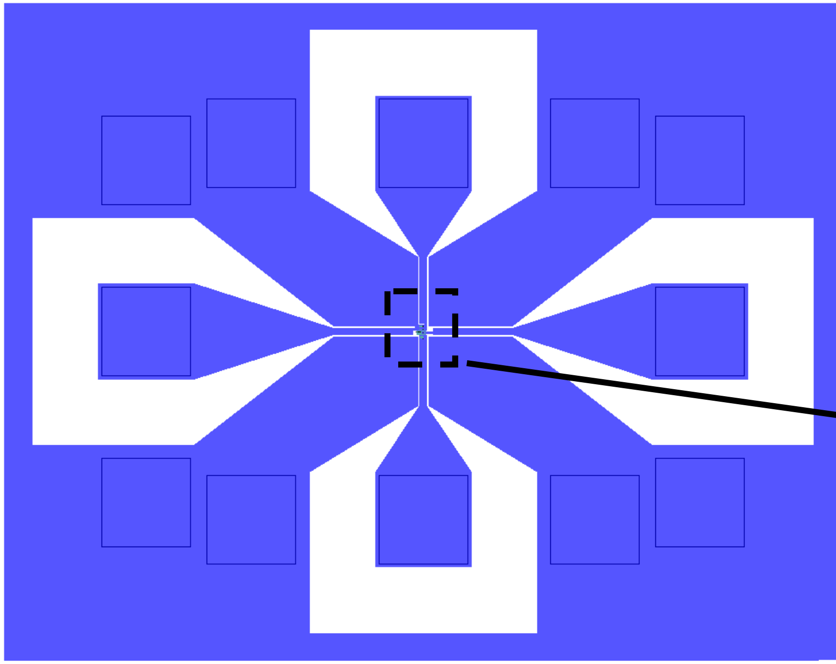
Free-free RSG

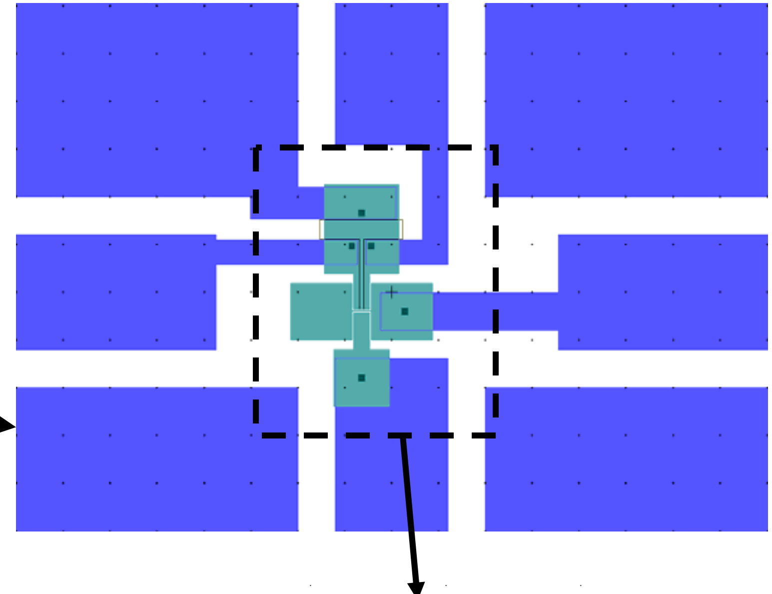
f_0=368.75 MHz b=3.5632x10^{-12} (N.s)/m Mass sensitivity= 0.2363 zg/Hz
Q_{Air}=8348.71 $Q_{Thermoelastic}$=1462838.84 Q_{Anchor}=10535972.28 Q_{Total}=8294.79

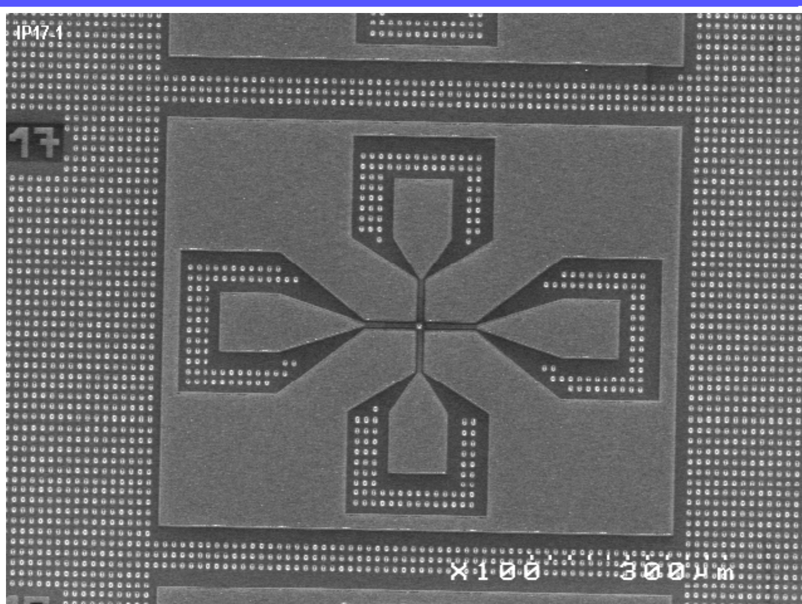


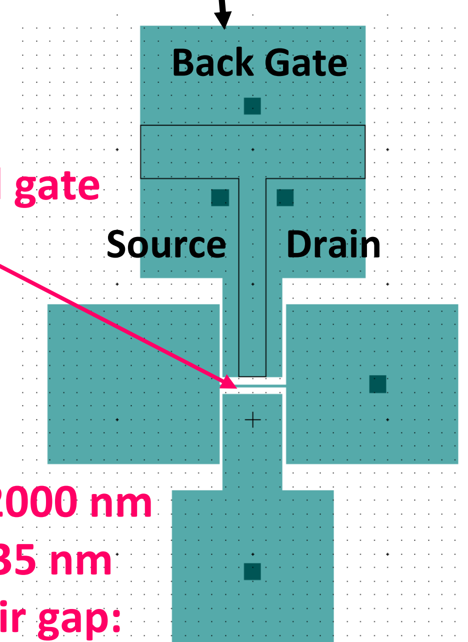
Q-value can be optimized by adjusting the anchor positions of RSG

IR-RSGFET design layout



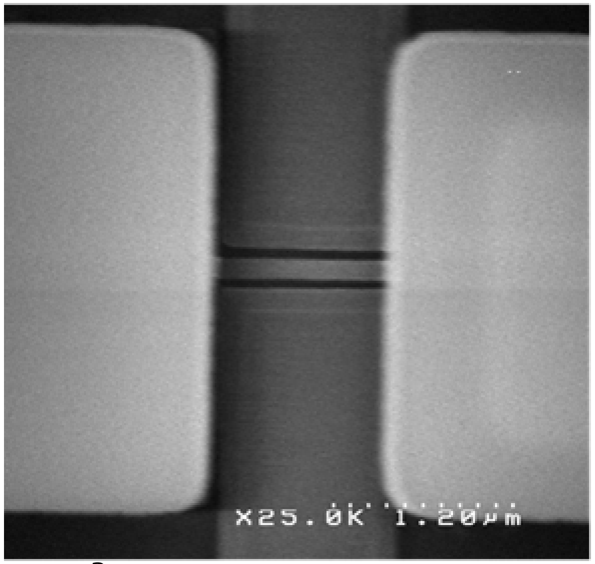






- L_{SG}: 1000 - 2000 nm
- W_{SG}: 45 – 135 nm
- SG – MOS air gap:
  80 – 200nm

Preliminary IR-RSGFET characteristics (DC)



Suspended gate:

Width=135 nm, Length=2000 nm, Thickness=40 nm

SG – MOS air gap = 80nm

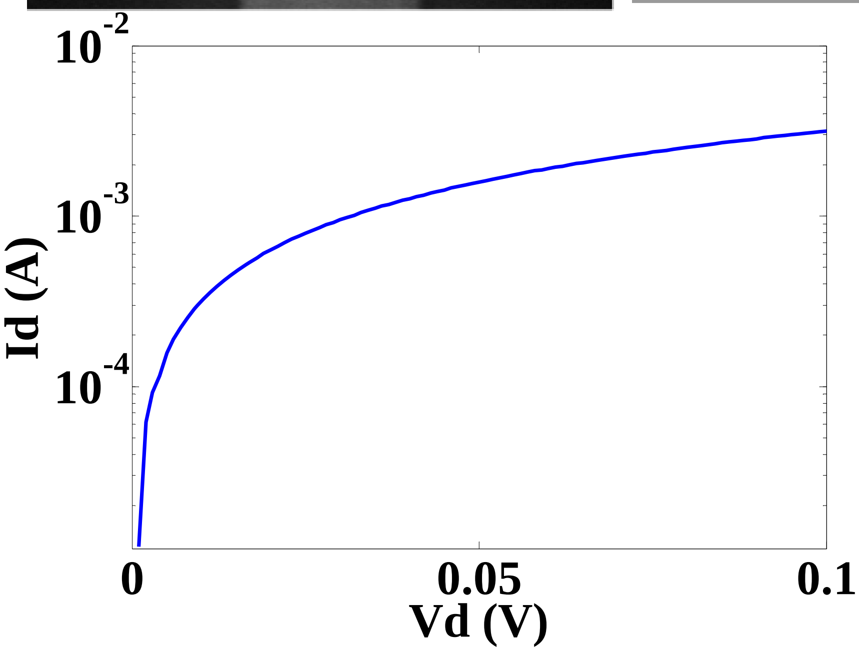
In-plane MOSFET:

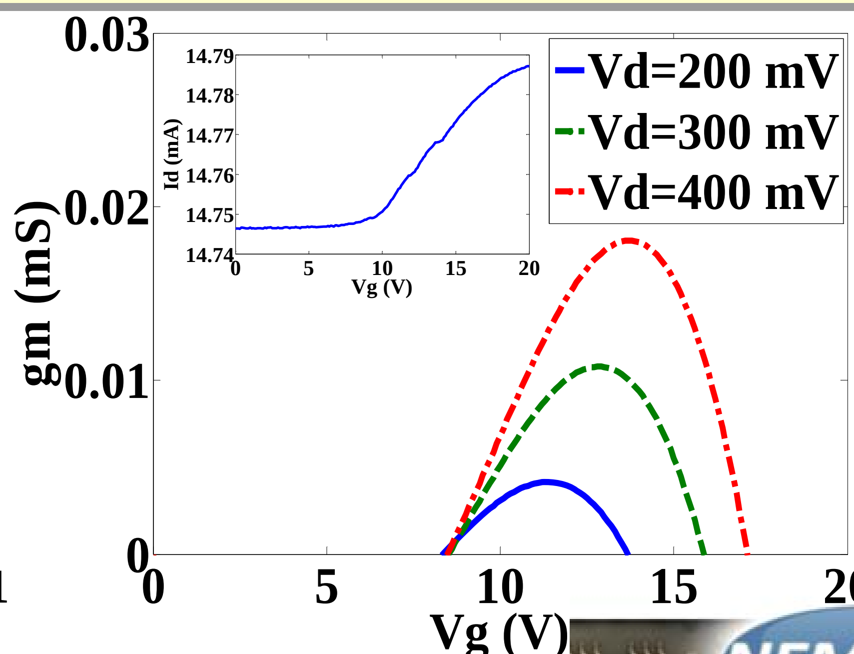
Channel length=1250 nm, Drain/Source length=295 nm

Doping:

Drain/Source /Suspended gate = (N^+) 4×10^{19} at.cm^{-3},

Channel=(P) 1×10^{16} at.cm^{-3}





Optimal V_d= 400 mV & V_g=14 V will be used for the subsequent RF measurement

Summary

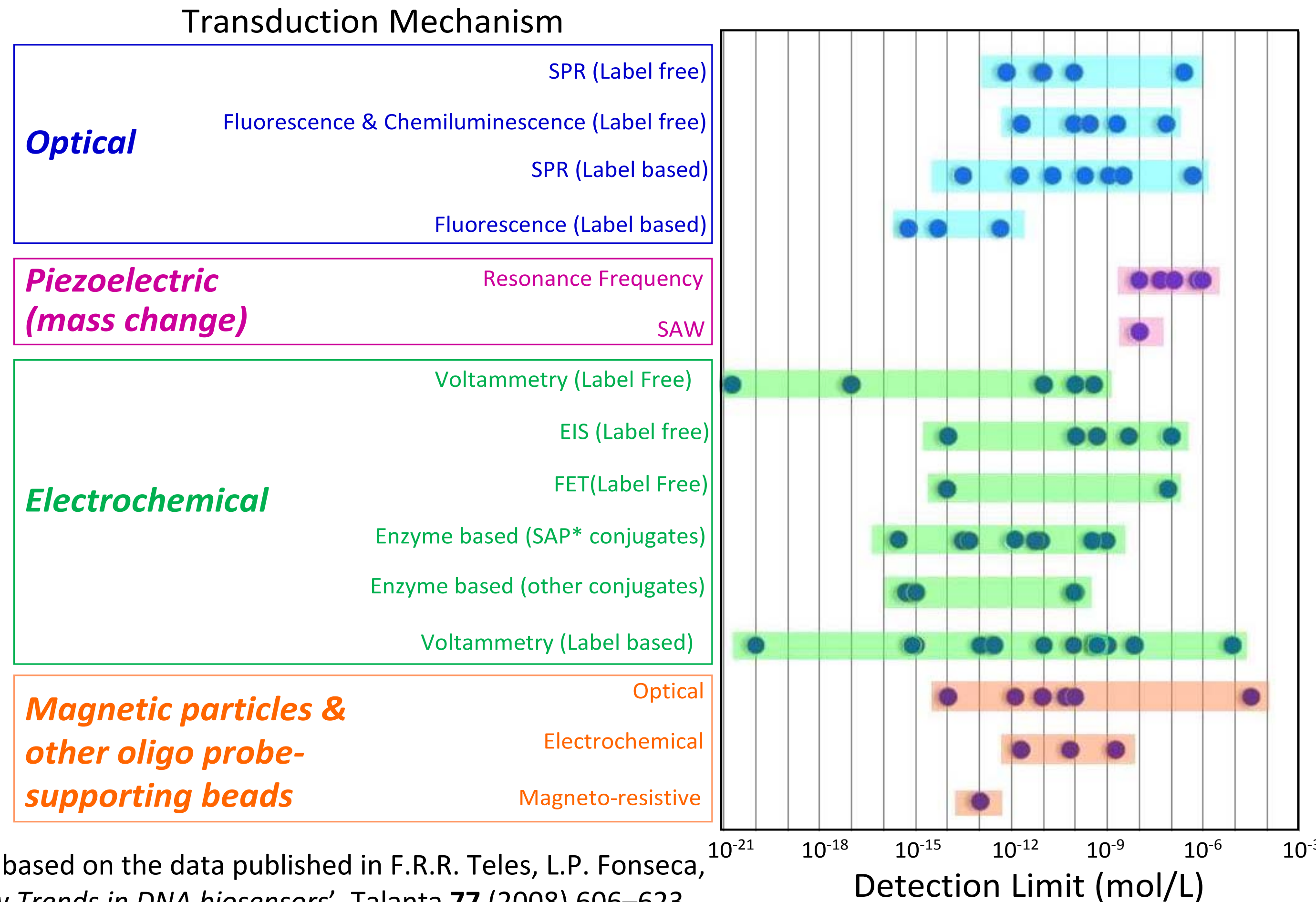
- Selective surface biofunctionalization techniques were developed successfully for suspended SiNWs: Joule heating method & ebeam lithography method.

- Detectable change in the conductance was observed with SiNW suspension and surface functionalization. Preliminary LFN spectra are studied for advanced sensing beyond conductance detection.

- IP-RSGFETs with zeptogram/Hz level mass resposibity were designed using new hybrid NEM-MOS simulation. Preliminary DC characteristics were measured for fabricated IP-RSGFETs.

Conductance or Mass?

DNA detection limit based on various transduction mechanisms



Drawn based on the data published in F.R.R. Teles, L.P. Fonseca, '*Review Trends in DNA biosensors*', Talanta **77** (2008) 606–623.