Nanowire Electronics, Photonics and Sensors

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Outline

1. III-nitride nanowires
    - motivation
    - growth
    - device fabrication
    - electrical/optical properties
    - role of surface states
    - 3D integration
2. Silicon nanowire transistors/chemical sensors
    - fabrication
    - device performance
    - chemical sensing

Why Nanowires?

•Unique electrical, optical, thermal properties due to dimensionality (ballistic transport, coulomb blockade, plasmonic resonance, lasing, chemical sensing)

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Extraordinary Mobility in Semiconducting Carbon Nanotubes

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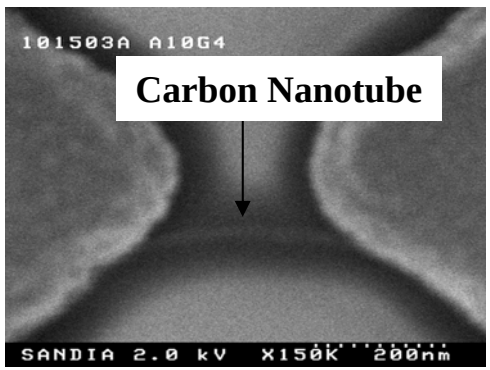
Department of Physics and Center for Superconductivity Research, University of Maryland, College Park, Maryland 20742

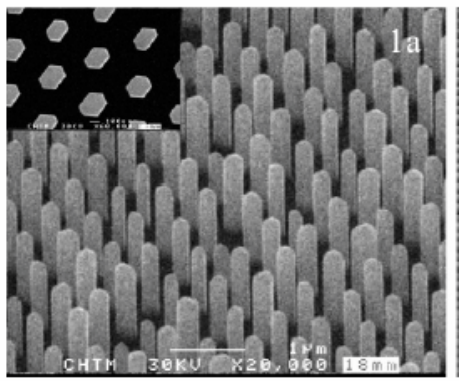
μ_{CNT} = 79 000 cm^2/Vs

(μ_{Si}~1500 cm^2/Vs)

•40+ materials synthesized as nanowires, lots more possible using similar methods *(Au, Ag, Pd, Sn, Te, ZnO, GaN, Si, Ge, GaAs, InP, SnO_2, TiO_2, C, Ag_2Se, Bi_2Te_3, ...)*

•Ideal building blocks for nanoscale circuits, 3D and Si/III-V integration





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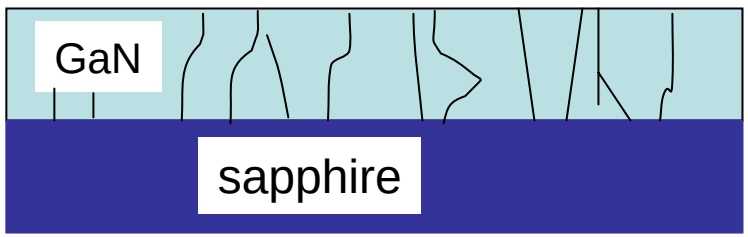
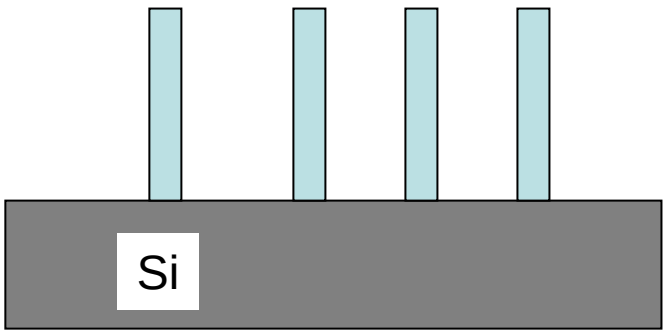
Why go the nanowire route for III-V semiconductors?

- *Low to zero dislocations* → *speed, lifetime, power*
- *Variety of substrates* → *Si integration, cost*
- *Tens of microns in ~hours* → *3D circuits, lower capac., cost*





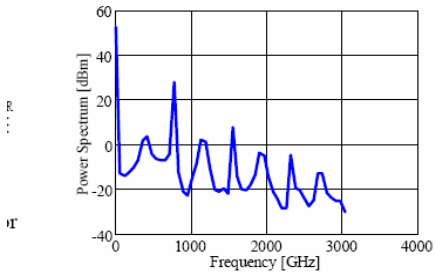


Fig.3. Simulated output power spectrum of $0.3\mu m$-thick GaN-based NDR diode oscillator designed for operation at THz frequencies.

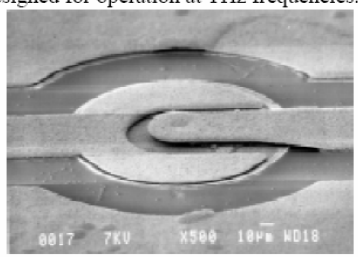
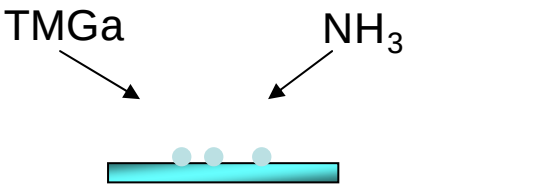


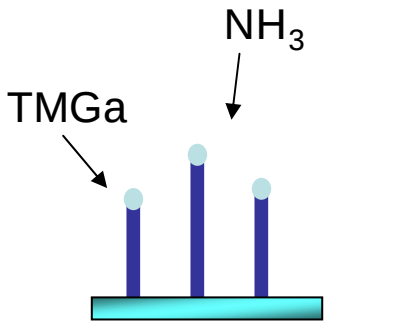
Fig.4. Fabricated GaN NDR Diode with air-bridge interconnects

previous GaN Gunn oscillators failed due to defects, thermal management (Alekseev, Pavlidis, Solid State Electronics 44, 941, 2000)

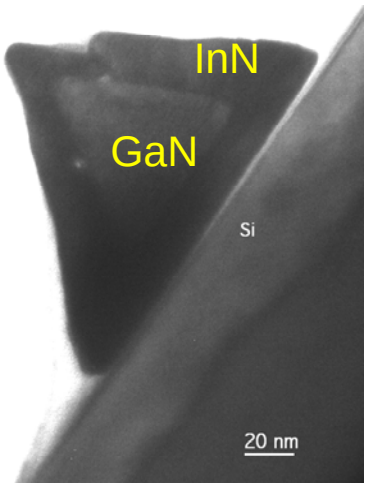
Metal catalyzed CVD growth of GaN nanowires

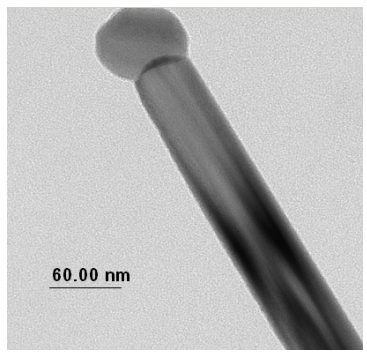


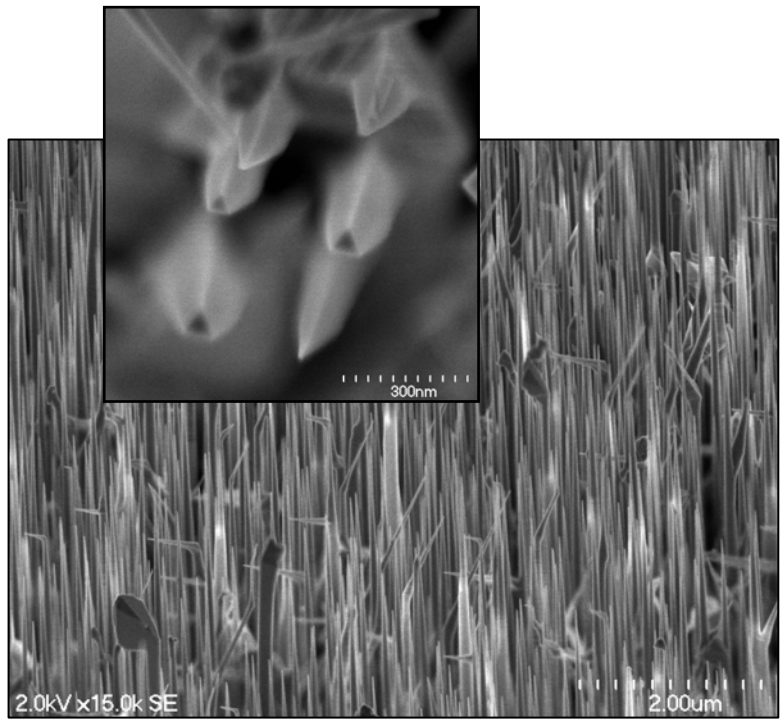
Catalyst nanoparticle



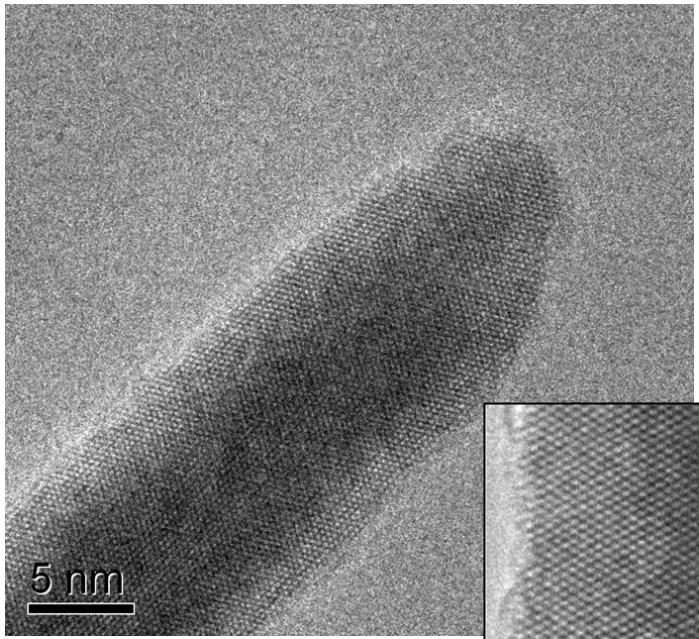
GaN nanowires

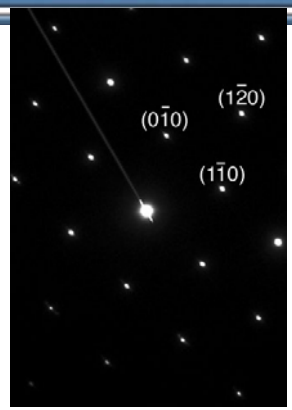


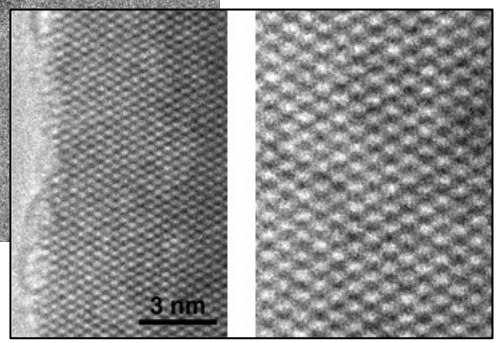




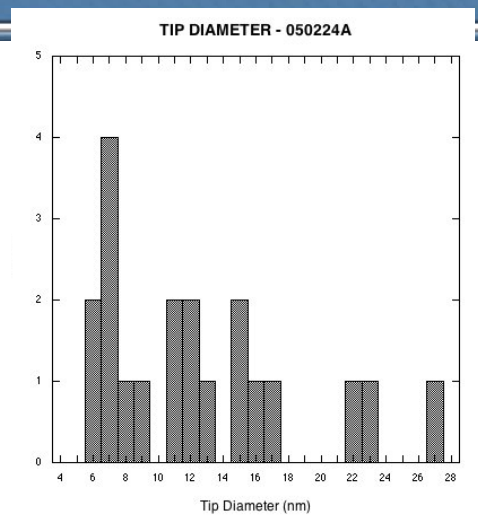
TEM of Nanowires 800°C, sapphire r-face

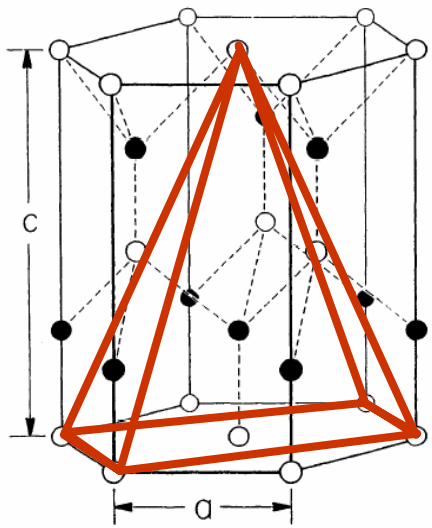


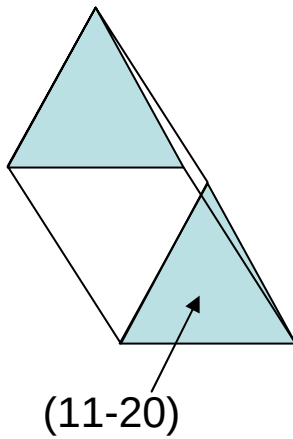




(10-11)







(11-20)

- Aligned nanowires single crystalline an
- Primary growth direction [010]

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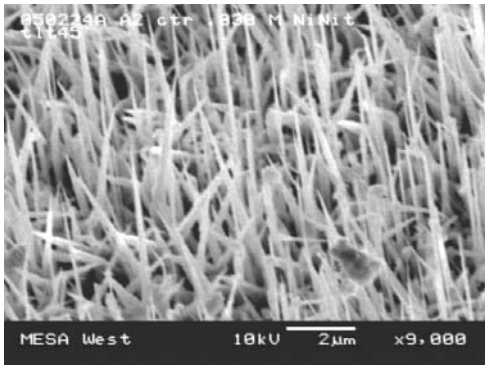
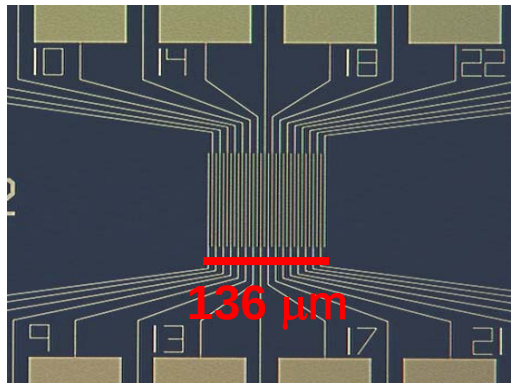
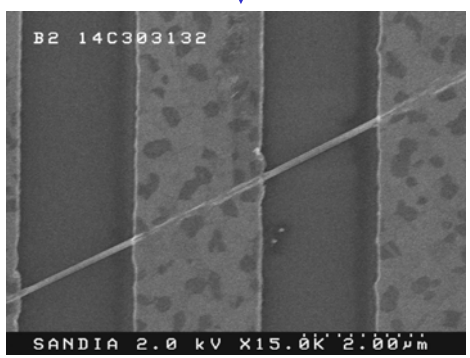
Device fabrication

- Sonication to transfer nanowires from growth substrate to test substrate
- UV aligner and lift-off to pattern individually addressable electrodes



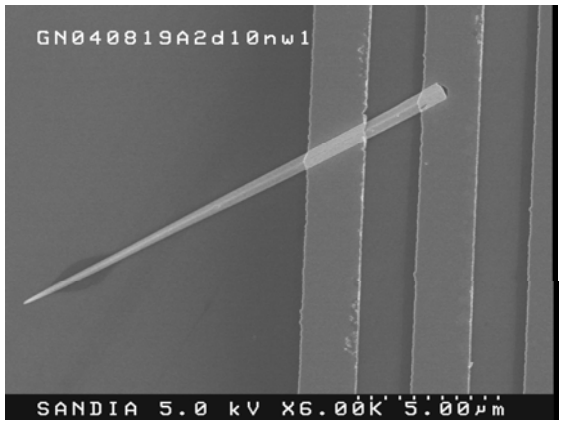


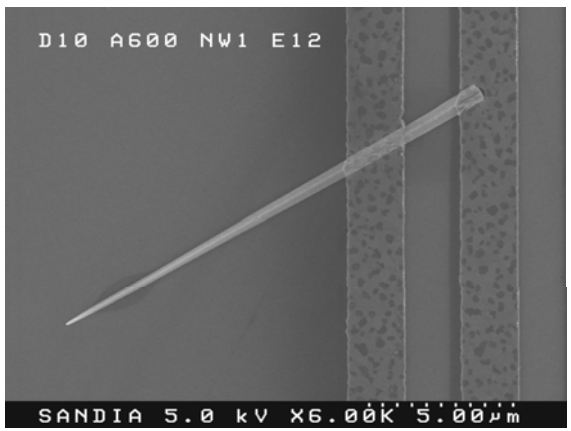


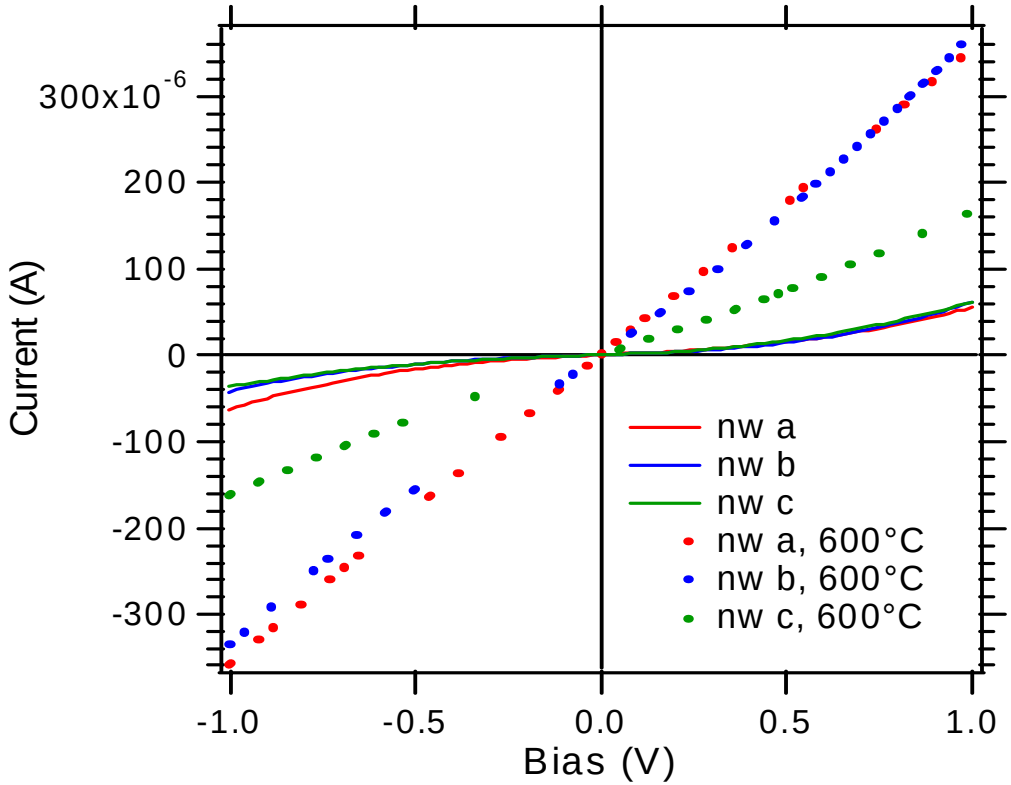
- <u>Simple</u> method of device fabrication resulting in high yield of testable nanowires
- Alternative to E-beam writing

Ohmic contact formation

- Ni/Au contacts mostly resulted in Schottky contacts
- After 20 minute 600°C anneal, all contacts become less resistive & most contacts become Ohmic







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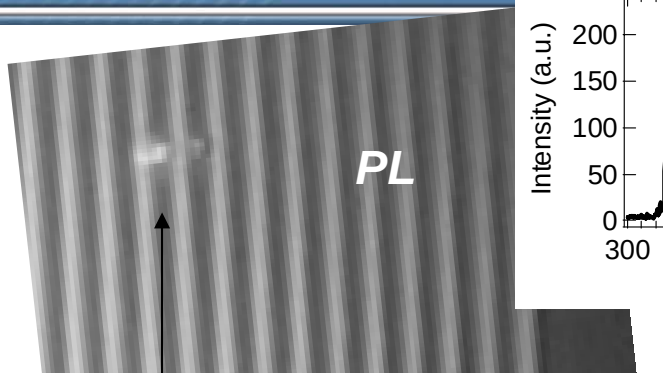
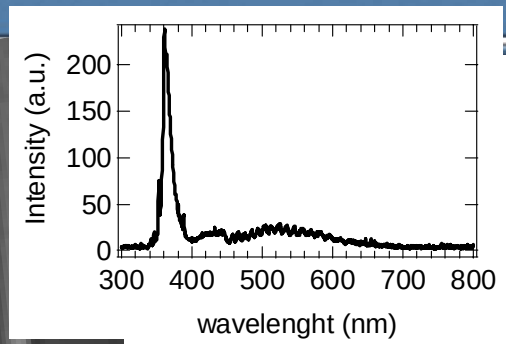
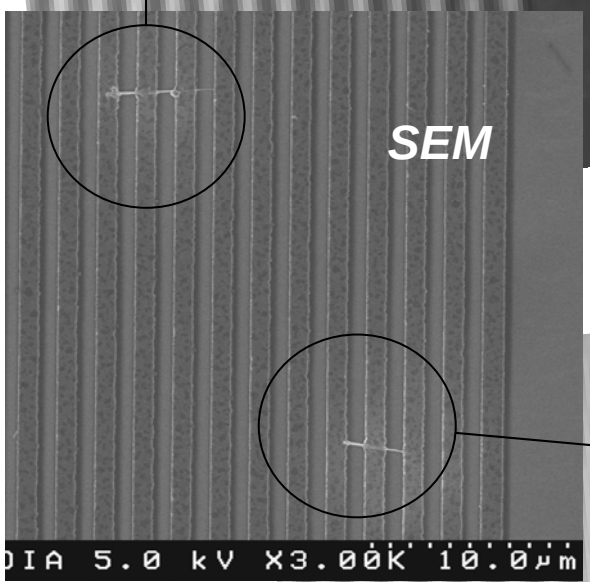
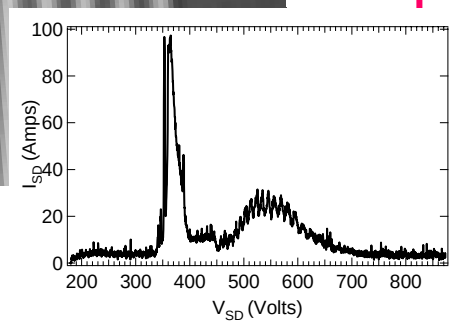
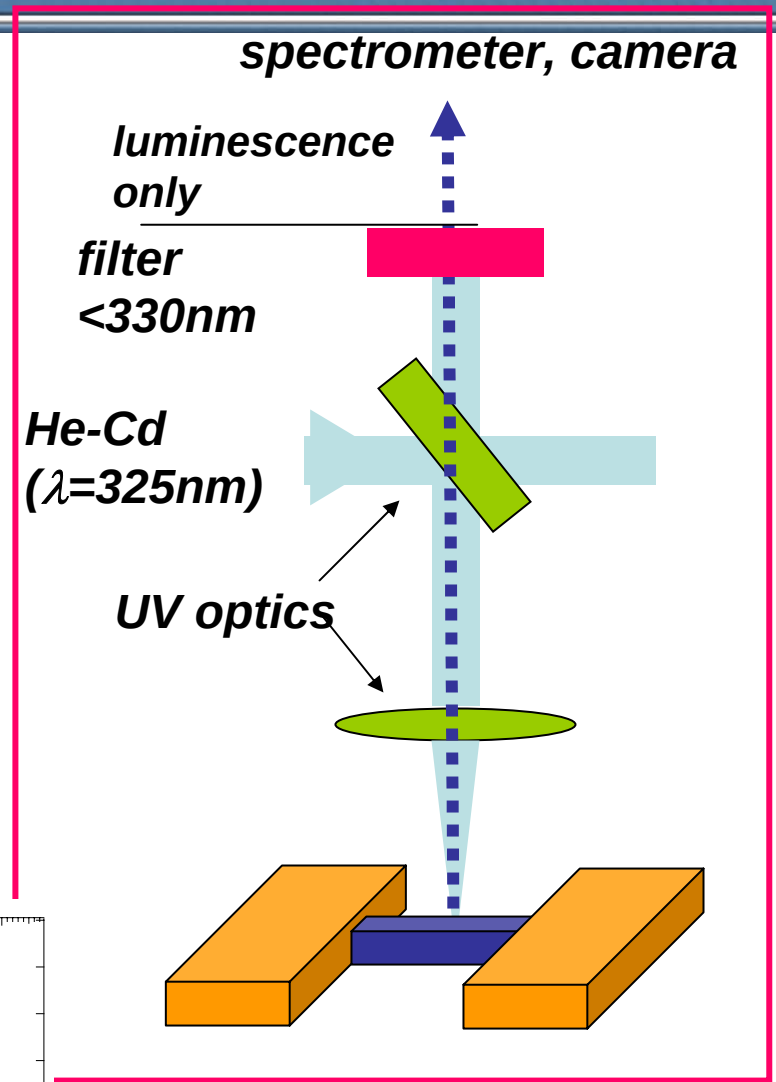
Single Nanowire PL Imaging/Spectroscopy System











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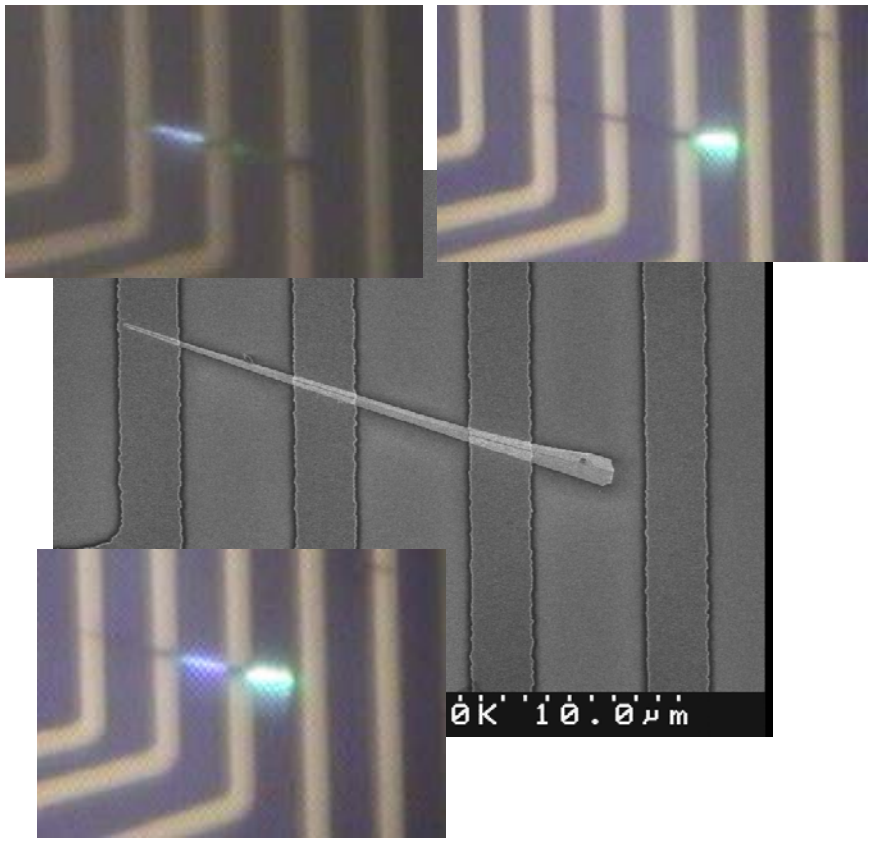
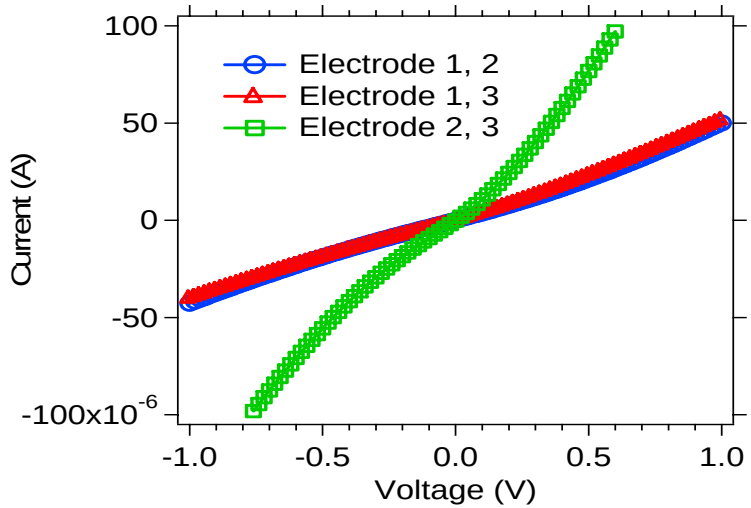
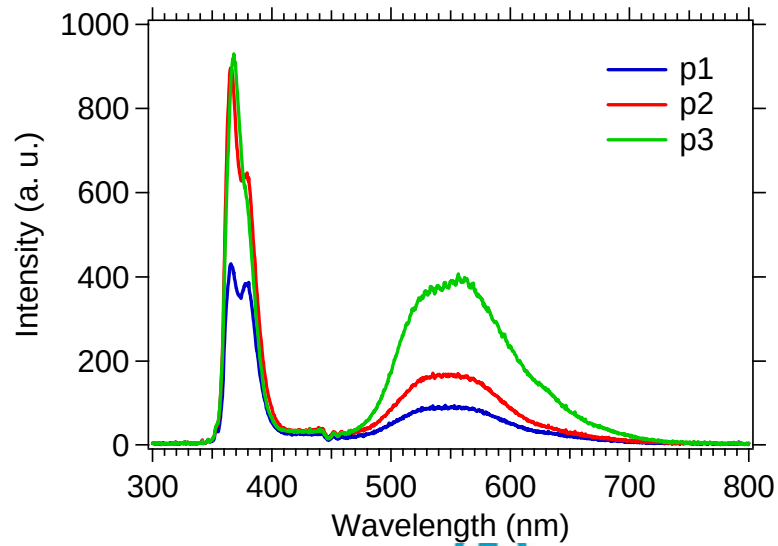
Spatially resolved PL imaging, spectra, I/V







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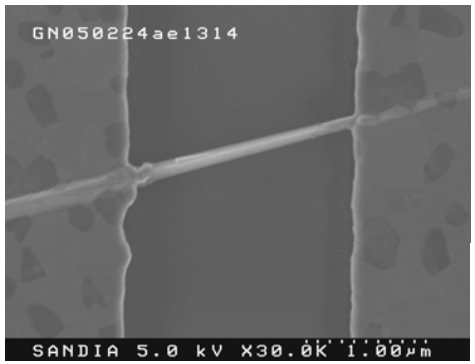
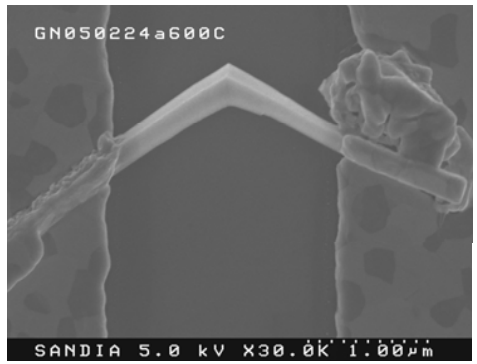
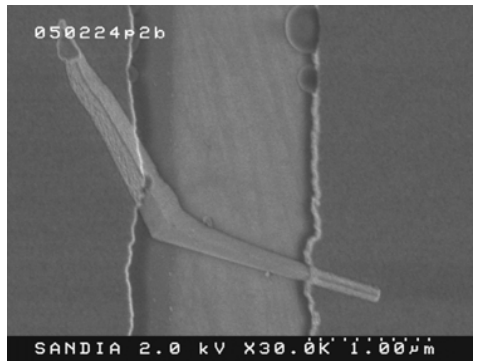
Morphology of ‘integrated’ nanowires: planar defect obvious in 800°C nanowires

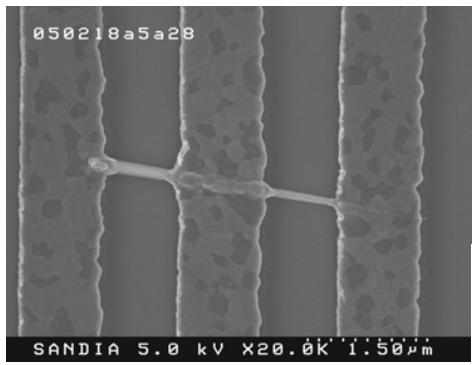
800°C

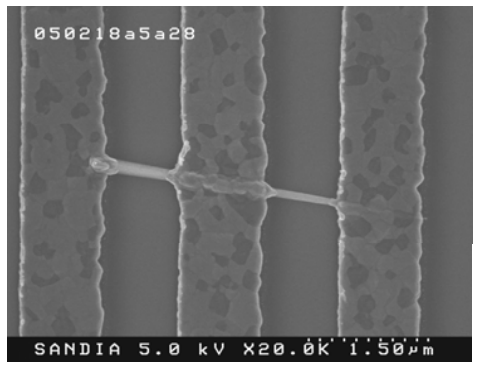


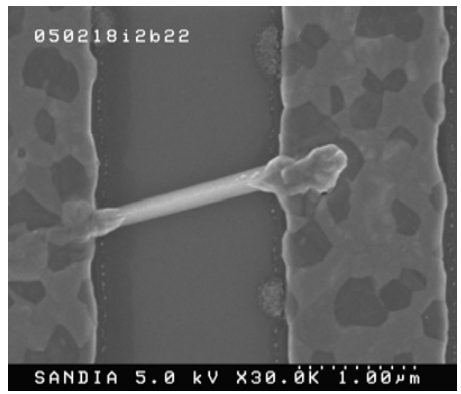




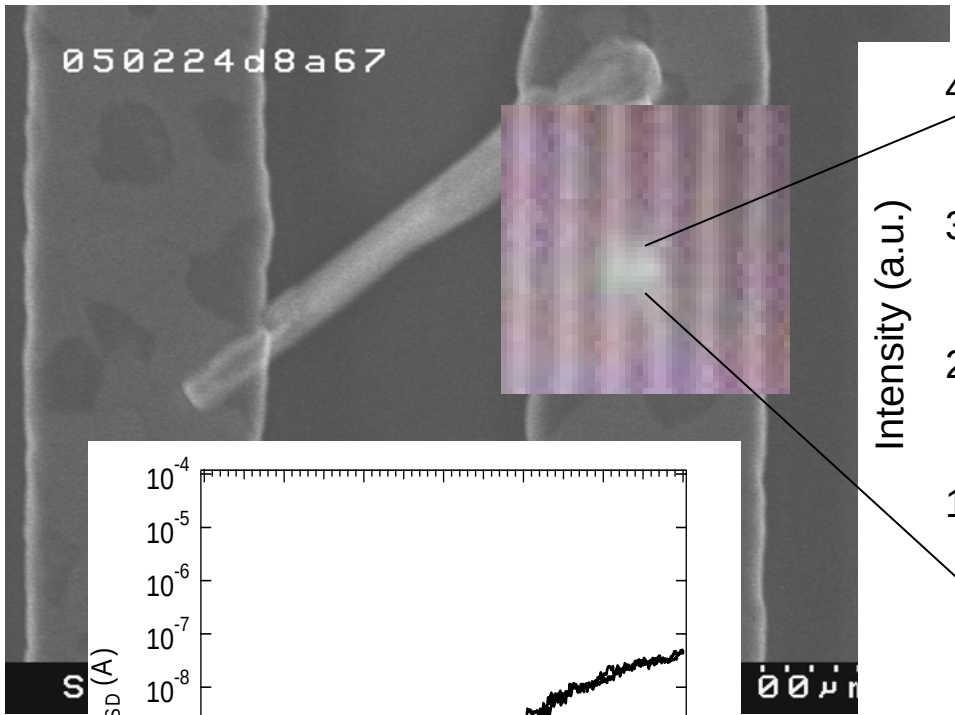
900°C

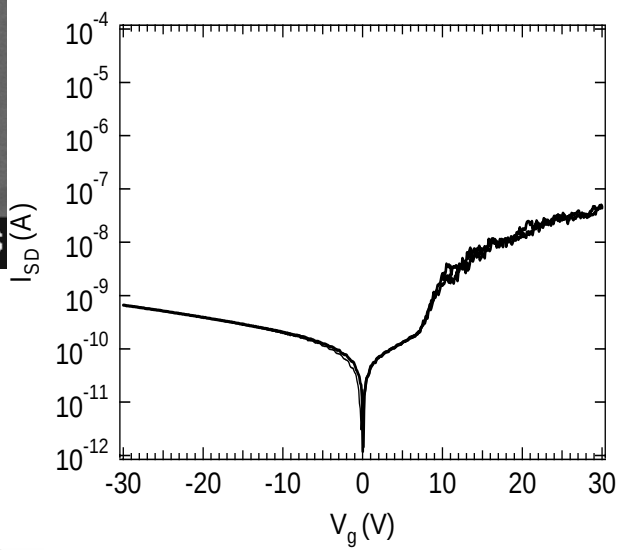


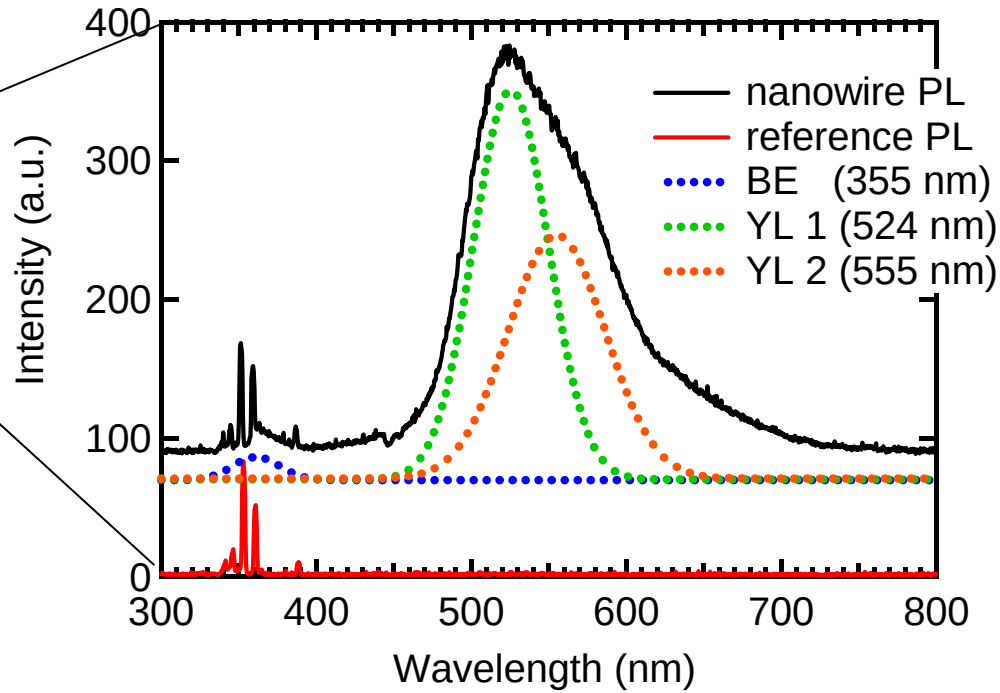




Nanowires grown at 800°C: PL intensity weak, at least 2 peaks in YL, high R



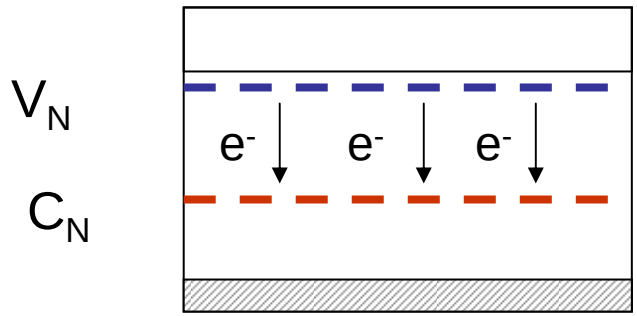


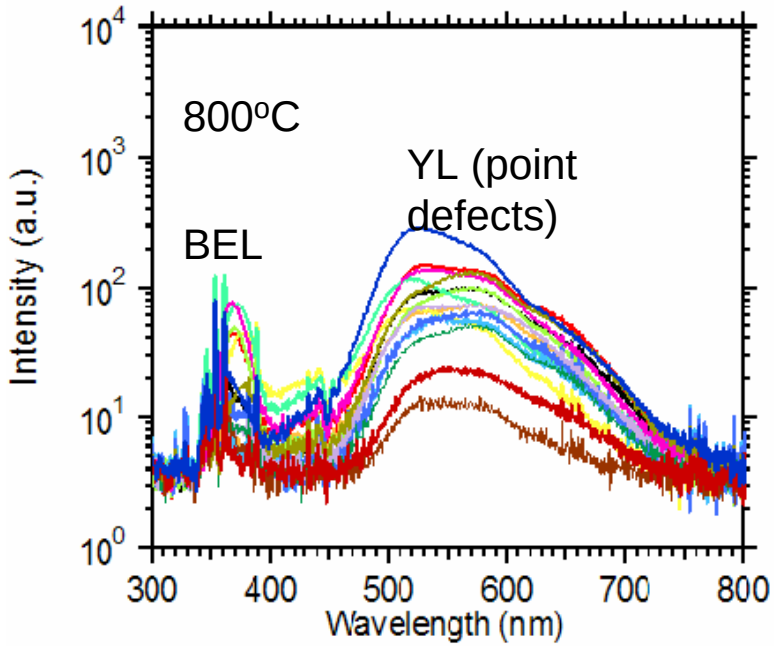


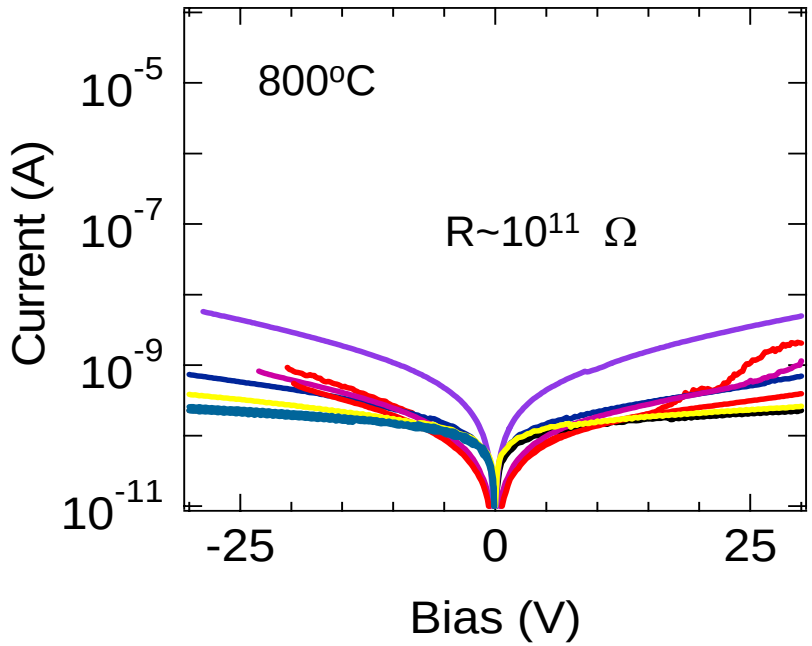
Effect of growth T on PL, I/V: GaN at 800°C

- PL dominated by YL
- Resistance ~10^9 Ω

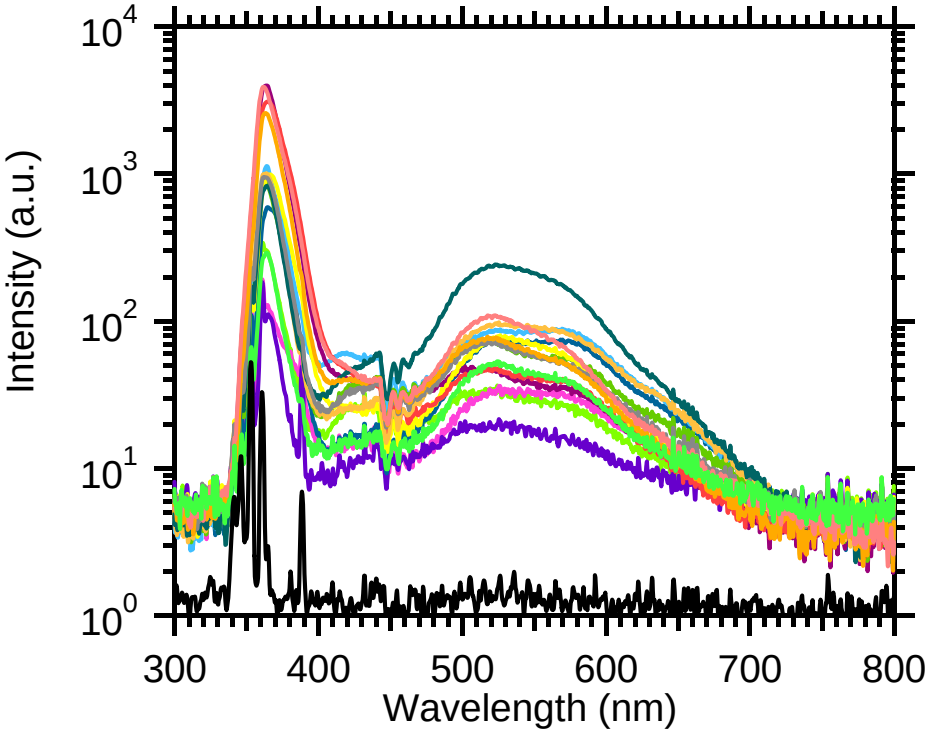
Carbon from TMGa may be deep level acceptor; lead to carrier compensation

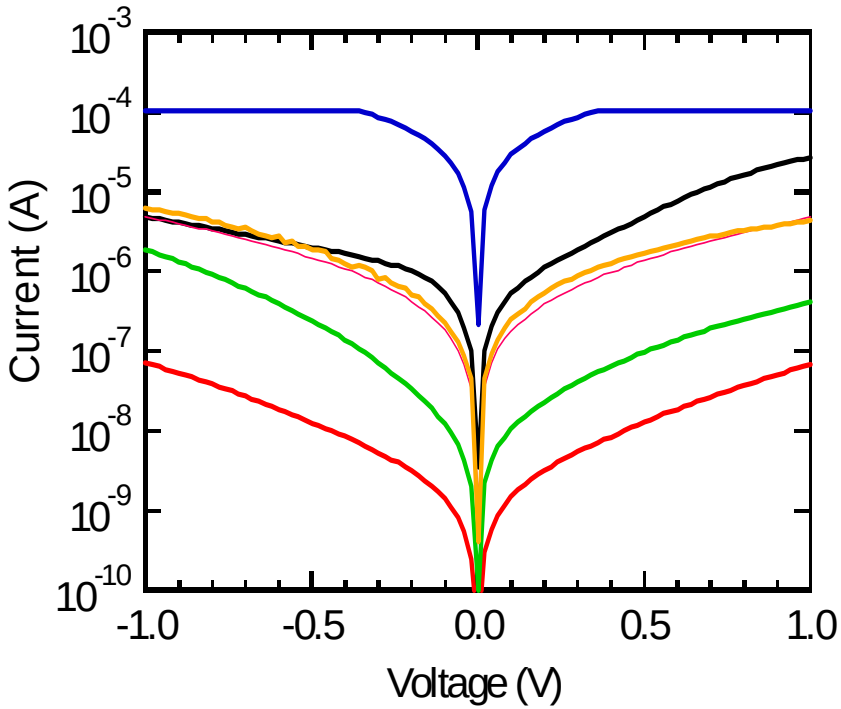




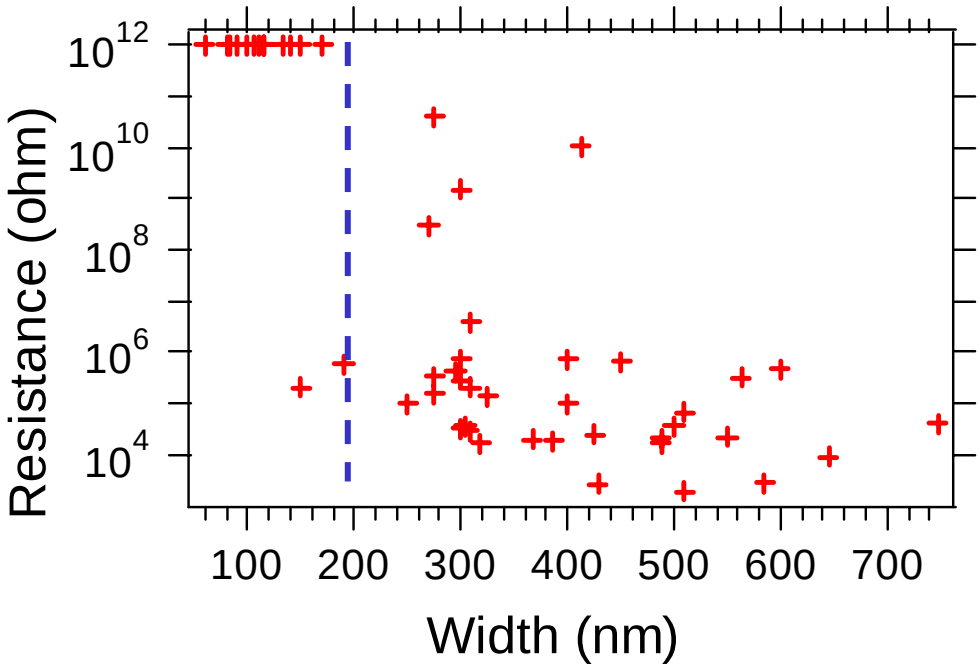


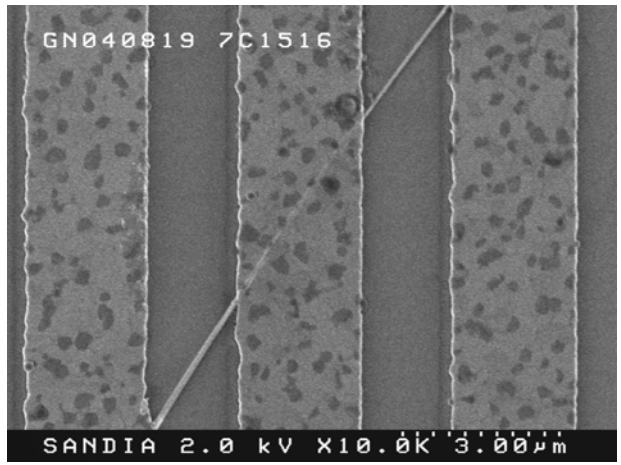
Effect of growth T on PL, I/V: 900°C-> BEL dominates, R~$10^5\Omega$



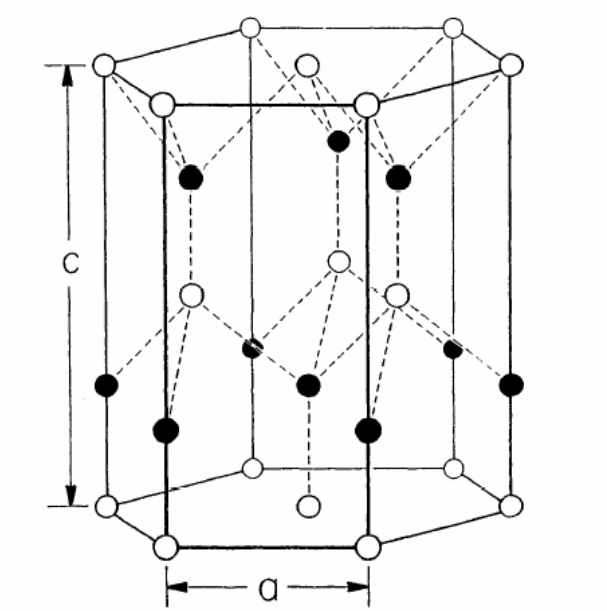


Bellow ~200 nm, GaN nanowires grown at 900°C are insulating!

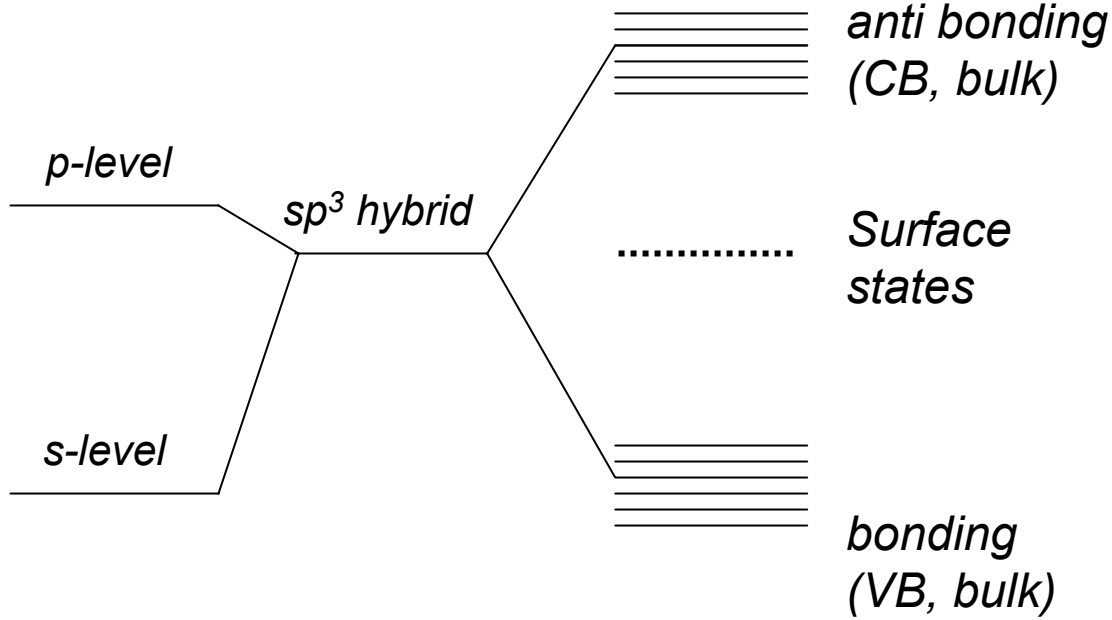




A short detour….creation of a surface creates broken, 'dangling' bonds



Periodic arrangement of atoms in solid leads to allowed energy bands, gaps

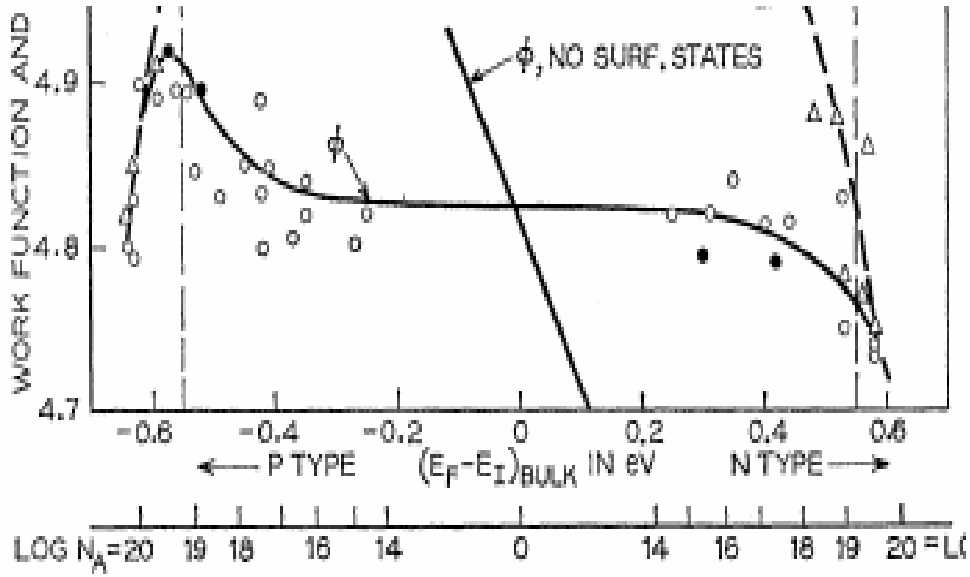


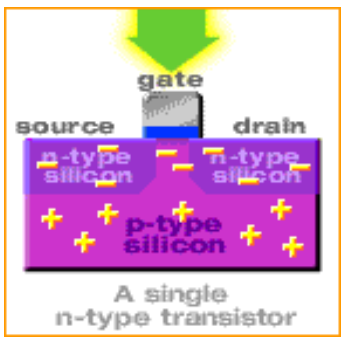
•Creation of a surface breaks the order, leads to energy states in the forbidden gap

•Surface reconstruction, adsorbates determine position and density of gap states

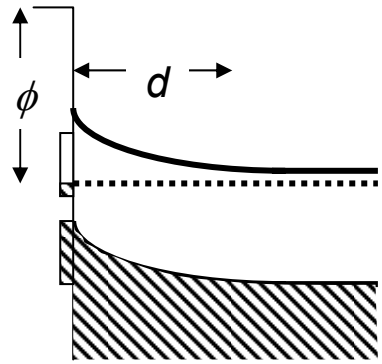
Most semiconductor surfaces have 'pinned' Fermi level due to surface states

Work function of cleaved Si(111) is only weakly dependent on doping

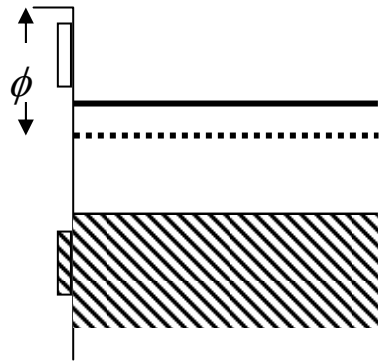




Fermi level pinning not an issue for bulk Si devices, since SiO_2 passivates dangling bonds



pinned Si(111)



unpinned GaAs(110)

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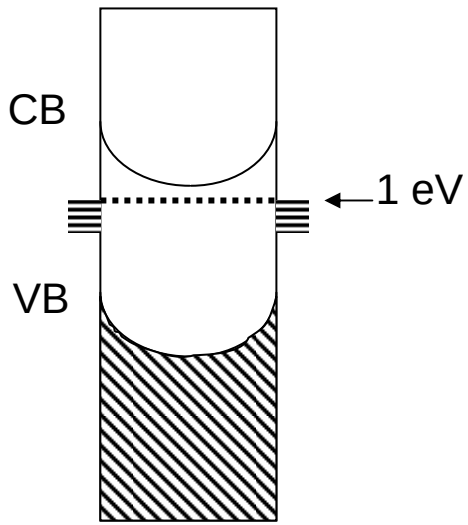
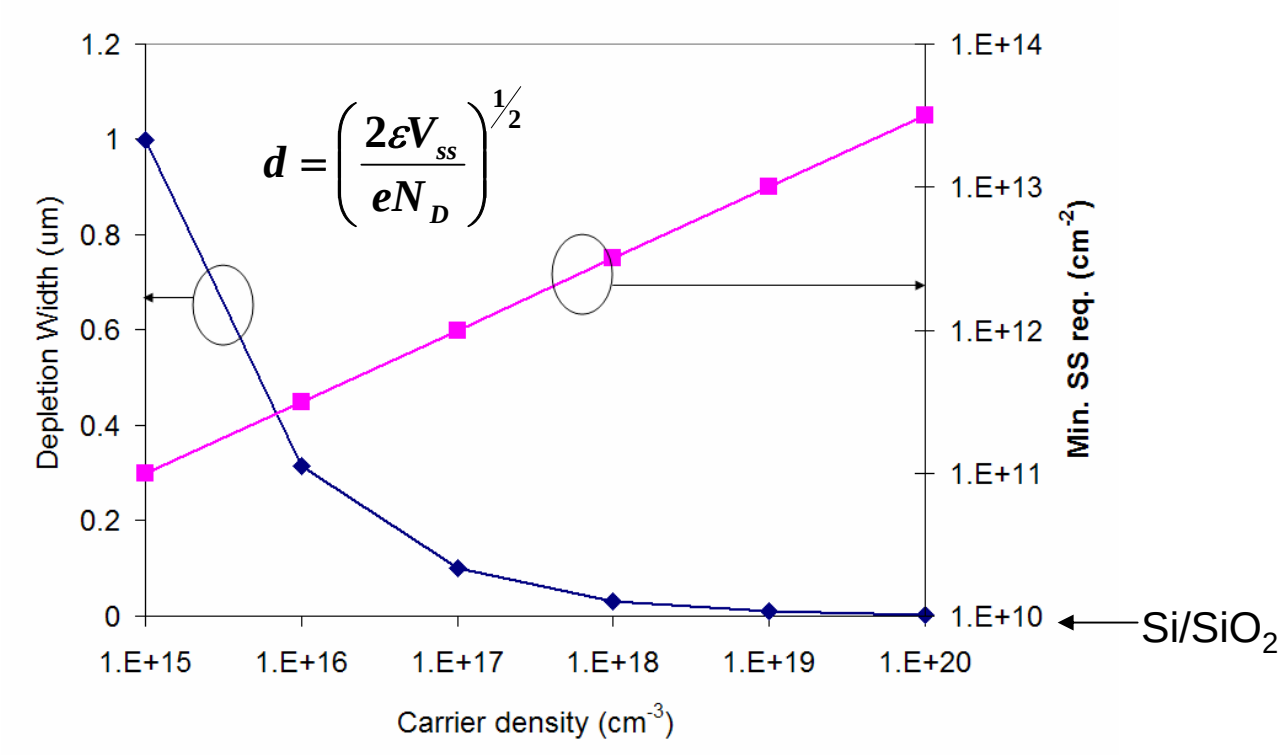
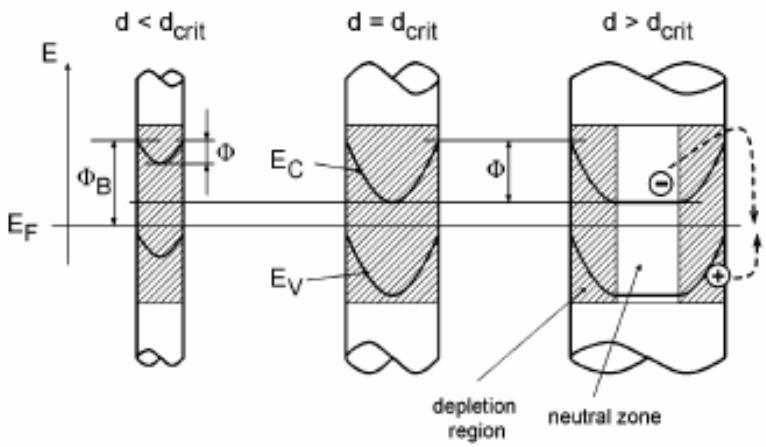
At [e^-]~$10^{17}/cm^3$, E_{ss} ~ 1V, and SS density >$10^{12}/cm^2$, complete depletion at diam. of 200 nm

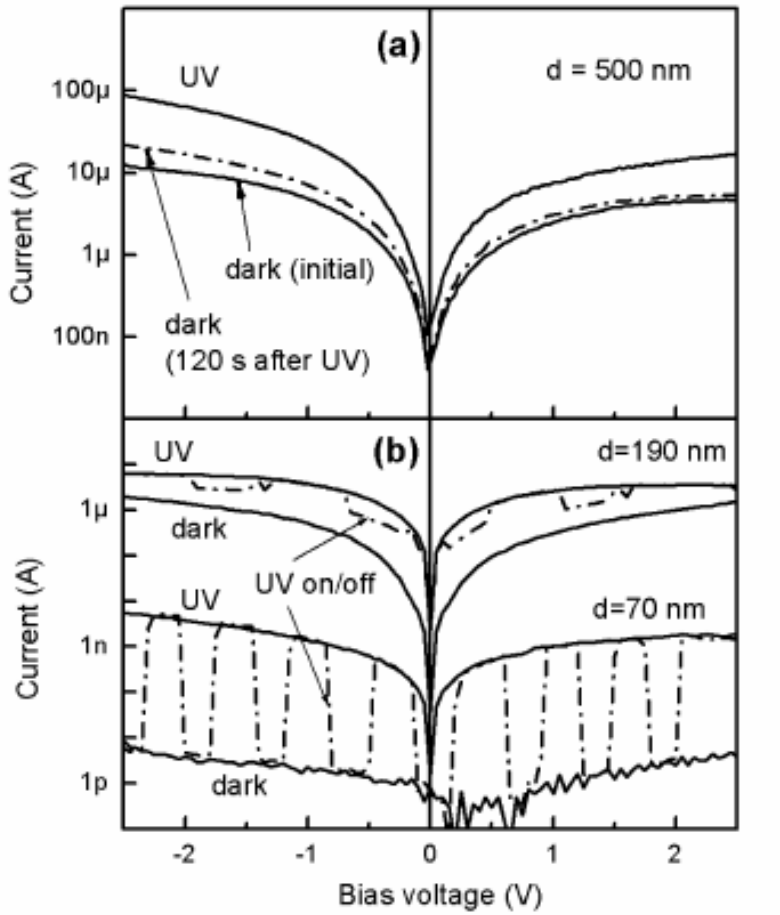




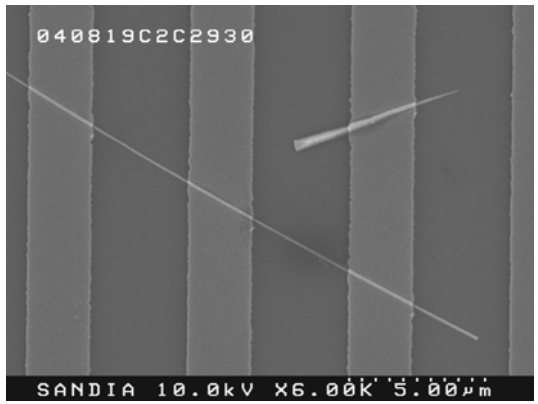
We are not the first to not role of surface depletion on optical, electrical properties of nanowires...

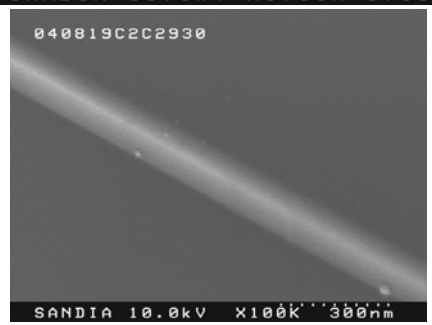


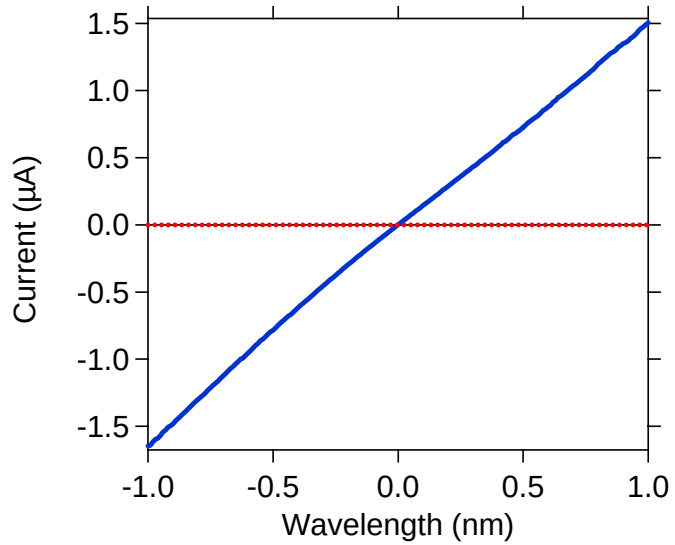
R. Calarco et. al Nano Lett. 5, 2005

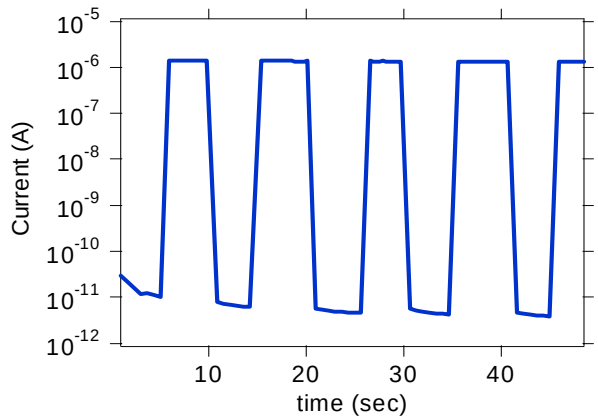


The depleted GaN nanowires are promising UV photodetectors, with low dark current, high gain









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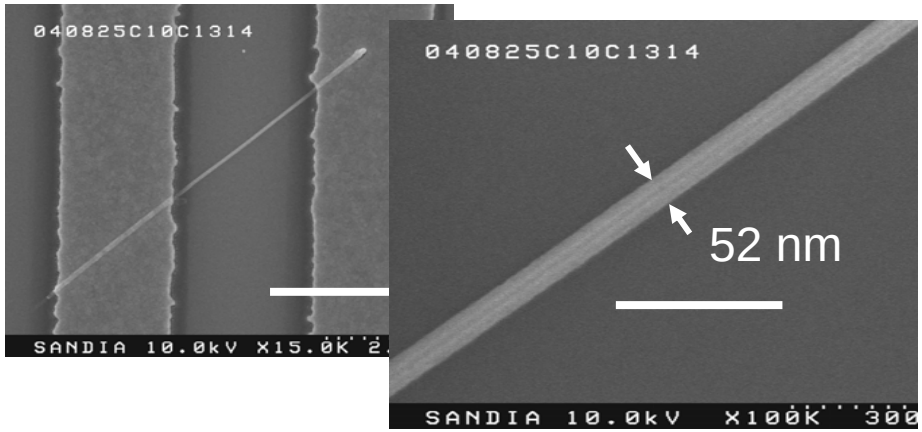
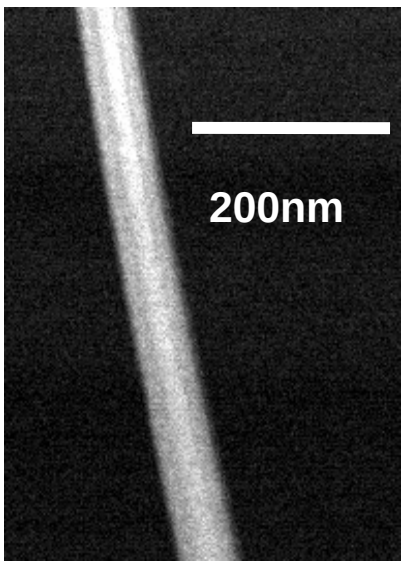
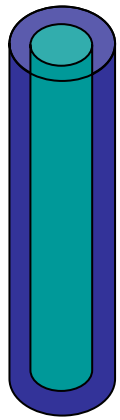
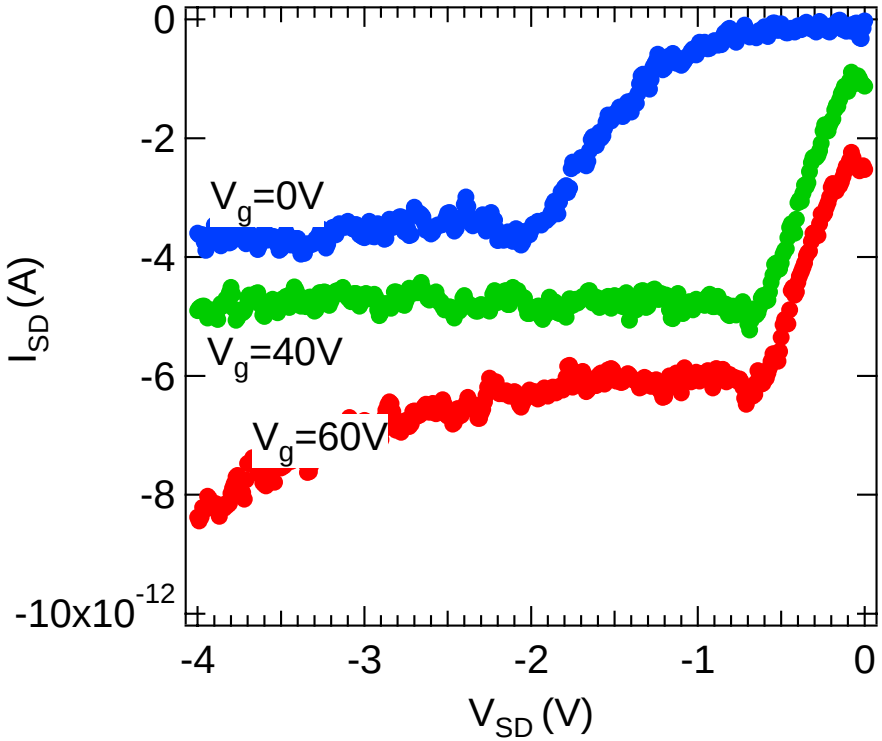
AlN cladding is a possible surface passivation layer for GaN nanowire devices









AlN/GaN core-shell nanowires: conduction observed even at 50 nm diam. for some, other are insulating

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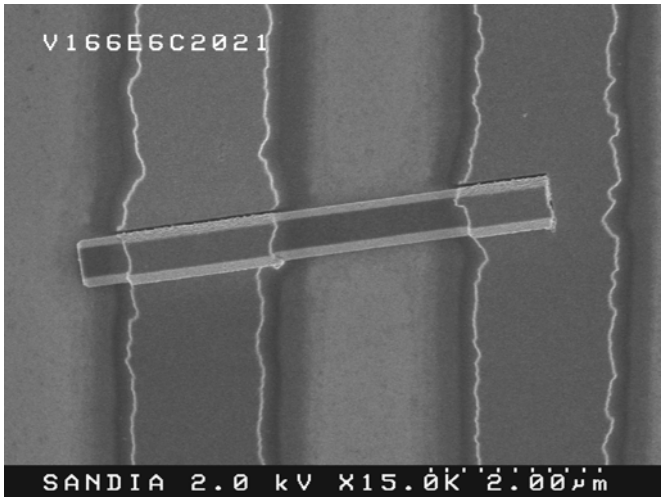
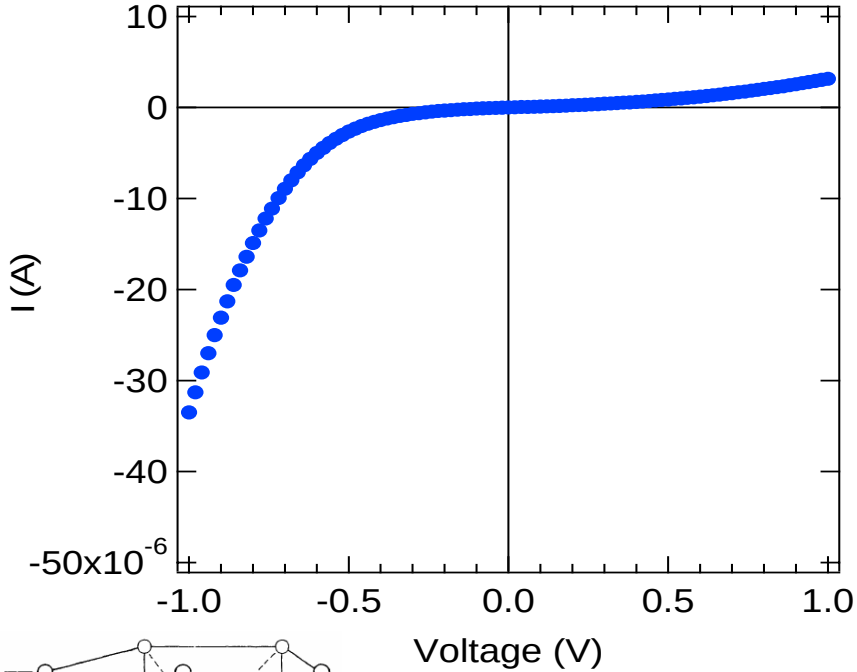
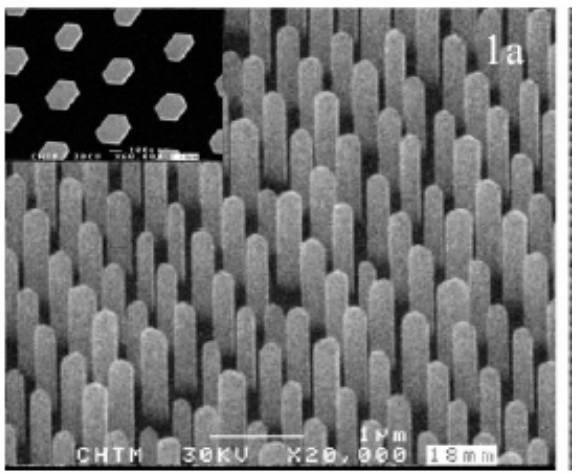
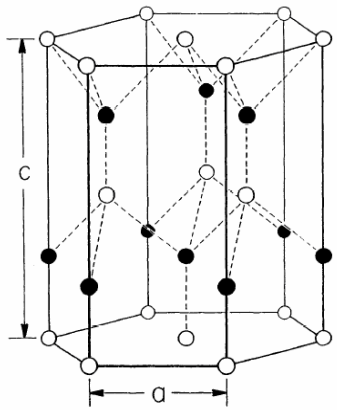
Another possible approach is to change the surface/orientation of the nanowire (w/S. Hersee, UNM)









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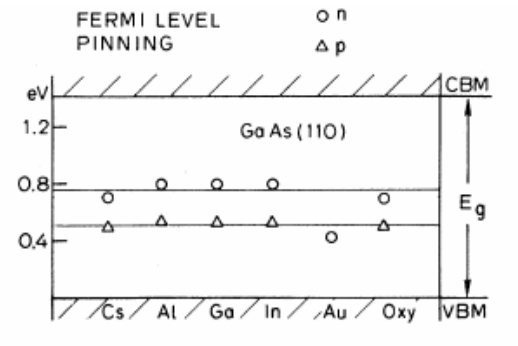
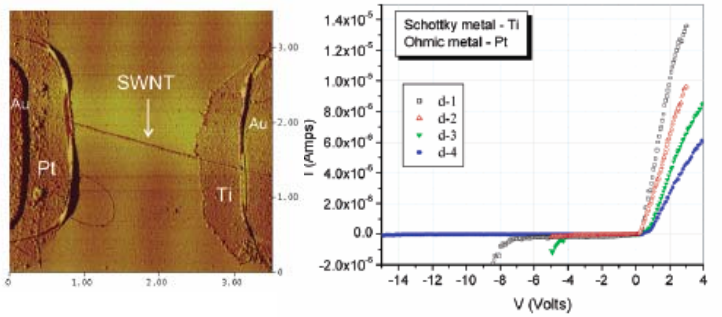
Metal contacts to CNTs and nanowires: Schottky barrier, Fermi level pinning depend on diameter

contacts to bulk semiconductors

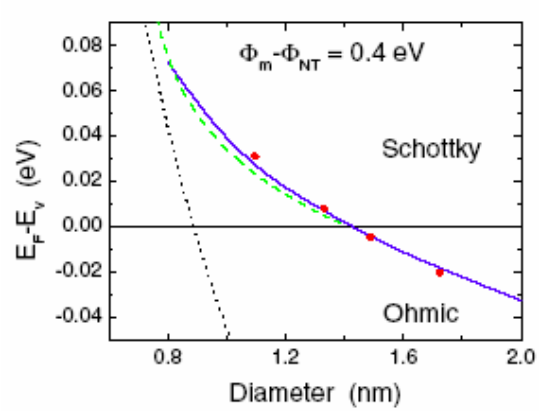


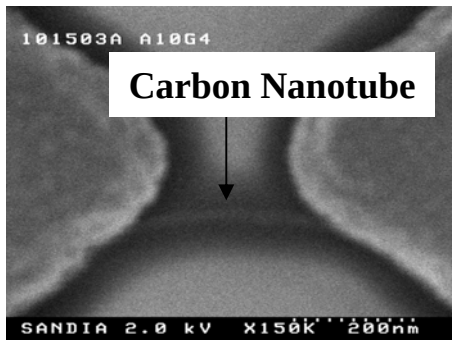
Spicer et al., PRL 44, 1980

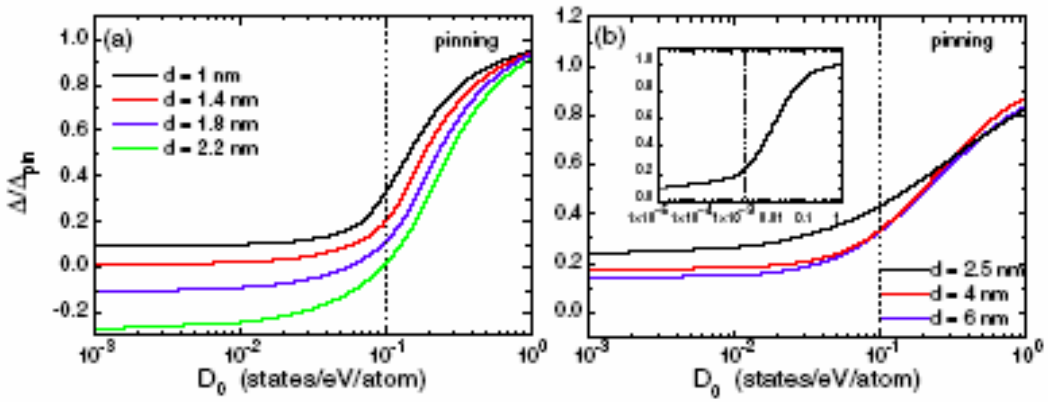


P. Siegel, Nano Lett. 2005)

contacts to CNTs, nanowires

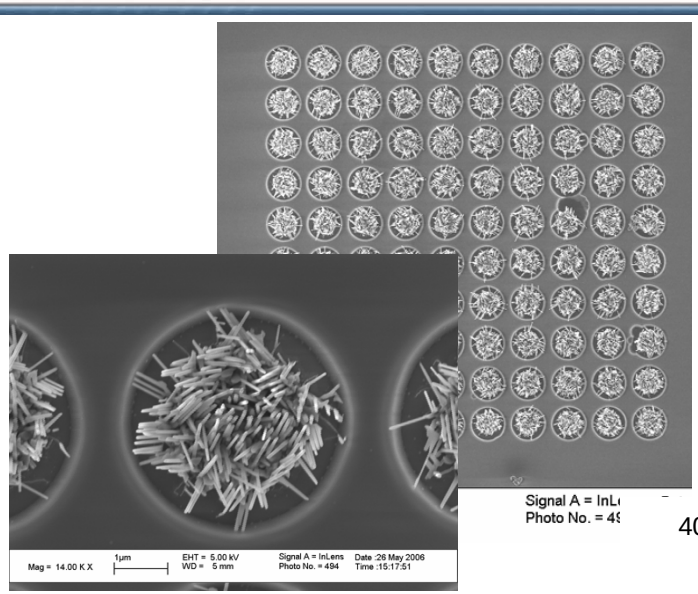


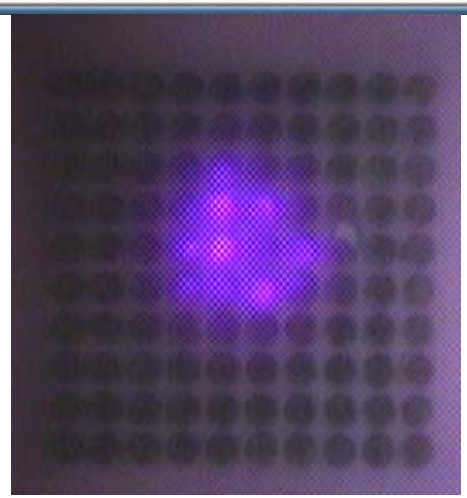


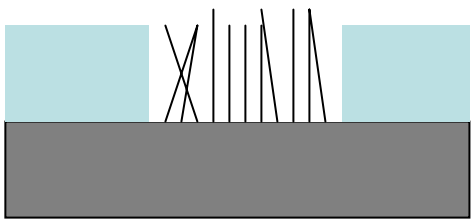


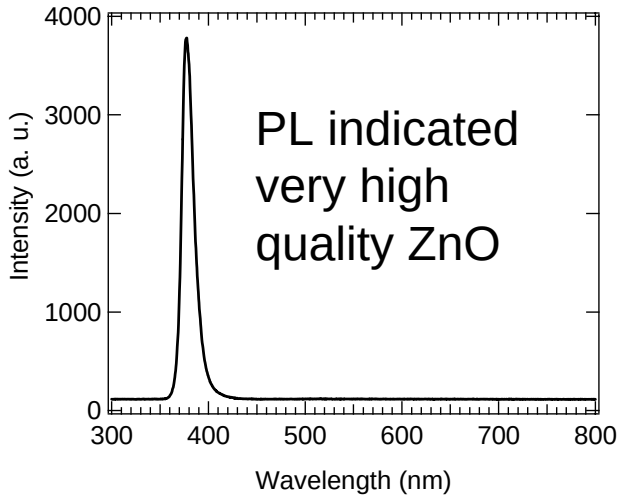
Leonard and Talin, PRL 97, 2006

Vertical integration: patterned VLS growth of ZnO nanowires in vertical wells *(SNL/UCB)*



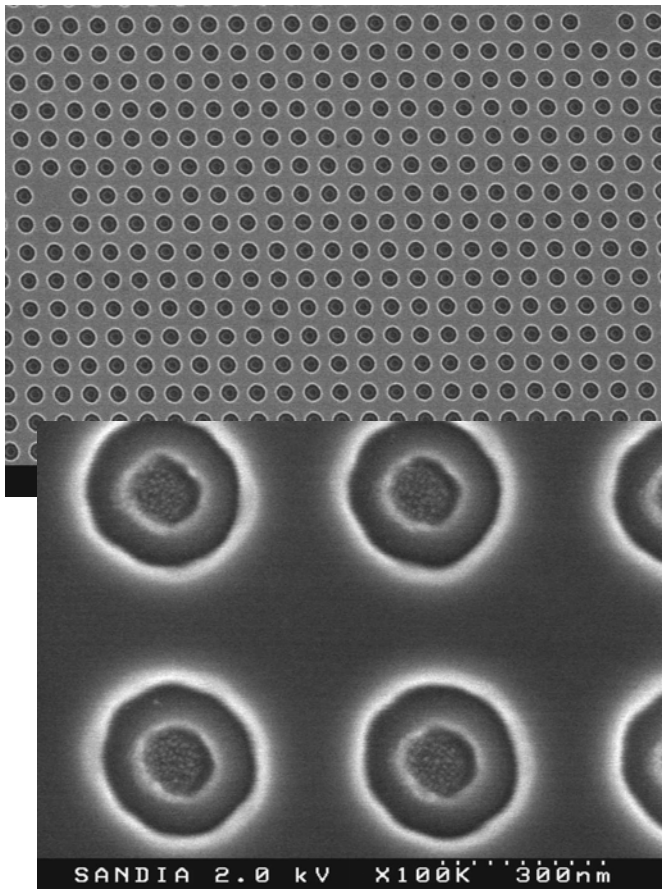


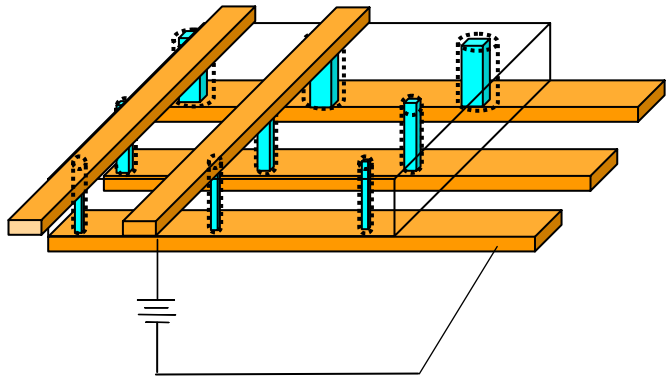


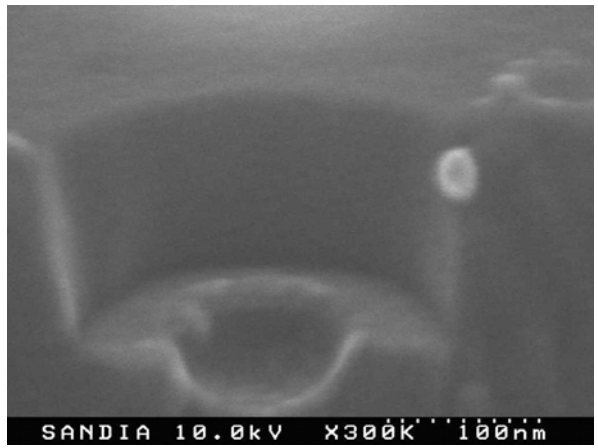


Patterned growth in vertical SiO_2 wells

Vertical integration with dimensional, position control of catalyst



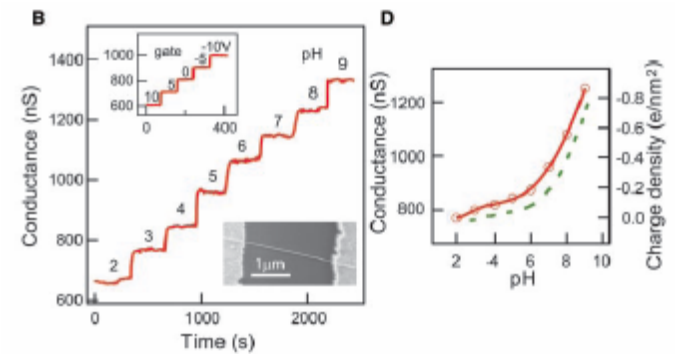




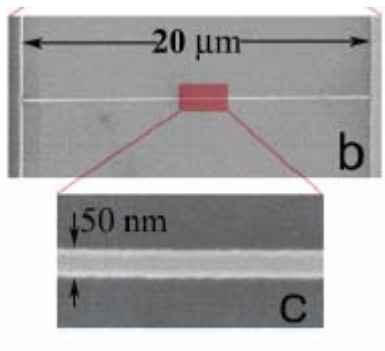
Nanowires for chemical and bio sensors

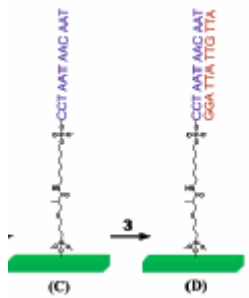
Nanowires exhibit excellent characteristics for sensors:

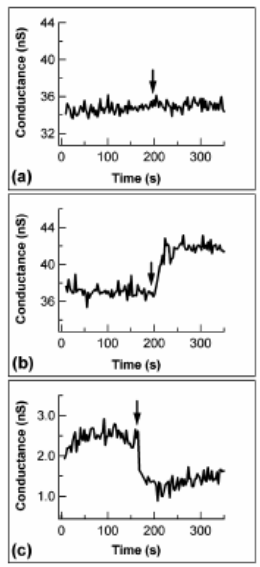
- Large surface/volume ratio.
- Electrical and optical properties are highly sensitive to the environment.
- Can be functionalized with chemically- and bio-active molecules.
- *Nanowires synthesized in bulk are difficult to integrate with input/output circuitry--need a practical, robust, reproducible method*



pH sensor fabricated by casting Si nanowires from sol'n, C. Lieber group, *Science* ***293*** *1289 (2001)*







Real-time detection of DNA hybridization w/o labels using Si nanowire, *R. S. Williams group, Nanoletters* ***4****, 245 (2004)*

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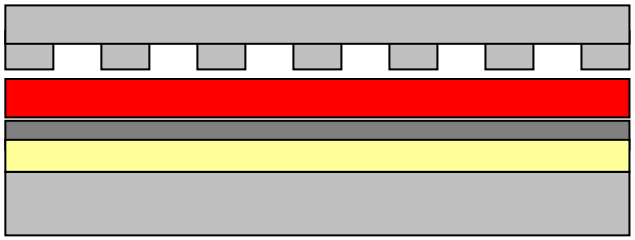
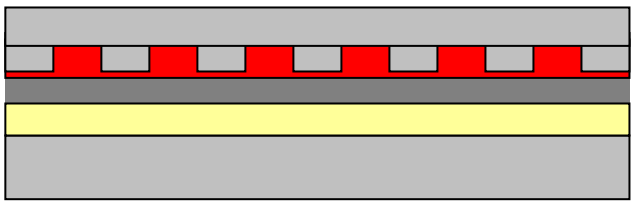
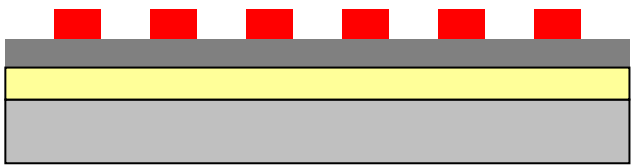
Device Fabrication

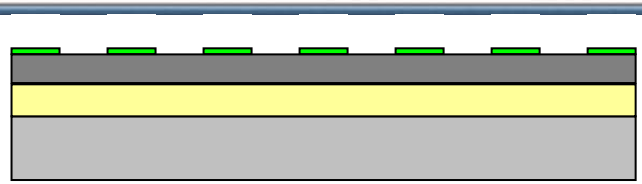




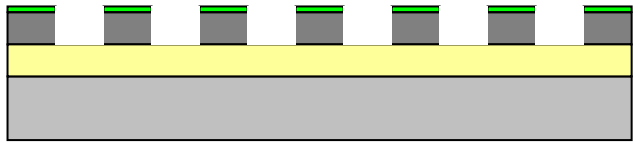
Thermally imprint



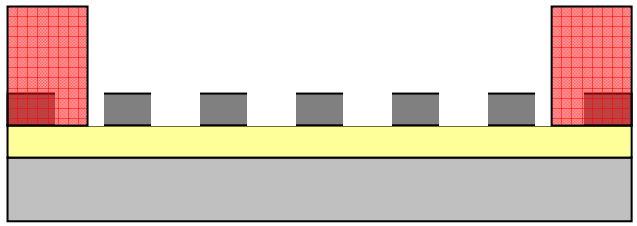
O2 break through



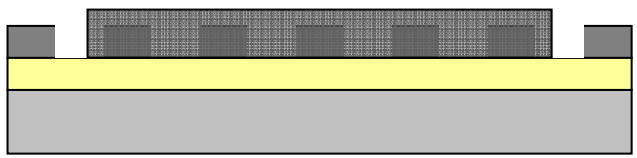
Cr dep and lift-off



Cl2 + HBr etch into Si device layer

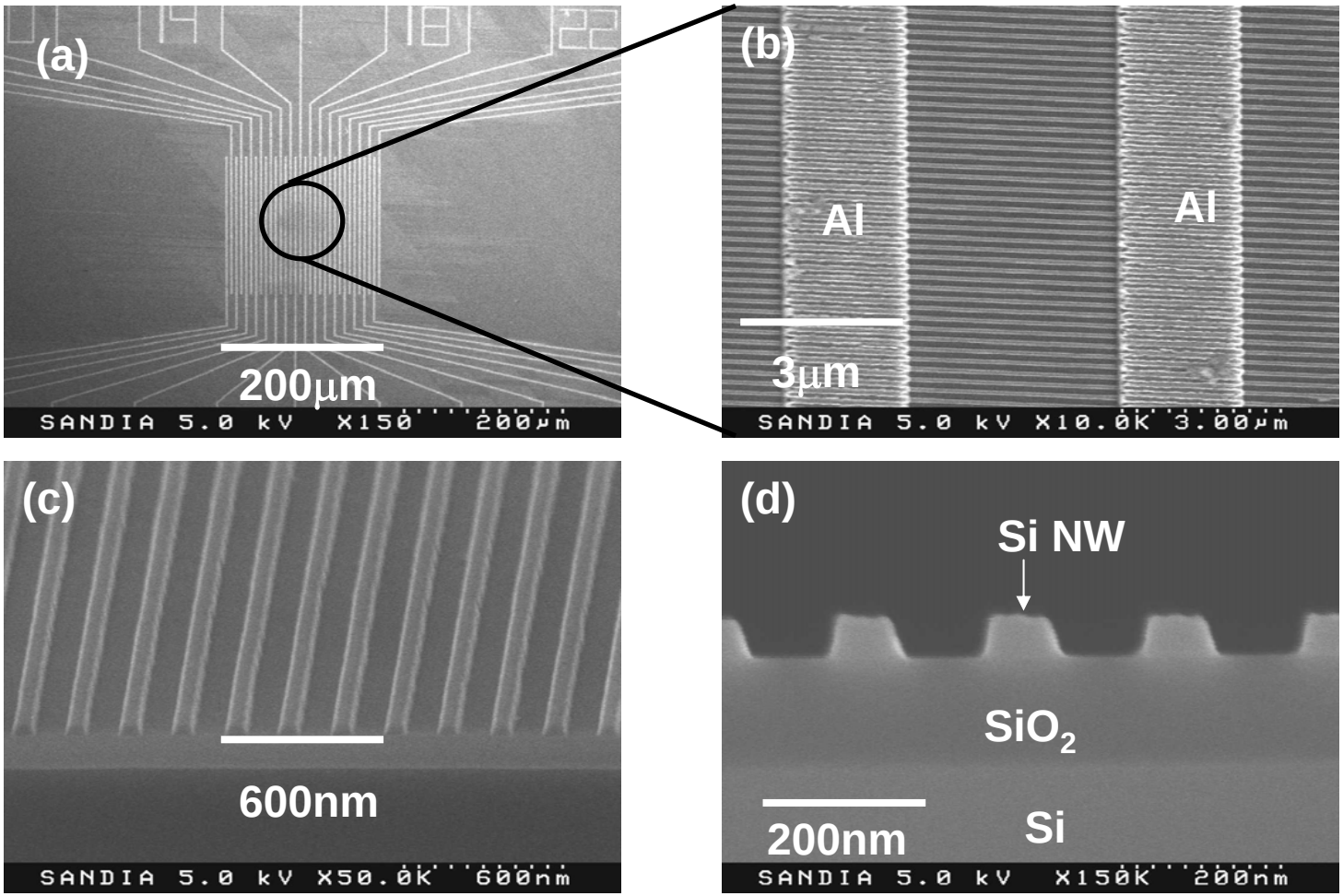


UV litho



Al dep and lift-off

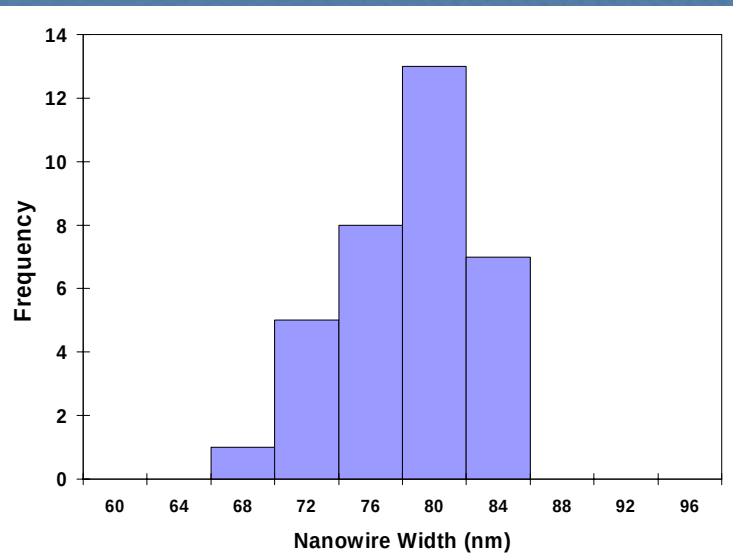
Fabrication Results

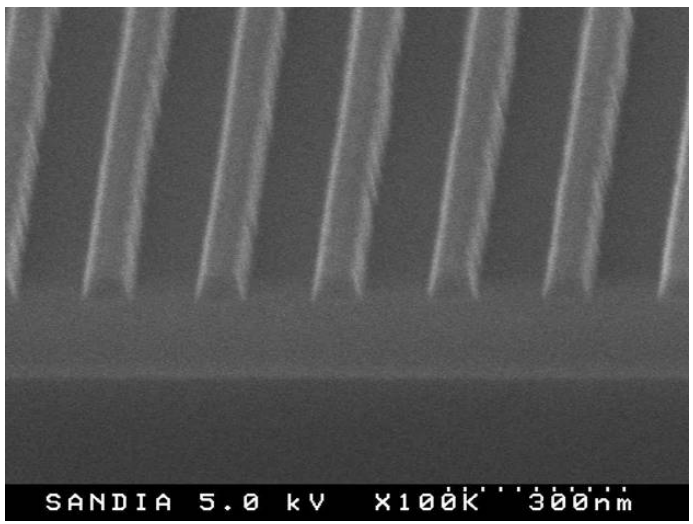


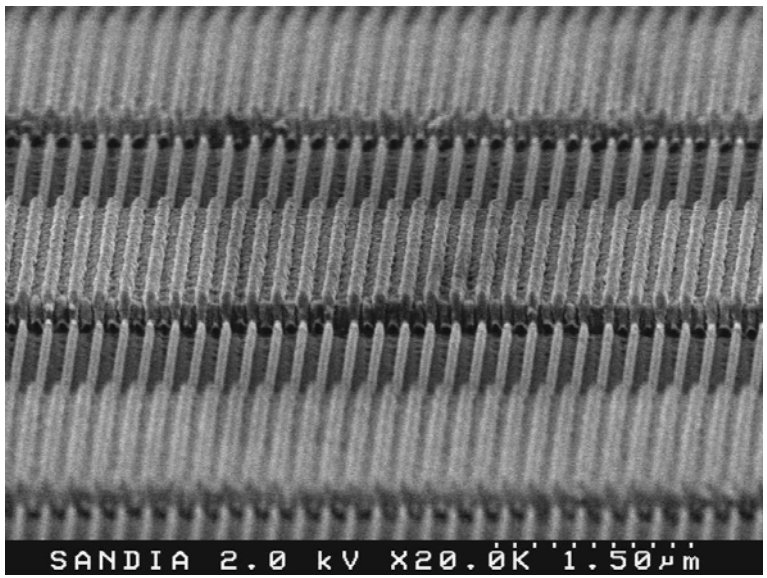
Talin et al., Appl. Phys. Lett., in press

Fabrication Results

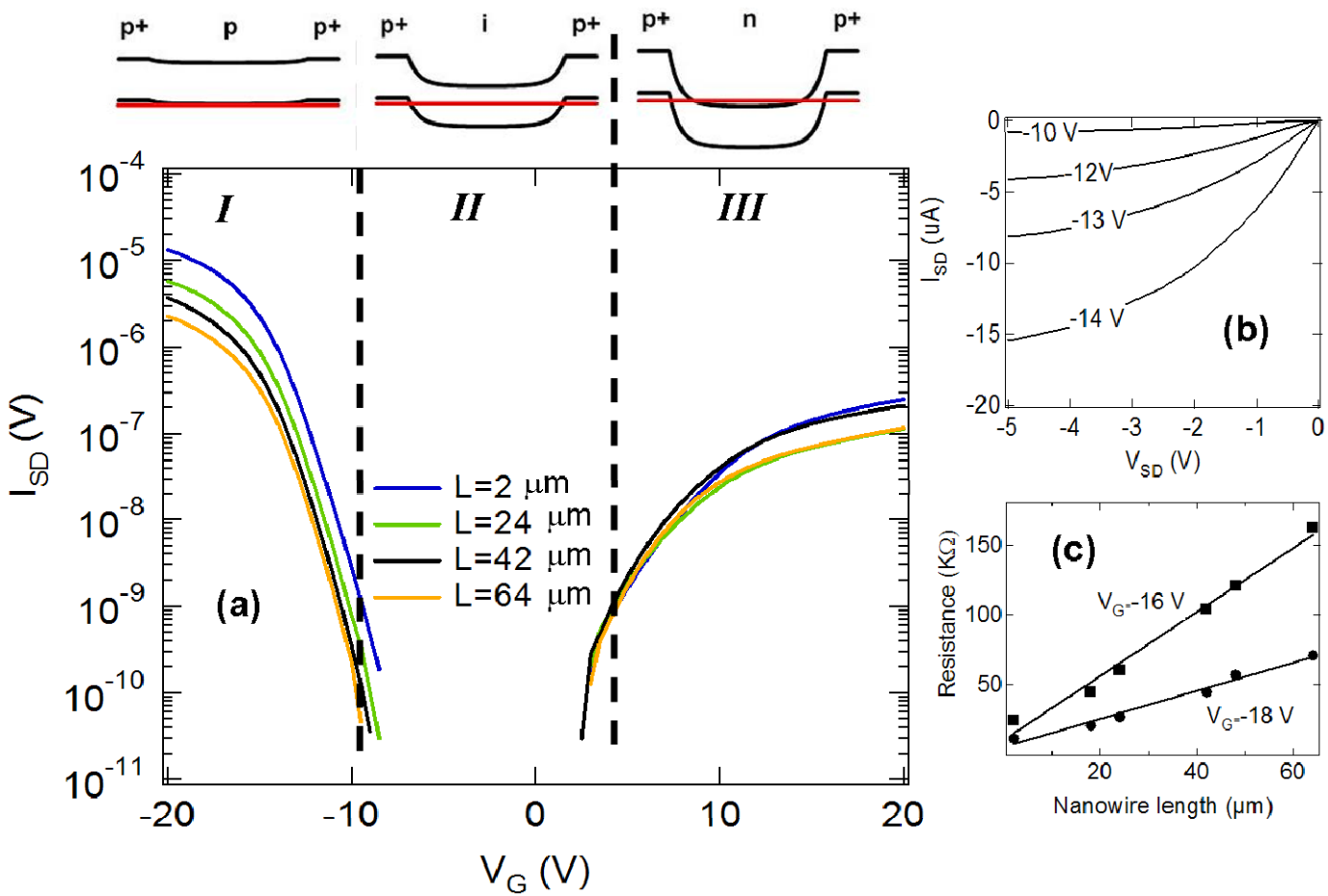
- 400 devices on a 4” wafer
- 76 nm average line width
- Narrow distribution of widths





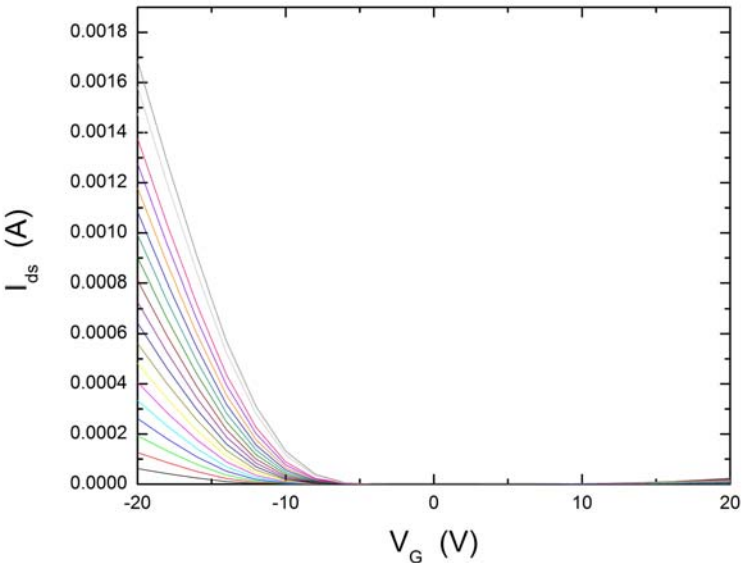


Electrical Characteristics

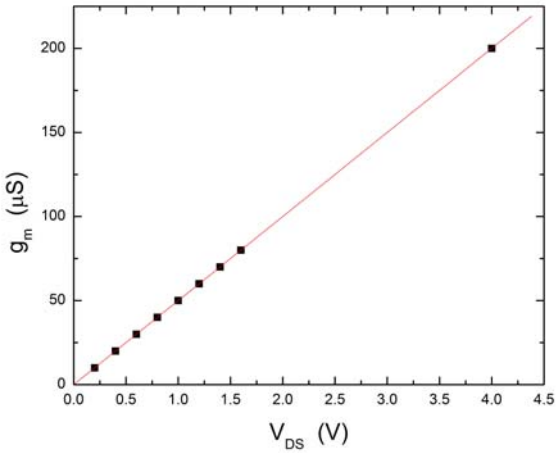


Talin et al., Appl. Phys. Lett., in press

Transconductance



$$g_m = \frac{\partial I_{ds}}{\partial V_g}$$



$$g_m = \mu C \frac{NW}{L} V_{DS}$$

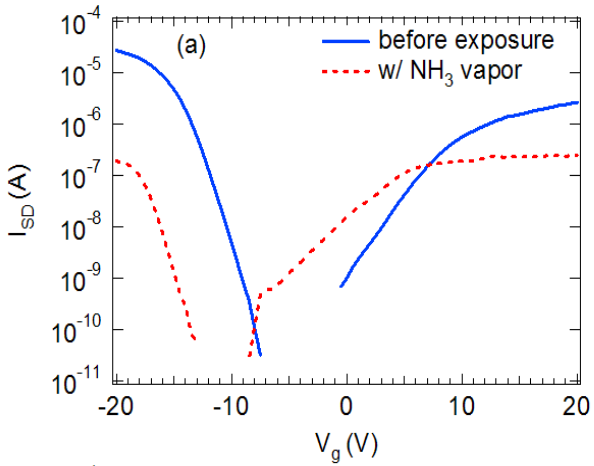
$$C = 2\pi\varepsilon L \Big/ \left[2\Sigma_{n=1}^{N} \ln\left(2\sqrt{h^2 + n^2 l^2} \,/\, r \right) + \ln(2h/r) \right]$$

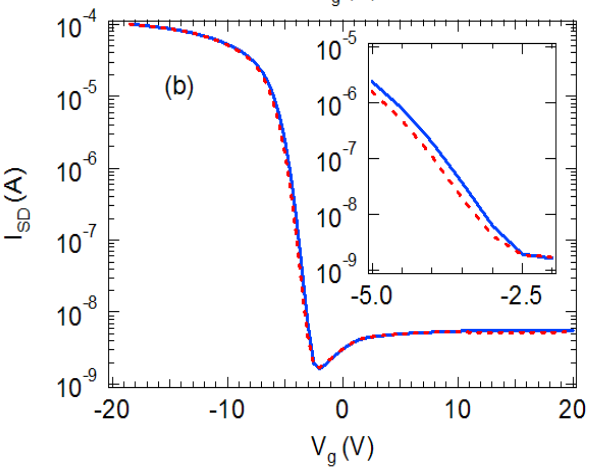
$$\mu = \frac{L}{slope * NWC} \approx 80 cm^2/Vs$$

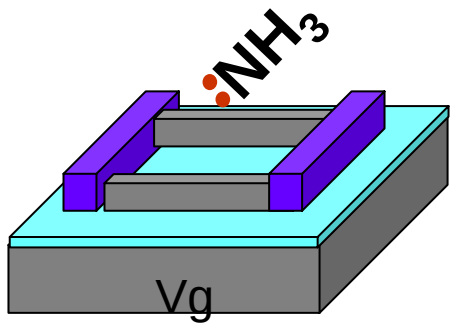
- ***Si hole mobility is ~500 cm²/Vs (Sze)***
- ***VLS Si nanowire mobility 0.006 – 3 cm²/Vs for 70 nm diam. (Lieber group, J. Phys. Chem. B 104, 5213, 2000***

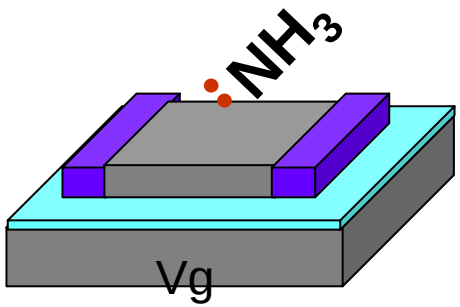
Sensors: nanowires more sensitive to ammonia vapor then thin films

Adsorption of electron donating ammonia makes Si nanowires more 'n-type', shifts I_{SD}-V_g to the left









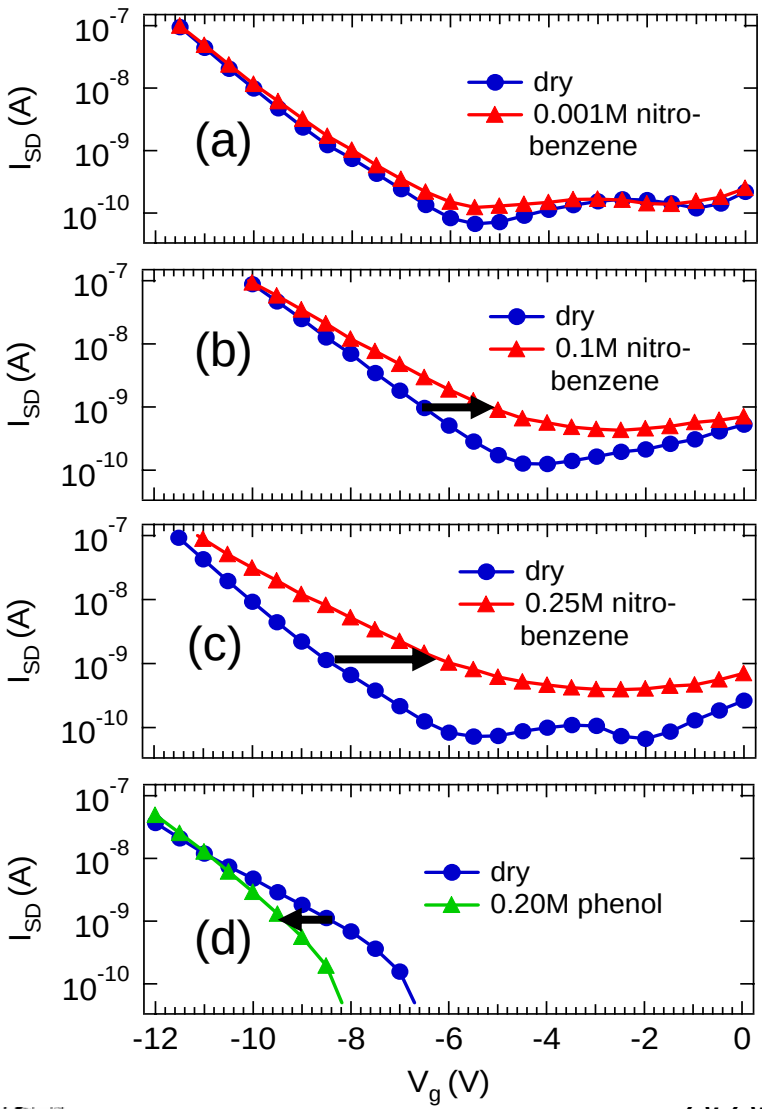
$$env = AC(V_t - V_g)$$

$$env + e\alpha a^{-1}\theta s = AC(V_t' - V_g)$$

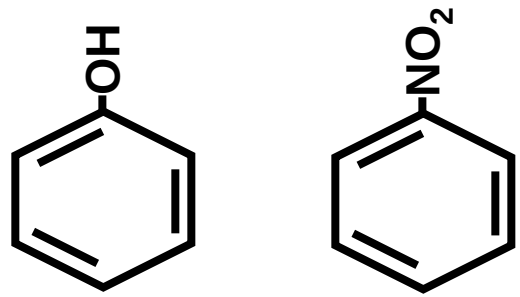
$$\Delta V_t = e\alpha a^{-1}\theta C^{-1}(s/A)$$

$$C \propto (l + \kappa w)/(l + w)$$

Sensing with Si nanowires: nitrobenzene, phenol



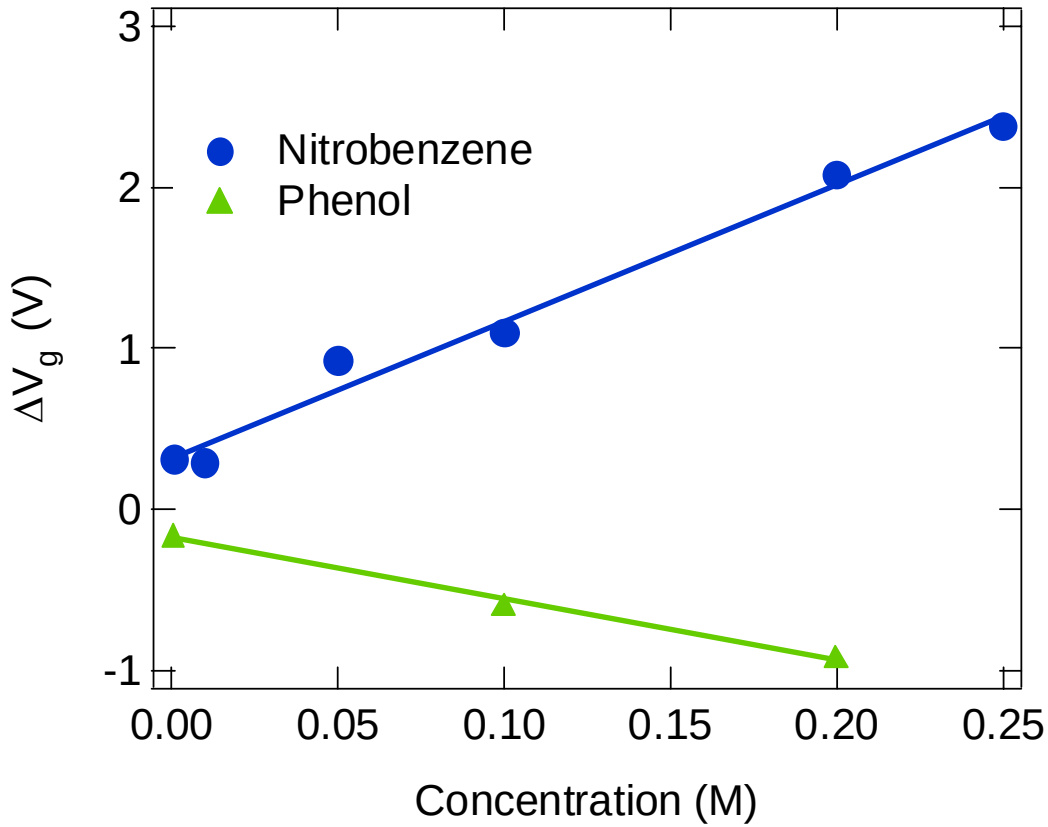
e⁻ donating *e⁻ withdrawing*



Hammet param. -0.4 ***+.78***

Sensing with Si nanowires: nitrobenzene, phenol

- *shift in V_g is linear with solute concentration*
- *scales with Hammet parameter (2:1 ratio for NB:Phenol)*



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