Sub-10 nm Diameter InGaAs Vertical Nanowire MOSFETs

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Lam RESEARCH

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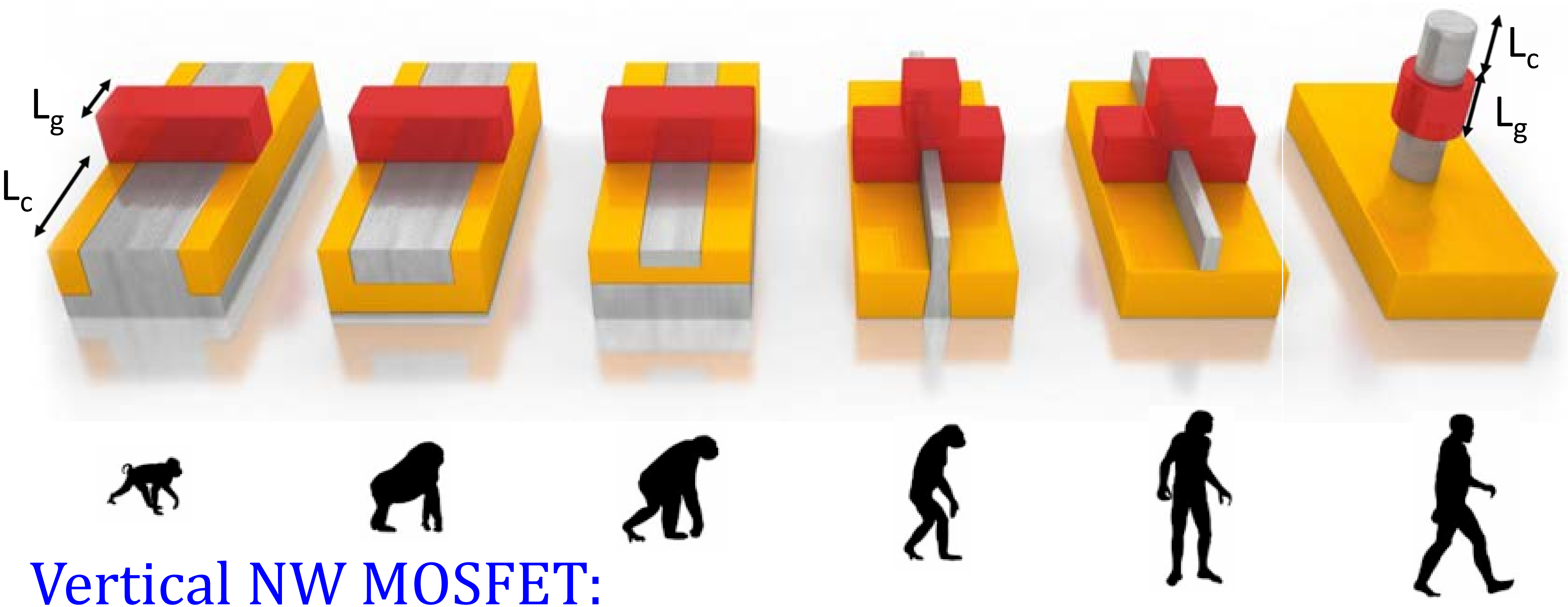
Outline

- Motivation
- Process technology
- Device electrical characteristics
- Conclusions

Vertical NW MOSFETs: ultimate scalable transistor

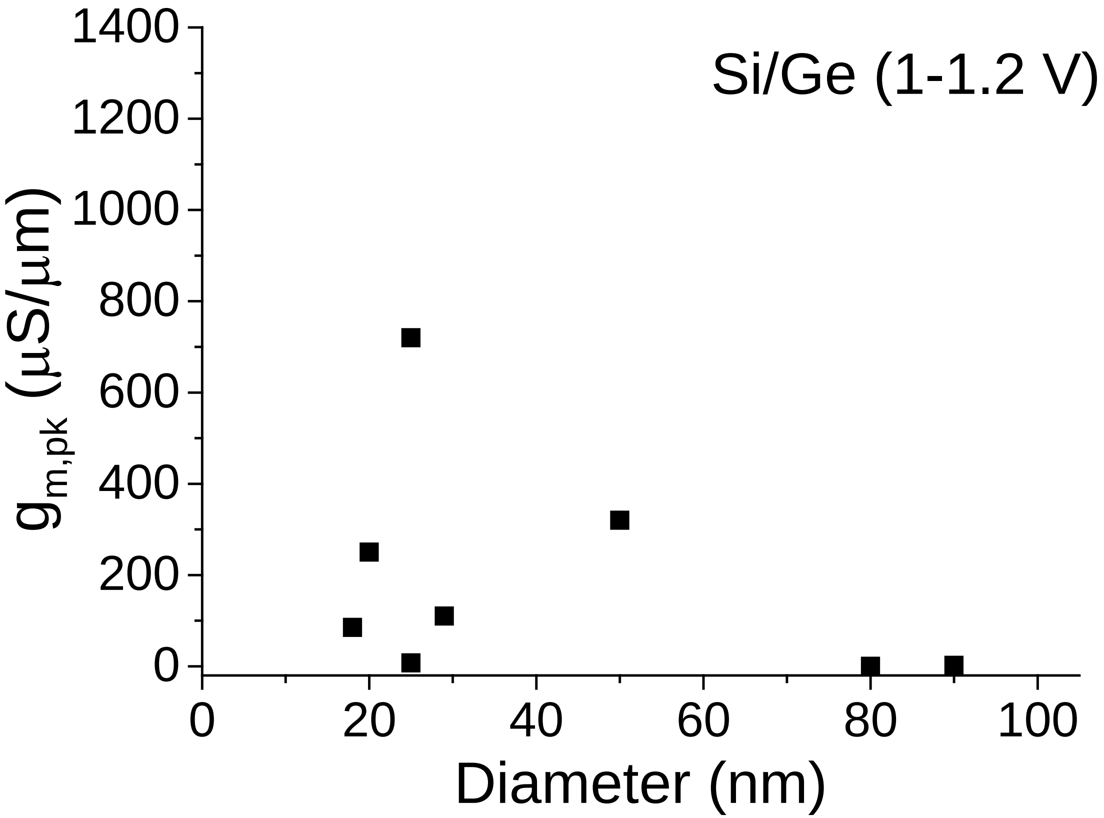


Vertical NW MOSFET:

→ uncouples footprint scaling from L_g, L_{spacer}, and L_c scaling

State-of-the-art VNW MOSFETs: Si/Ge

Peak g_m of Si and Ge VNW MOSFETs (V_{ds} = 1-1.2 V)

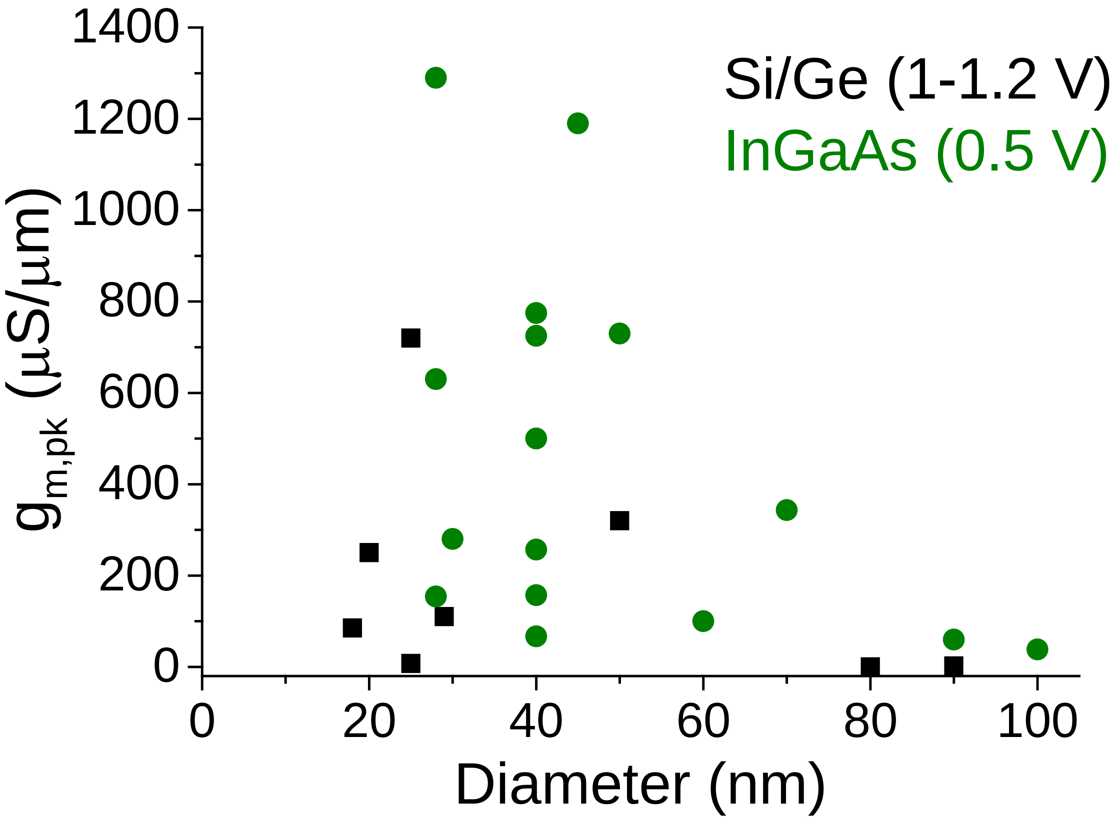


* Normalization by the total circumference

- D = 18 nm devices demonstrated

State-of-the-art VNW MOSFETs: InGaAs

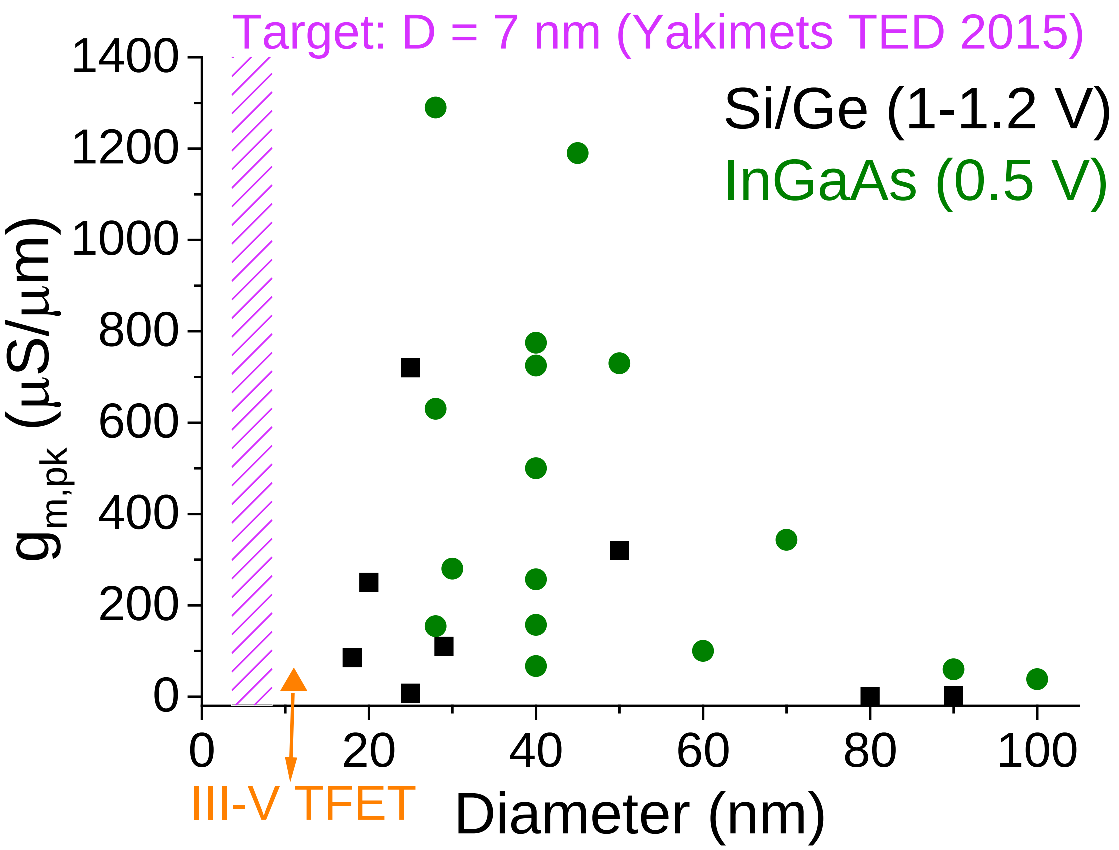
Peak g_m of InGaAs (V_{DS}=0.5 V), Si and Ge VNW MOSFETs



- InGaAs competitive with Si

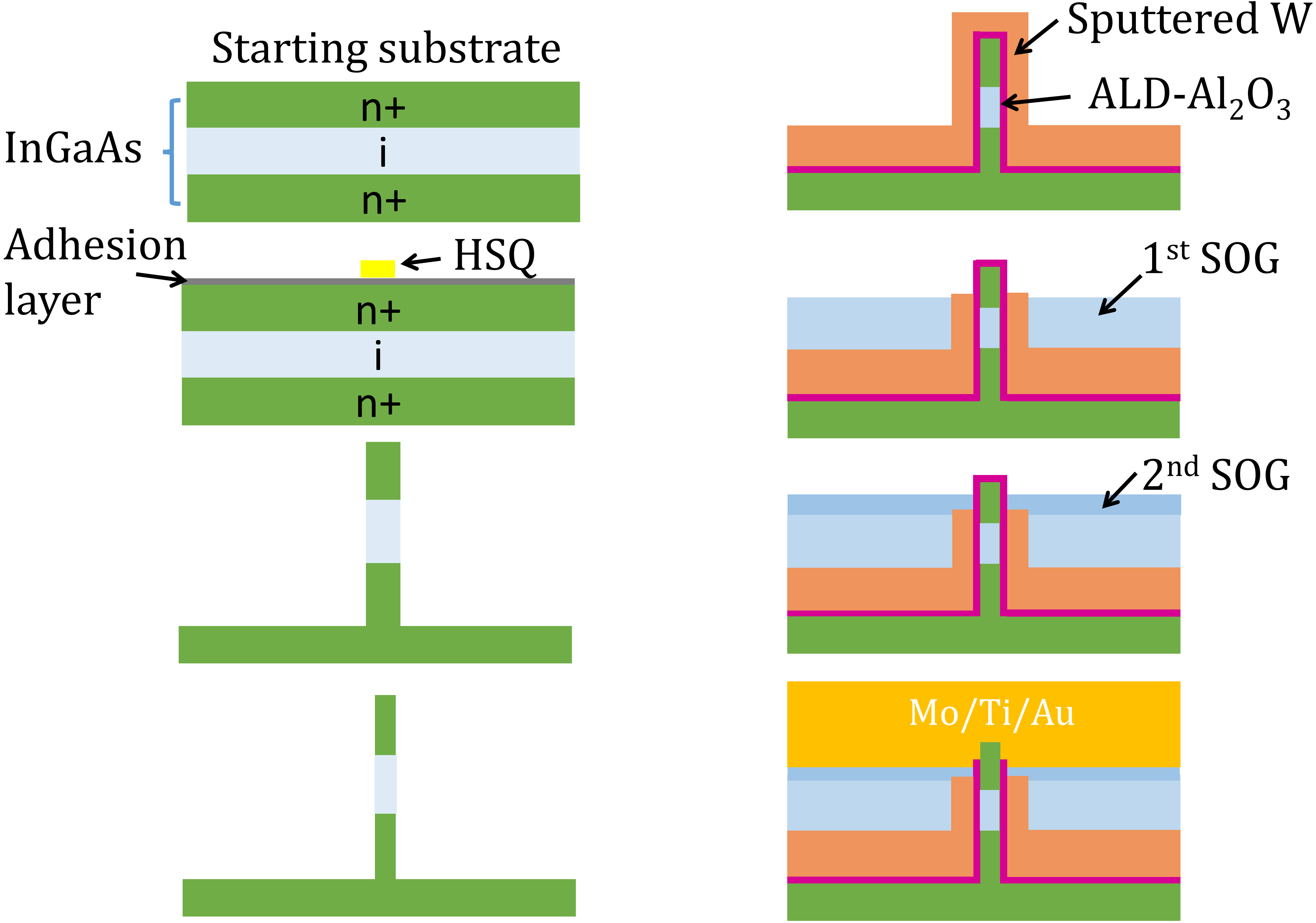
State-of-the-art VNW MOSFETs: InGaAs

Peak g_m of InGaAs (V_{DS}=0.5 V), Si and Ge VNW MOSFETs



- InGaAs competitive with Si
- ***Need to demonstrate VNW MOSFETs with D<10 nm***

III-V VNW MOSFET process flow @ MIT



Starting substrate

InGaAs

Adhesion layer

HSQ

Sputtered W

ALD-Al_2O_3

1^{st} SOG

2^{nd} SOG

InGaAs vertical nanowires @ MIT

Key enabling technologies:

- RIE = $BCl_3/SiCl_4/Ar$ chemistry
- Digital Etch (DE) =

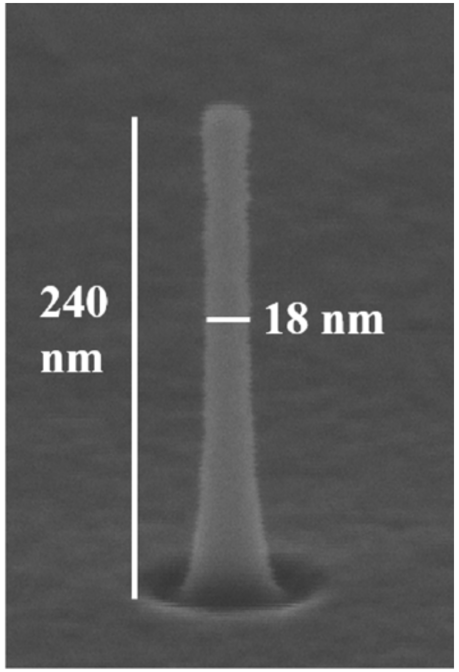
self-limiting O_2 plasma oxidation + H_2SO_4 or HCl oxide removal

- Radial etch rate=1 nm/cycle
- Sub-20 nm NW diameter
- Aspect ratio > 10
- Smooth sidewalls

Zhao, IEDM 2013
Zhao, EDL 2014
Zhao, IEDM 2014

RIE

+ 5 cycles DE

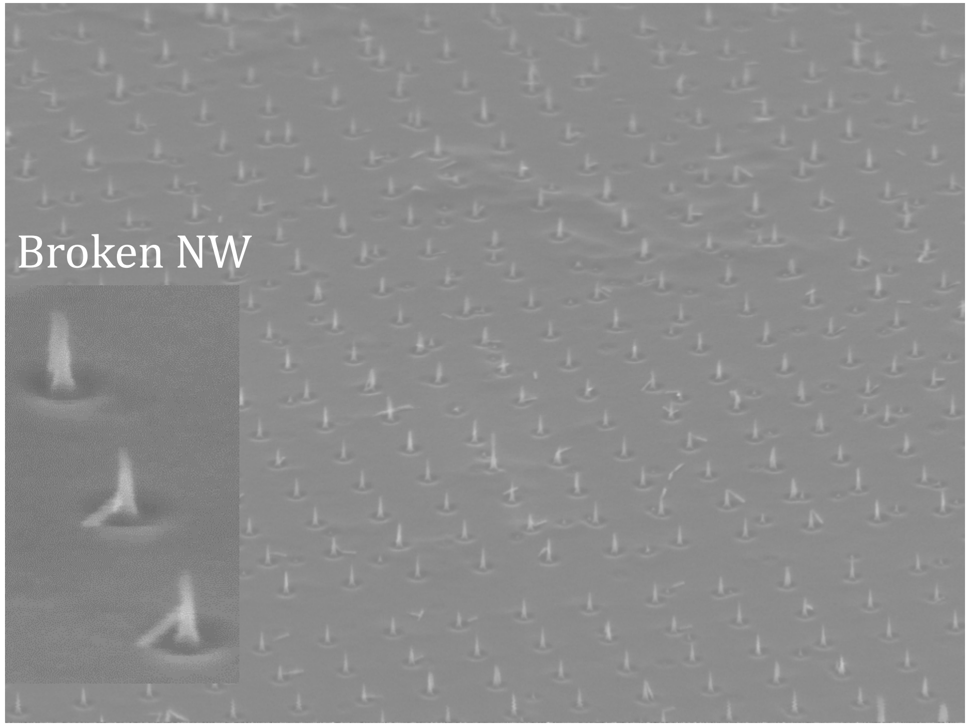


Challenge for sub-10 nm VNW: mechanical stability

Lu, EDL 2017

Difficult to reach 10 nm VNW diameter due to breakage

8 nm InGaAs VNWs: Yield = 0%



Water-based acid is problem:

Surface tension (mN/m):
- Water: 72
- Methanol: 22
- IPA: 23

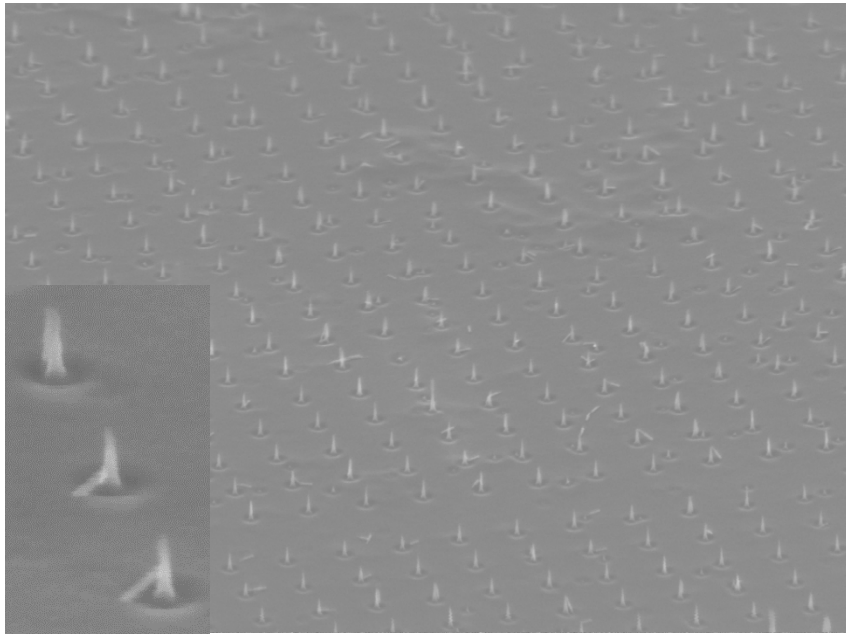
Solution: *alcohol-based digital etch?*

Alcohol-Based Digital Etch

8 nm InGaAs VNWs after 7 DE cycles:

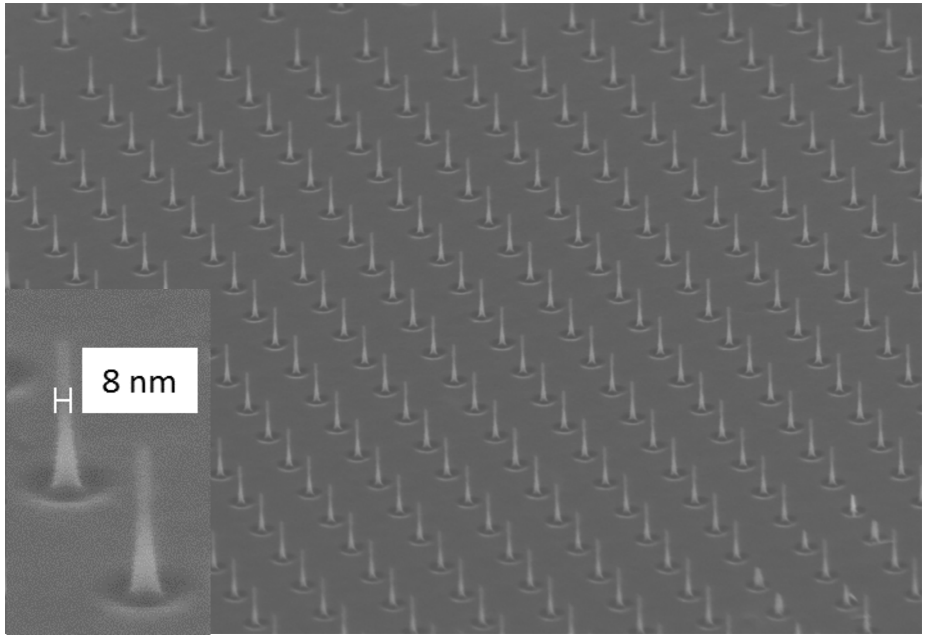
Lu, EDL 2017

10% HCl in DI water
Yield = 0%



Radial etch rate: 1.0 nm/cycle

10% HCl in IPA
Yield = 97%



Radial etch rate: 1.0 nm/cycle

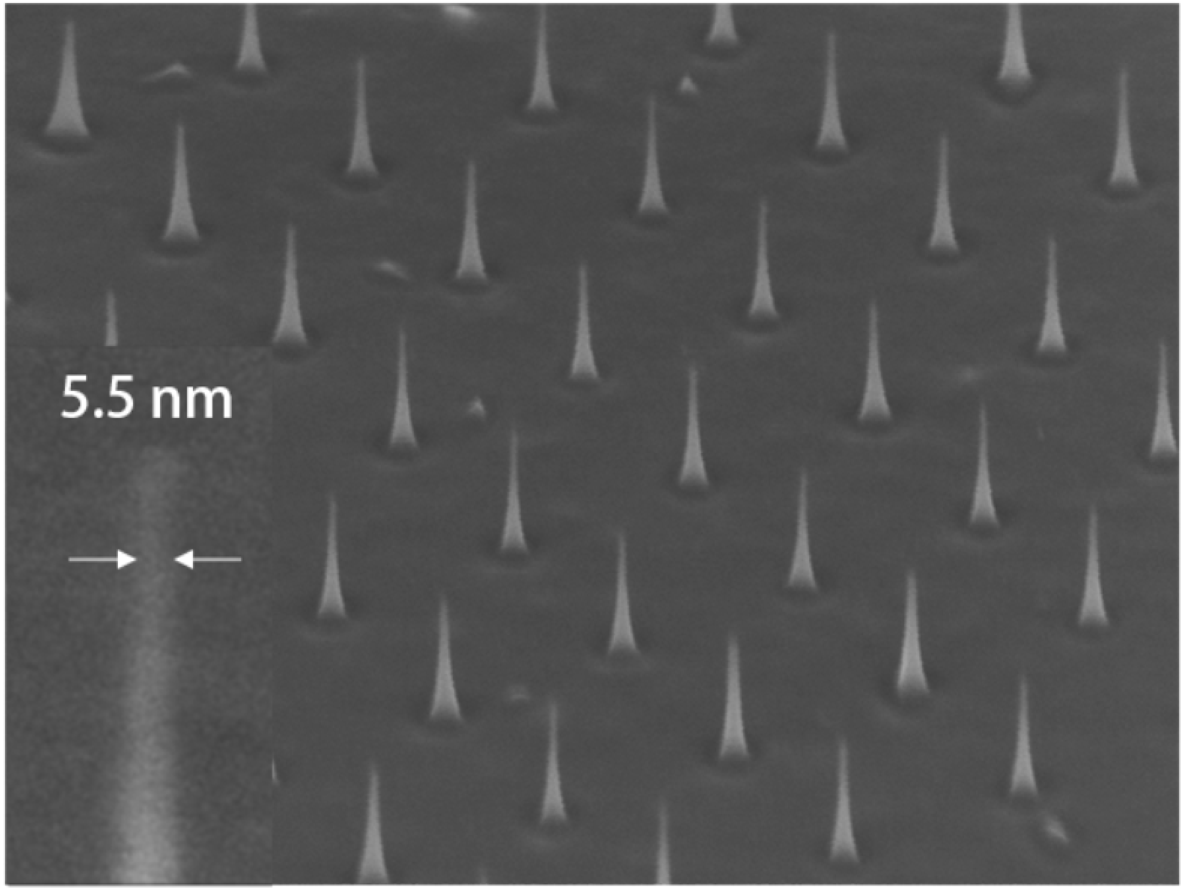
Alcohol-based DE enables D < 10 nm

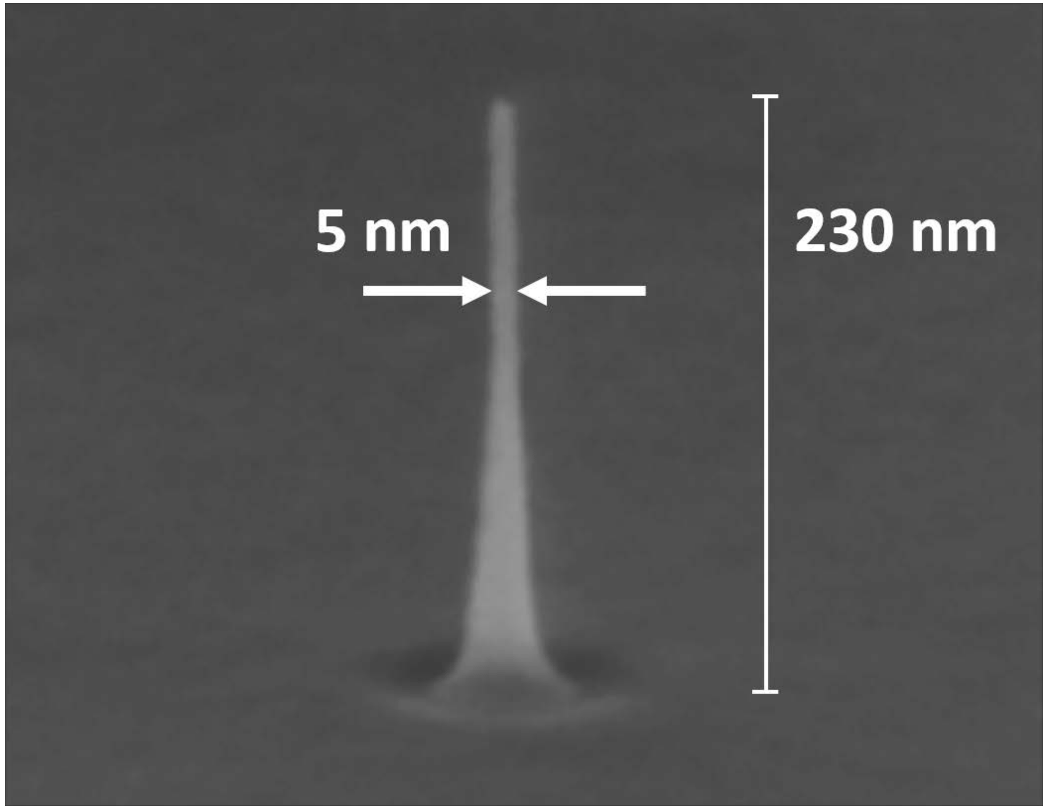
D=5.5 nm VNW arrays

90% yield

10% H_2SO_4 in methanol

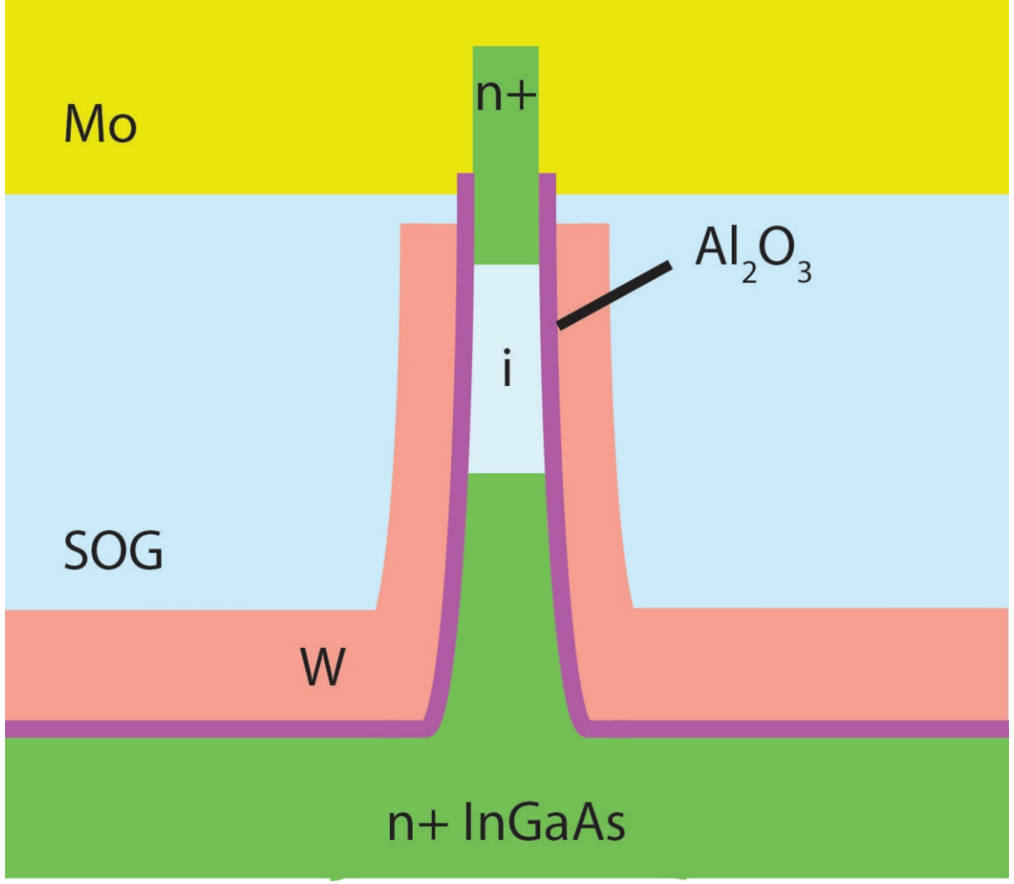
Lu, EDL 2017



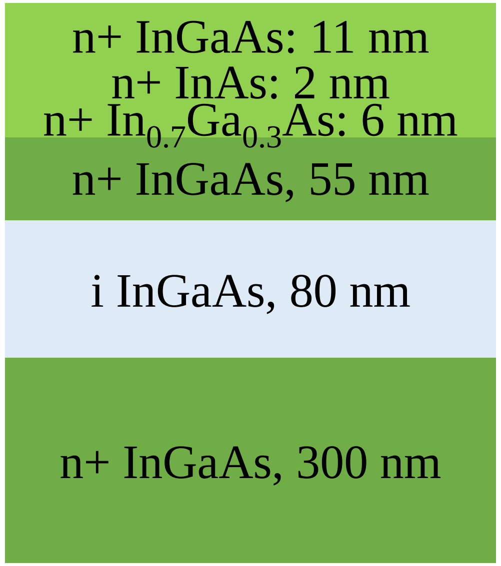


- H_2SO_4:methanol yields 90% at D=6 nm!
- Viscosity matters: methanol (0.54 cP) vs. IPA (2.0 cP)

Toward sub-10 nm InGaAs VNW MOSFETs



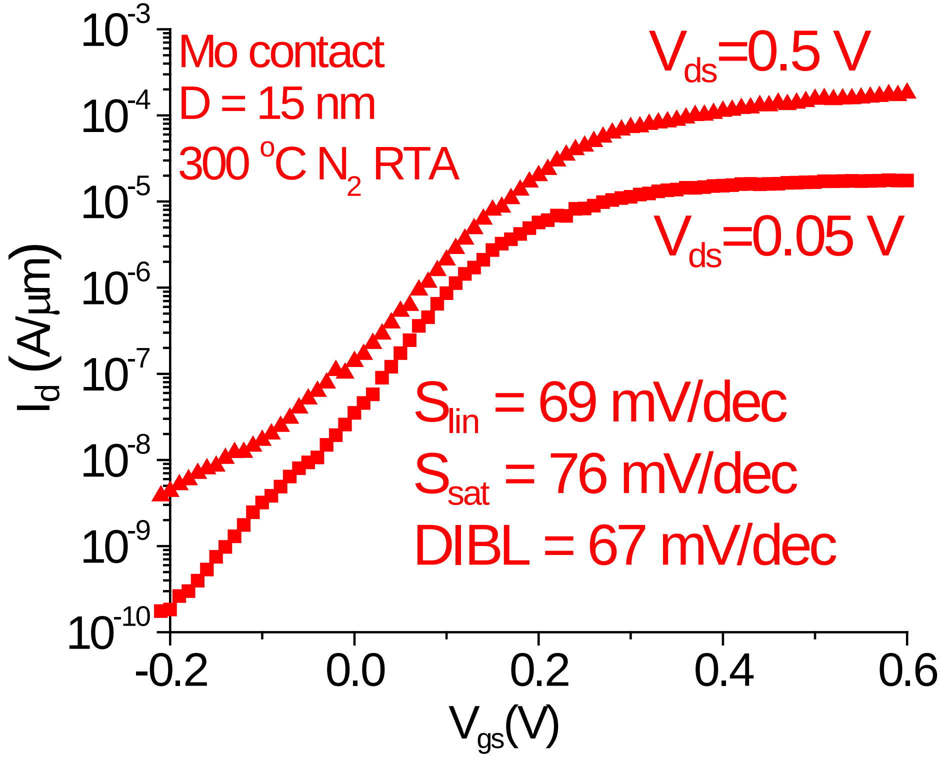
Starting heterostructure:

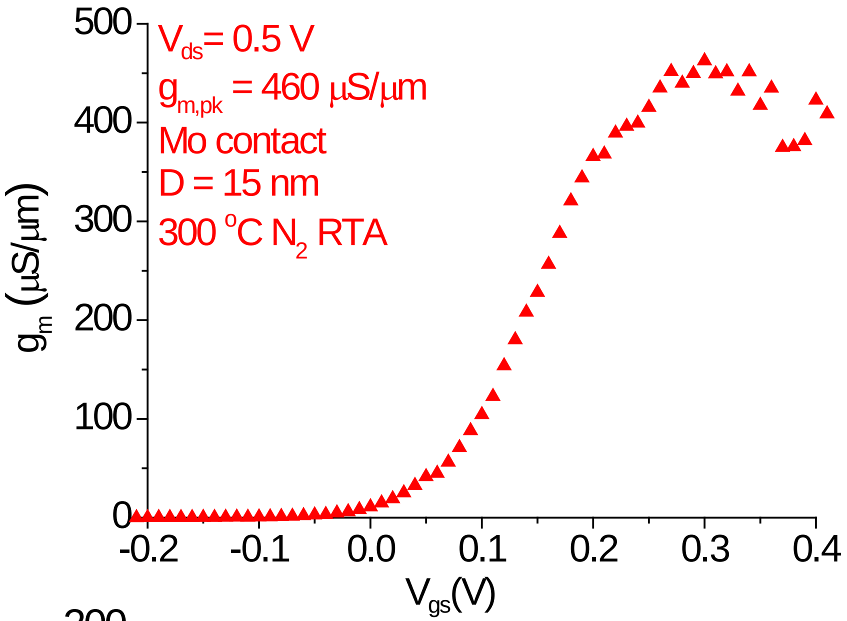

n+ InGaAs: 11 nm
n+ InAs: 2 nm
n+ $In_{0.7}Ga_{0.3}As$: 6 nm
n+ InGaAs, 55 nm
i InGaAs, 80 nm
n+ InGaAs, 300 nm

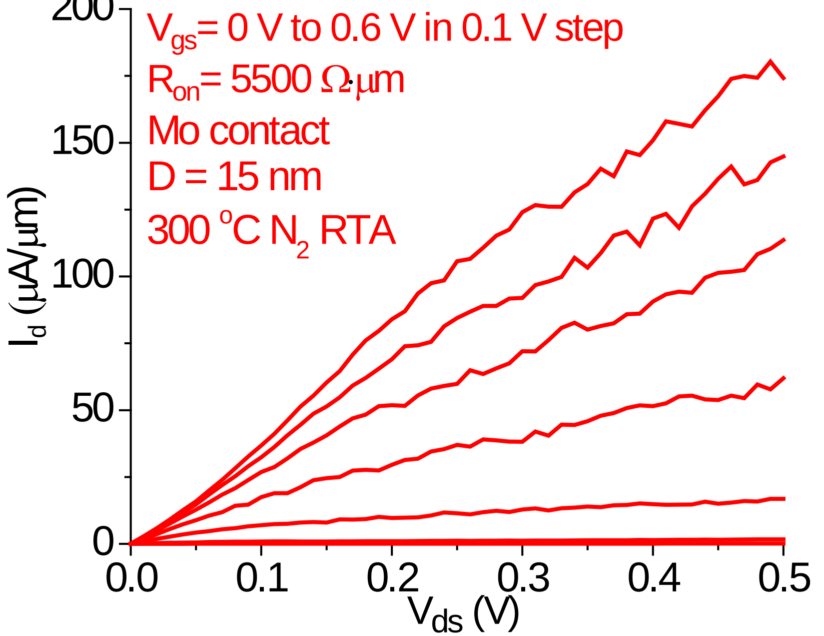
D = 40, 30, 18, 15, 11, 7 nm
No. of wires = 1
L_{ch} = 80 nm
EOT = 1.25 nm

New element: H_2SO_4:methanol DE

D = 15 nm Mo-contacted device



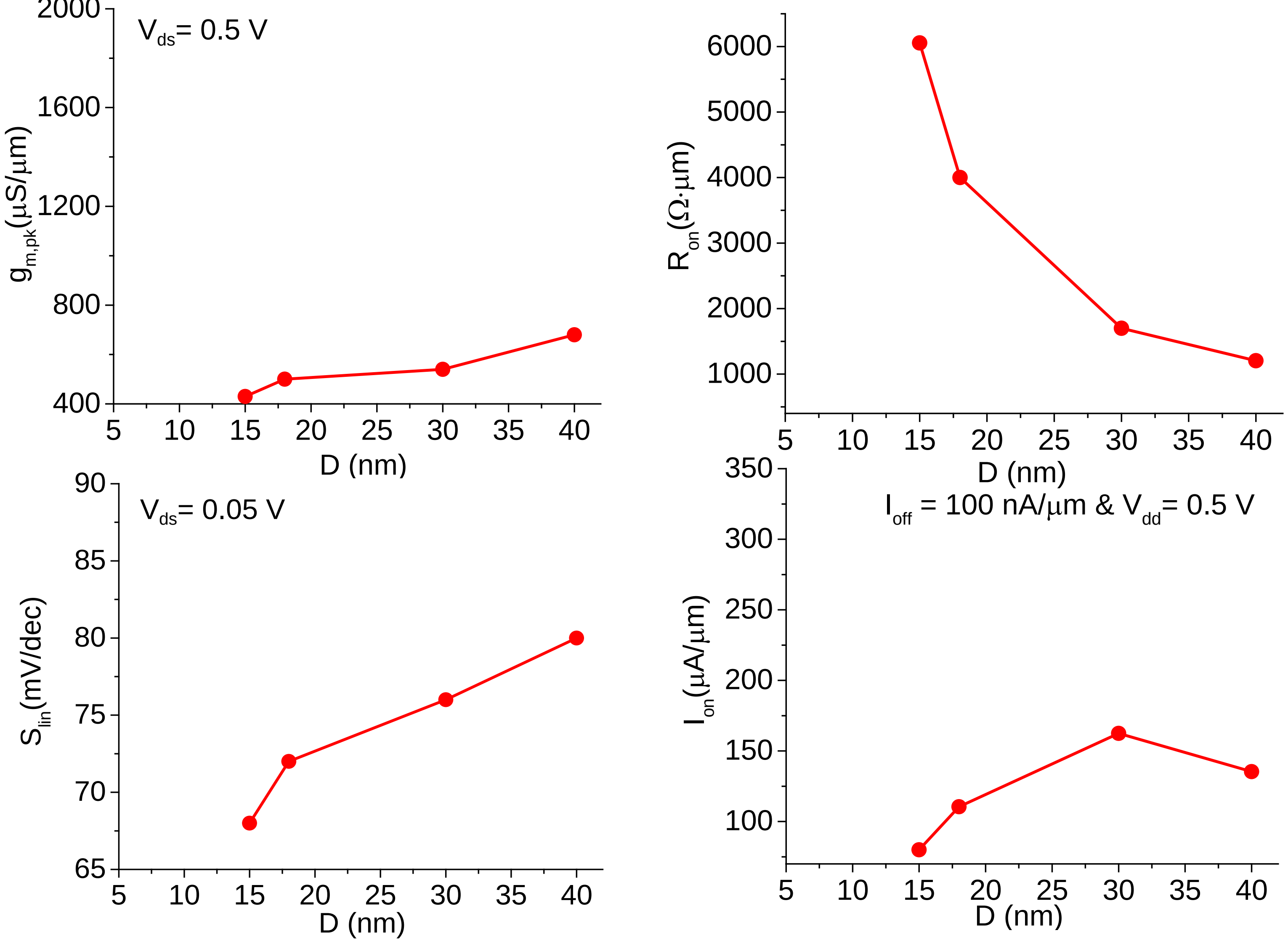




Single nanowire MOSFET:

- D = 15 nm & L_{ch}= 80 nm
- S_{lin}= 69 mV/dec
- 2.5 nm Al_2O_3 (EOT = 1.25 nm)
- 300 °C N_2 RTA, 1 min

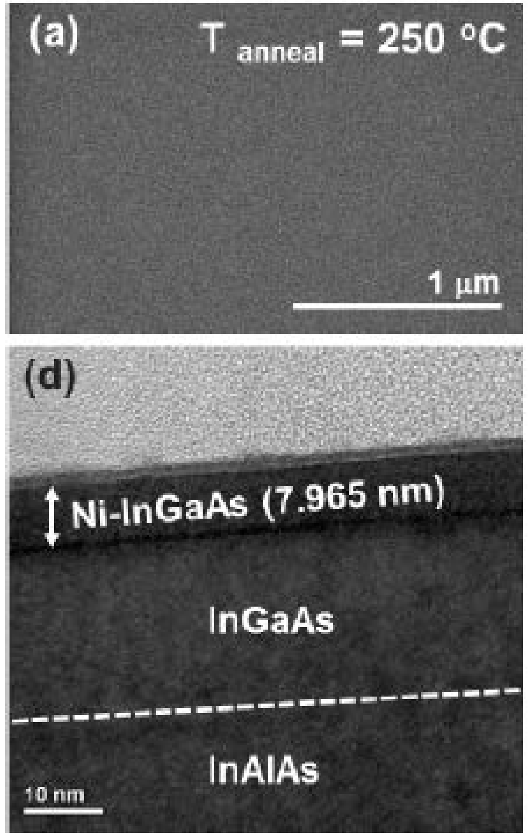
Diameter scaling of Mo devices



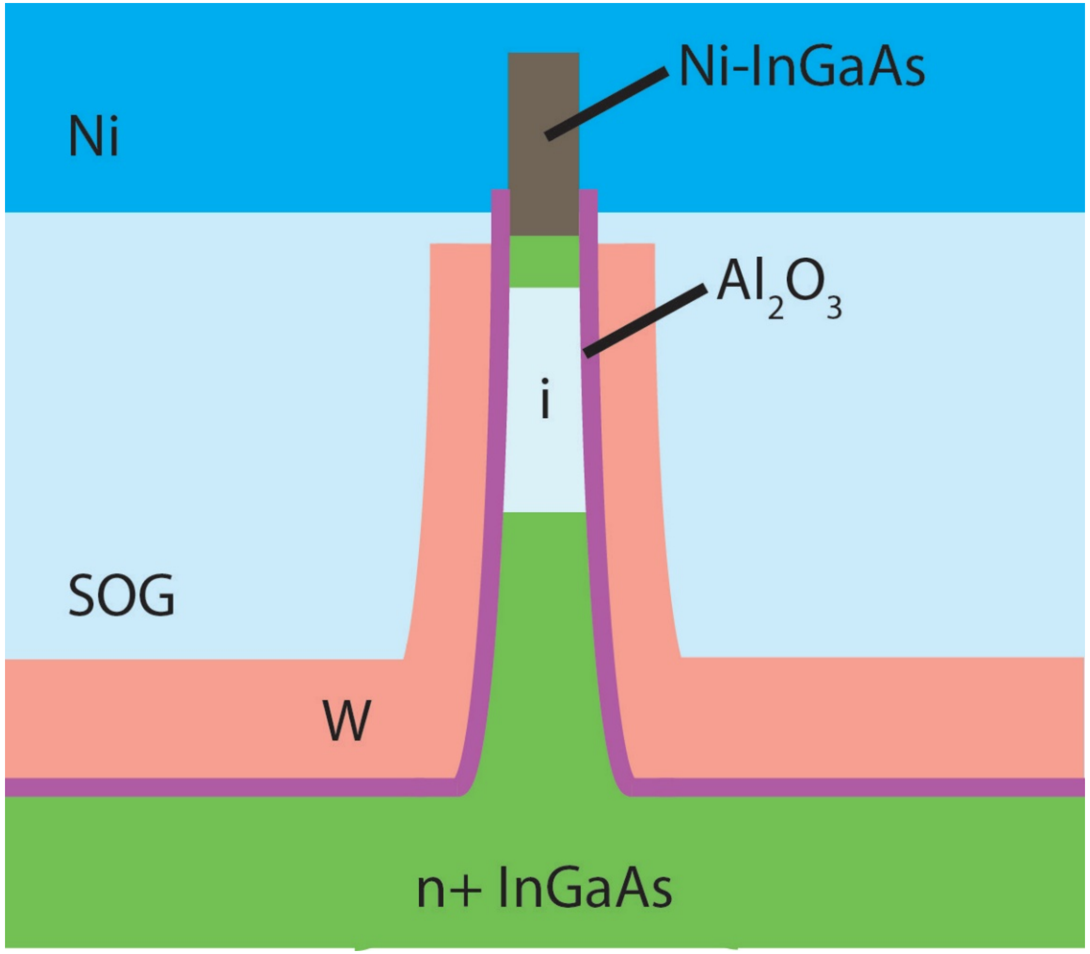
* Mean values
of 3 individual
devices

- Narrowest working device has D = 15 nm
- R_{on} skyrockets with D ↓

Challenge for sub-10 nm VNW: top contact

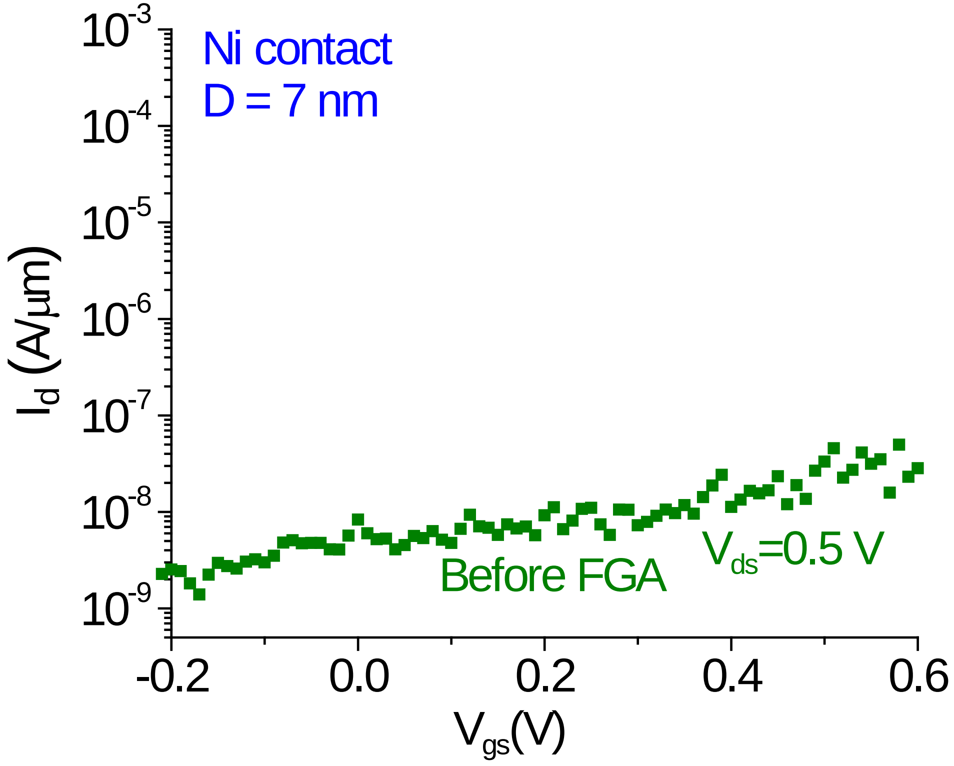


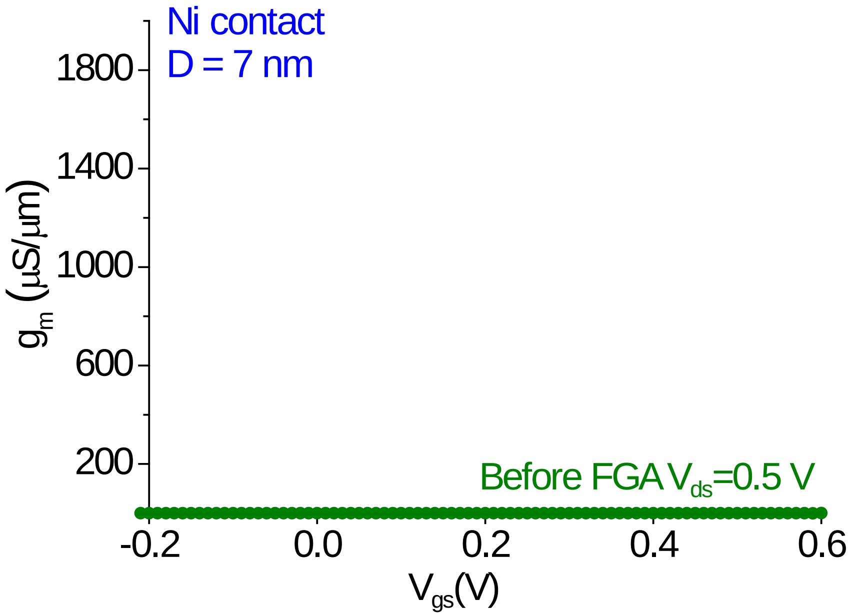
Lee IEDM 2013

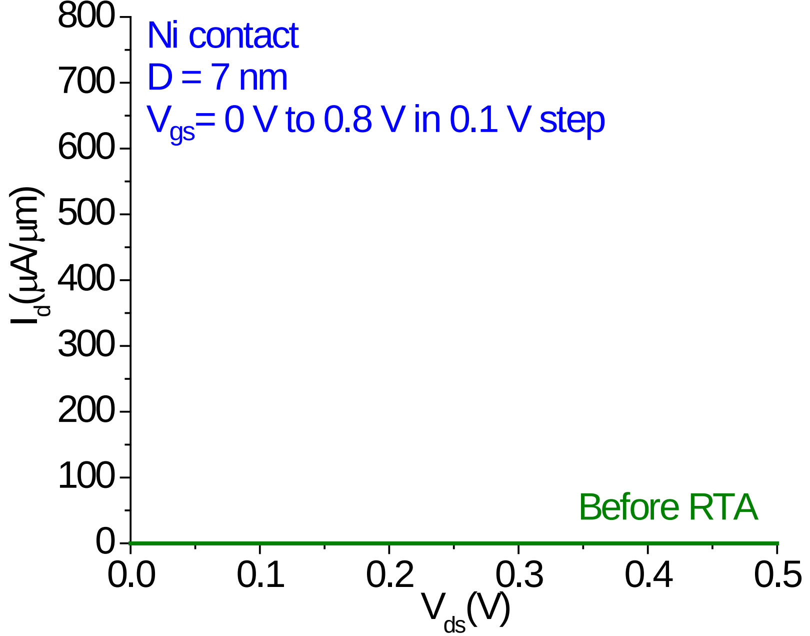


Solution: *alloyed contacts?*

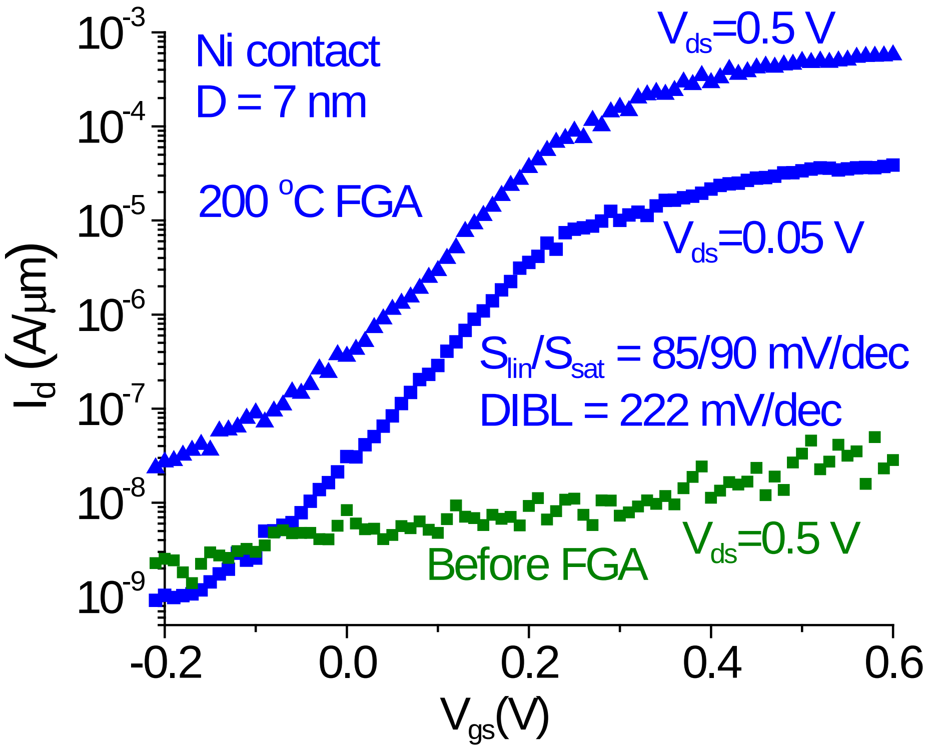
Ni contacted D = 7 nm MOSFET





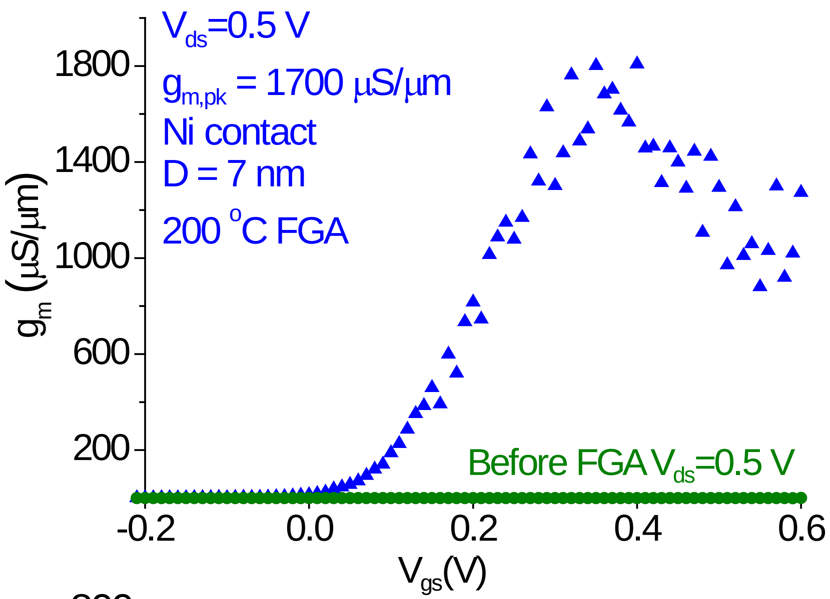


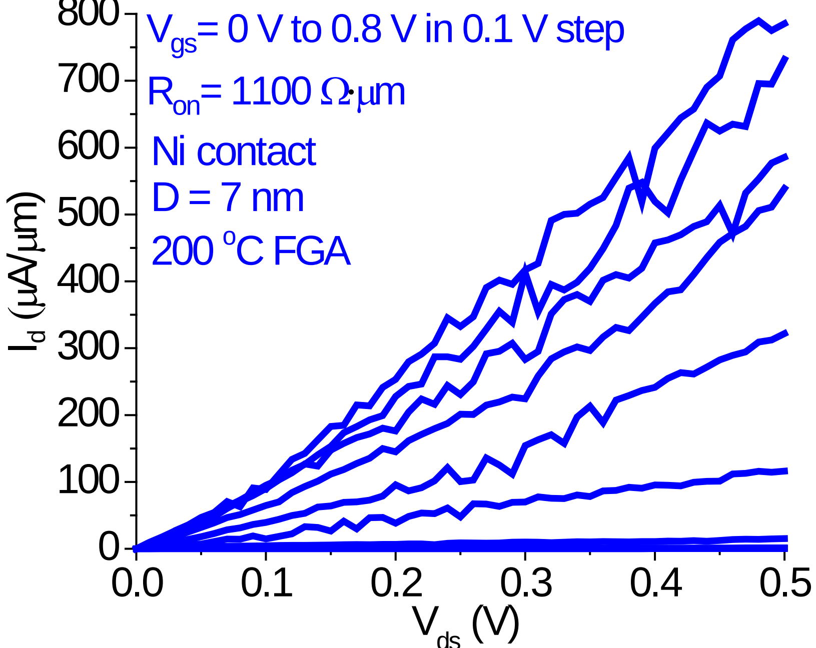
Ni contacted D = 7 nm MOSFET



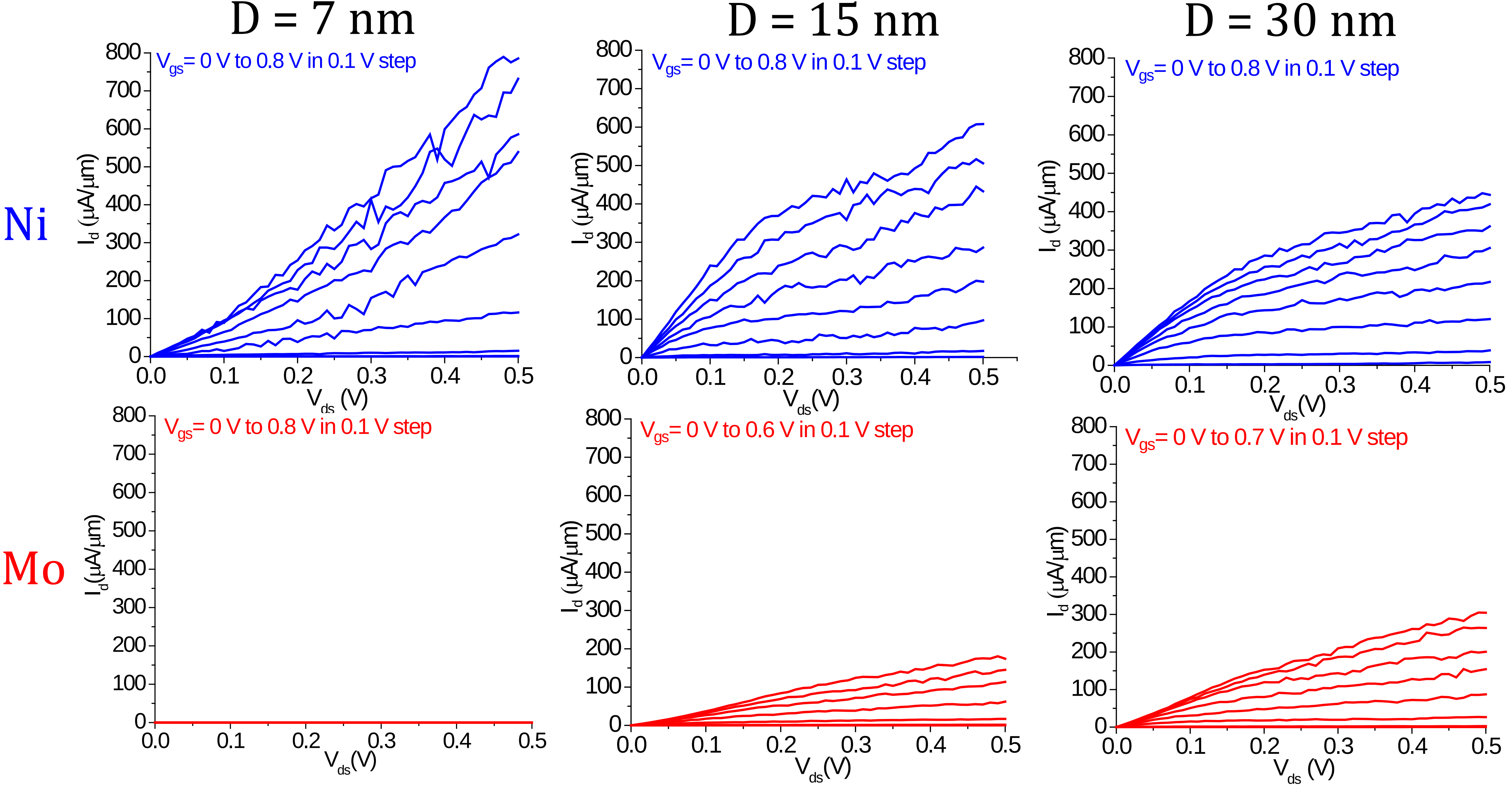
Single nanowire MOSFET:

- D = 7 nm & L_{ch}= 80 nm
- 2.5 nm Al_2O_3 (EOT = 1.25 nm)
- 200 °C FGA, 1 min
- I_{on} = 350 μA/μm @ V_{DD}= 0.5 V & I_{off} = 100 nA/μm



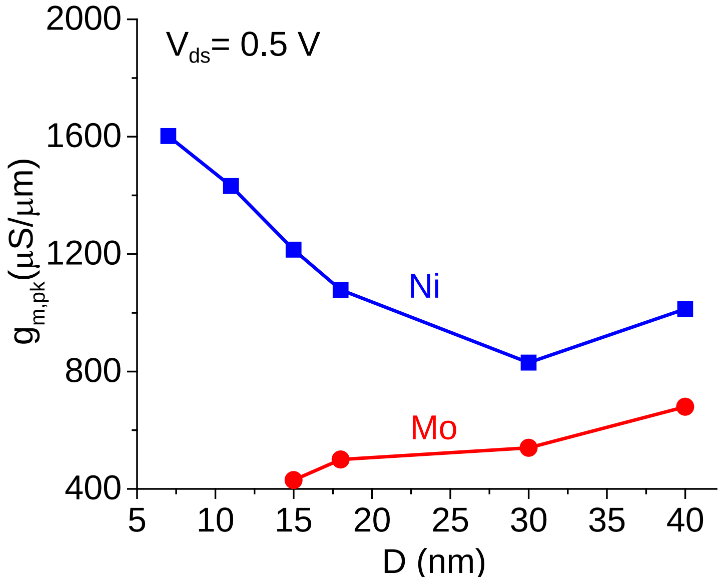


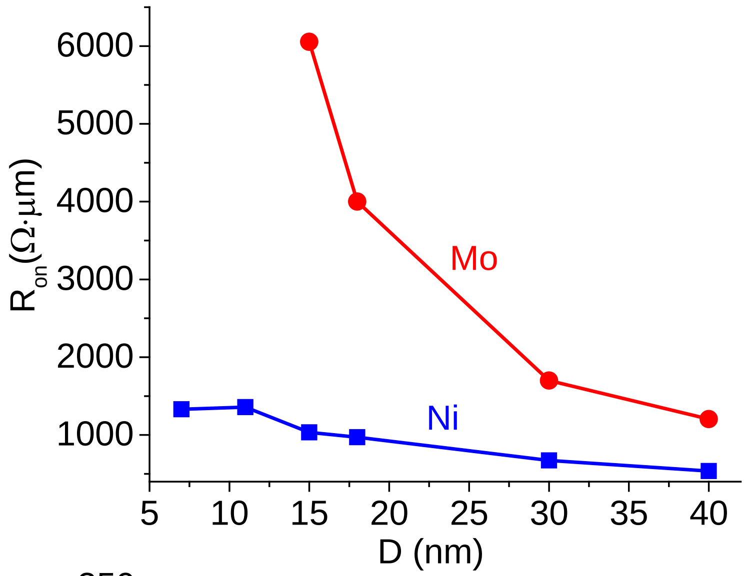
Output characteristics vs. D



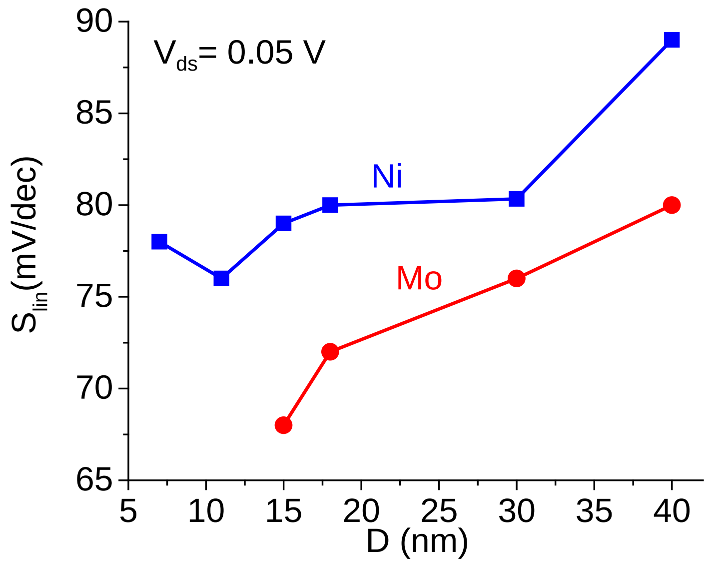
Better current situation at D = 15 nm devices

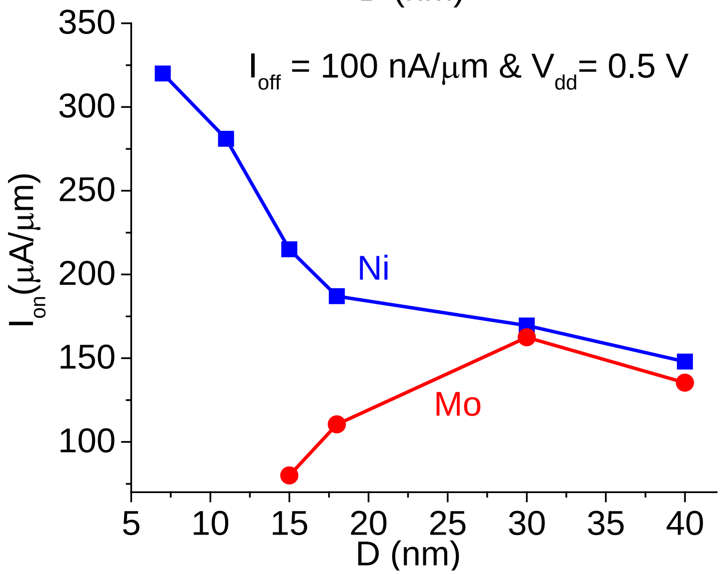
Diameter scaling of Ni vs Mo devices





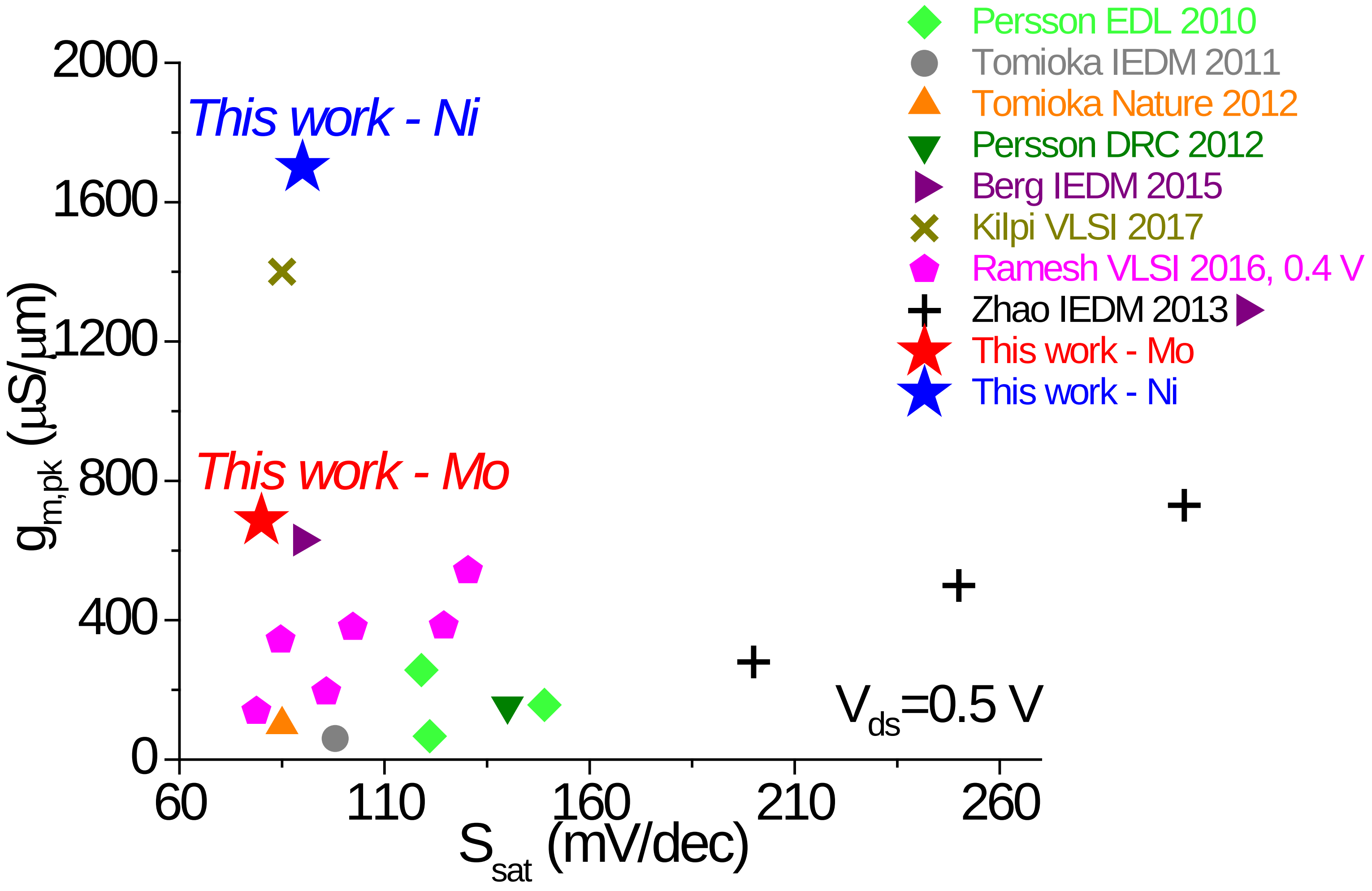
* Mean values of 3 individual devices





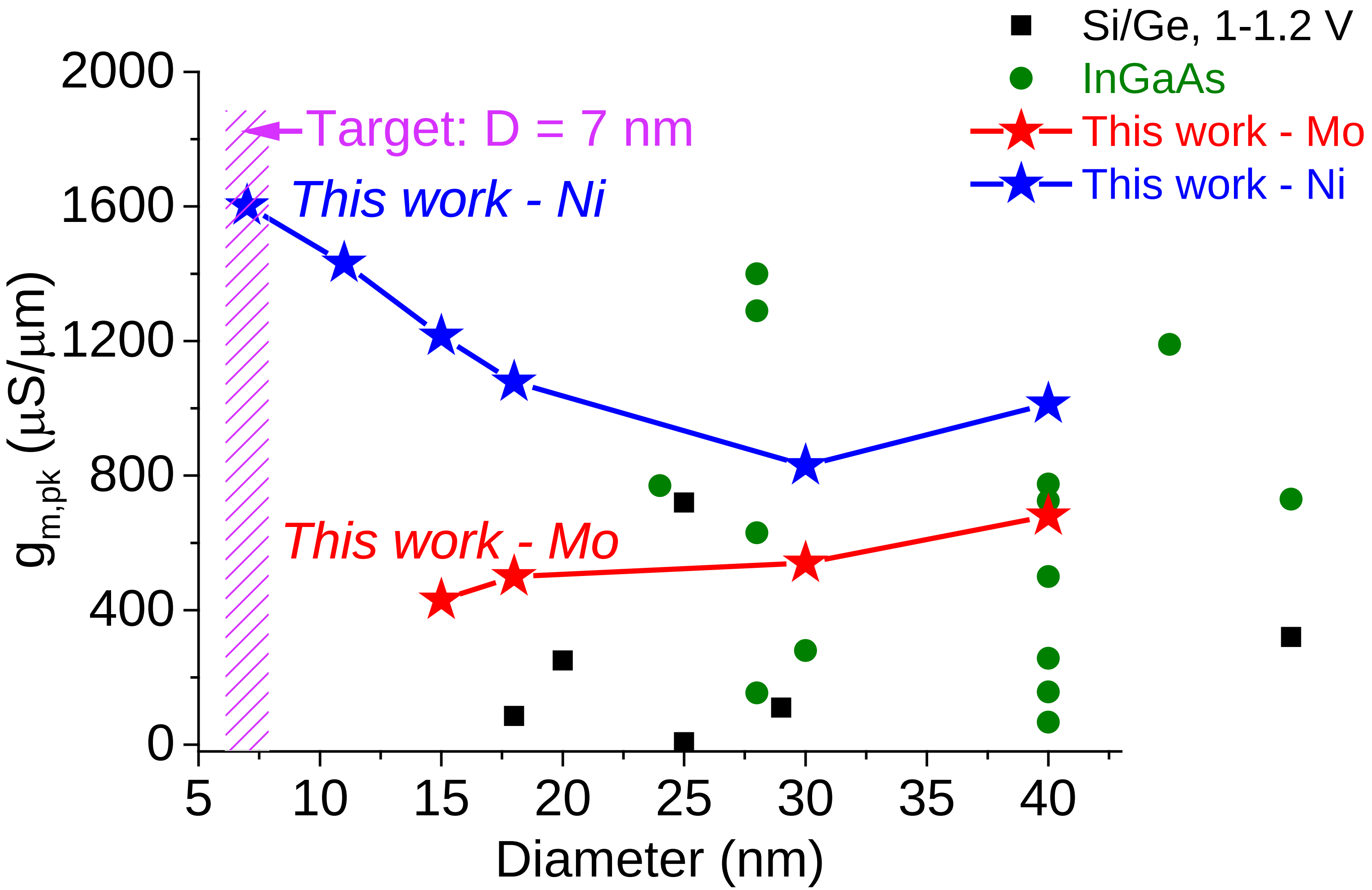
Excellent g_m & I_{on} scaling with D for Ni devices

Benchmarking



High performance and good electrostatics

Benchmarking



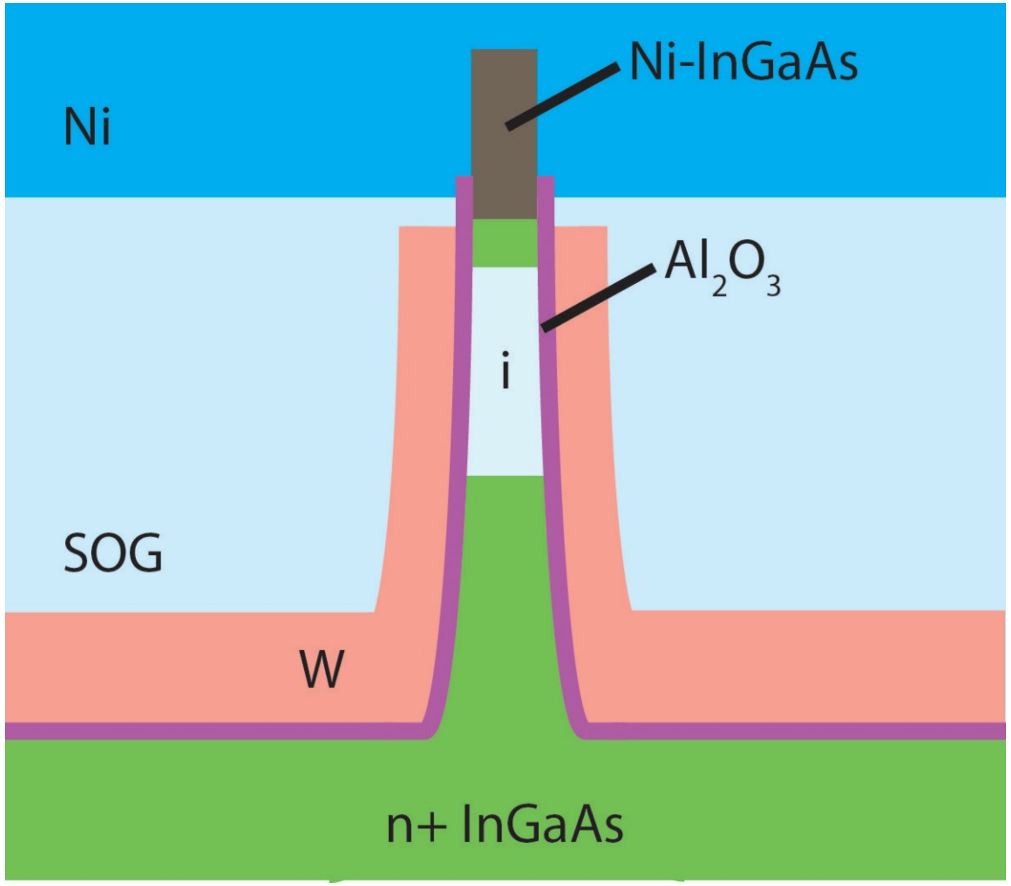
- First sub-10 nm diameter VNW transistor of any kind
- Record performance

Conclusions

- First sub-10 nm diameter VNW transistors of any kind in any material system
- Key technologies: alcohol based DE + Ni alloyed contact
- Record performance demonstrated
- Top contact: key challenge for VNW MOSFET technology

Appendix

Ni contact for sub-10 nm InGaAs VNW MOSFETs



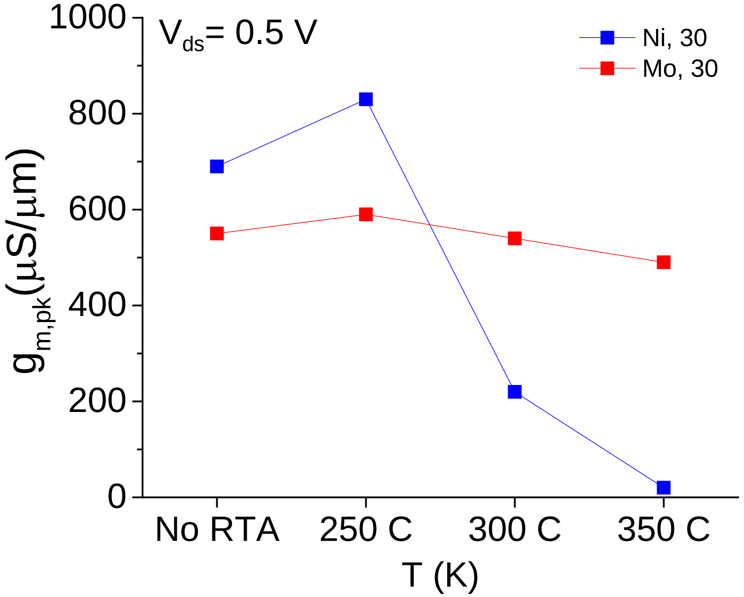
Starting heterostructure:

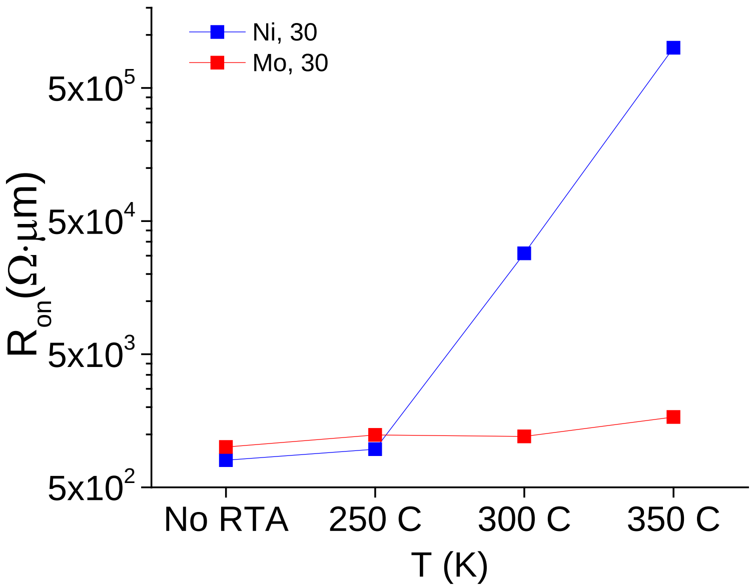
n+ InGaAs: 11 nm
n+ InAs: 2 nm
n+ $In_{0.7}Ga_{0.3}As$: 6 nm
n+ InGaAs, 55 nm
i InGaAs, 80 nm
n+ InGaAs, 300 nm

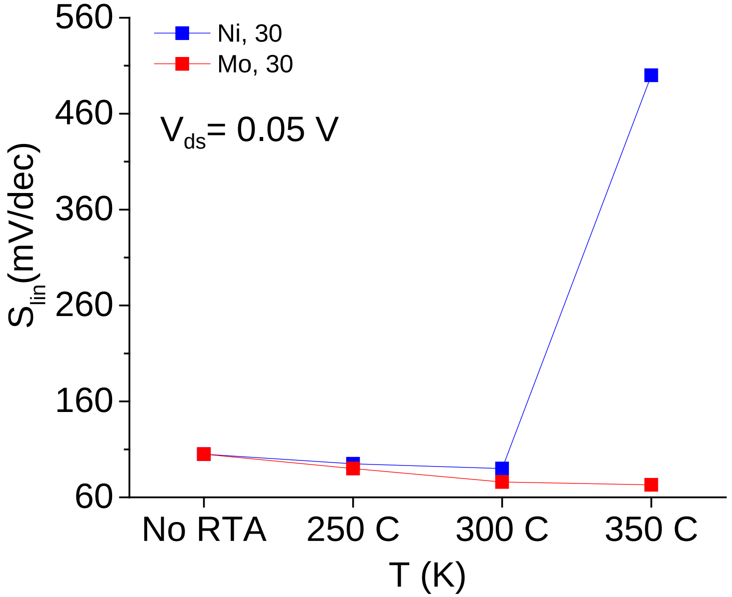
D = 40, 30, 18, 15, 11, 7 nm
No. of wires = 1
L_{ch} = 80 nm
EOT = 1.25 nm

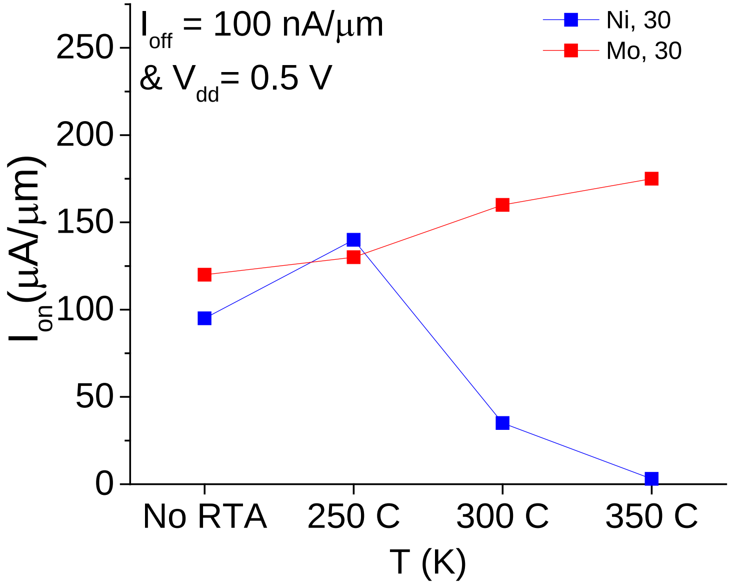
New elements: H_2SO_4:methanol DE + Ni alloyed contact

Effect of RTA



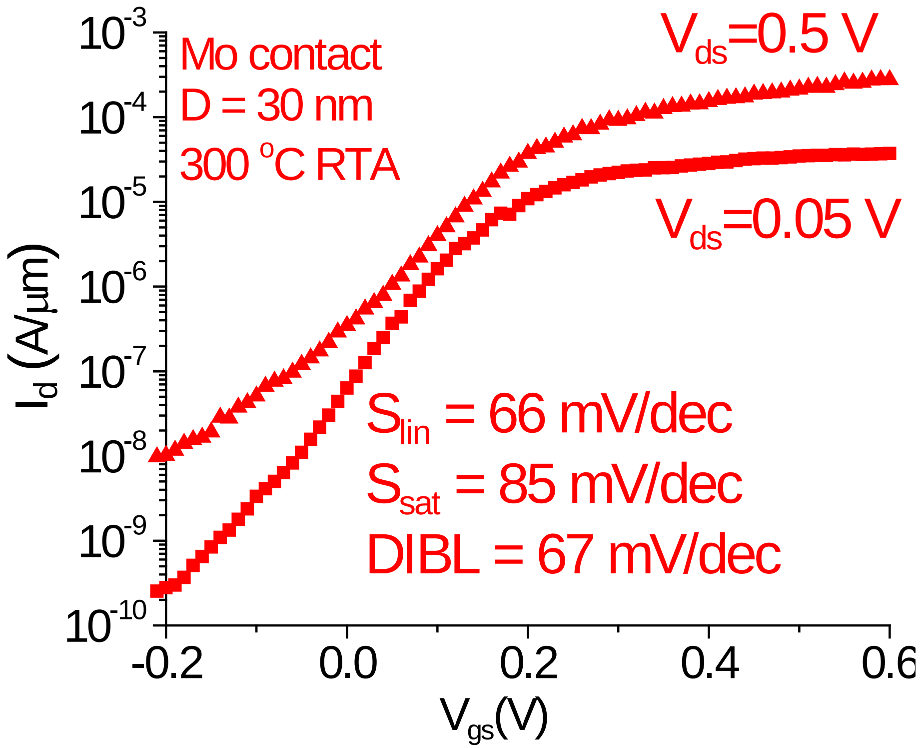


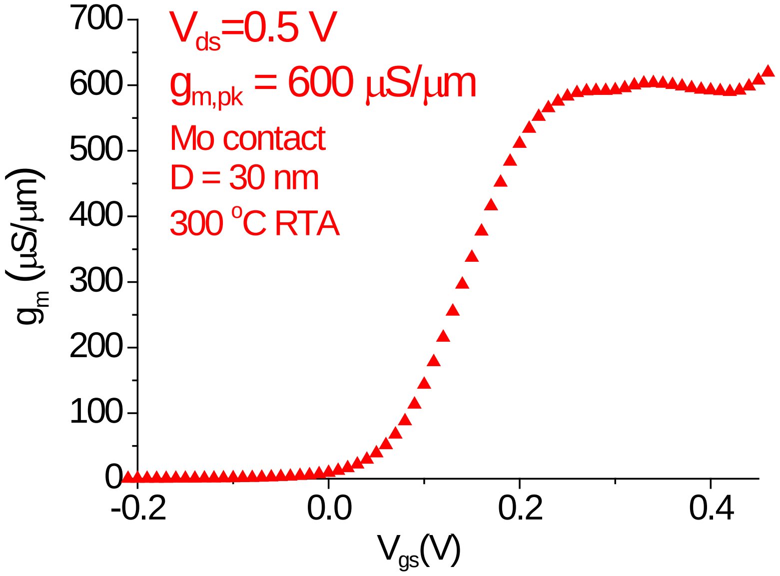




- Performance for Ni devices ↓ then ↑ with ↑ T
- Refractory metal Mo contact → thermal stability

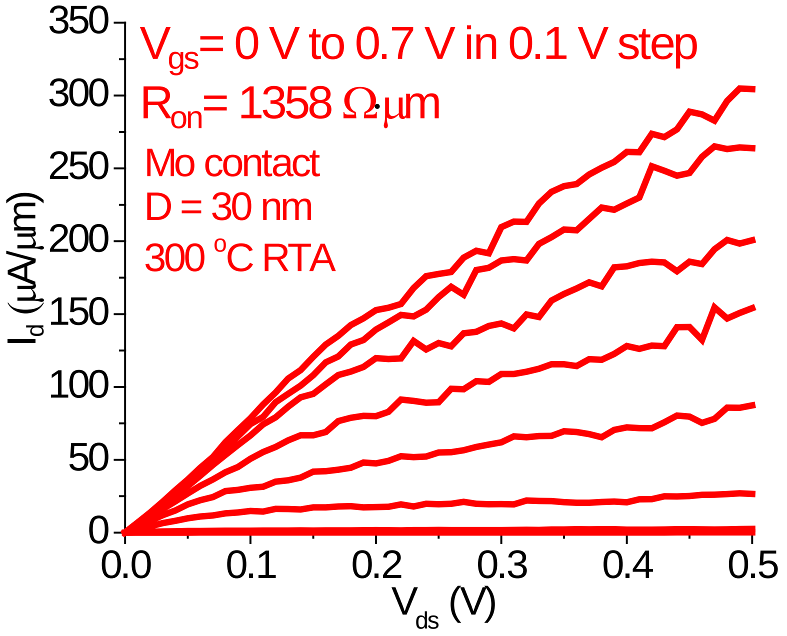
D = 30 nm Mo-contacted device



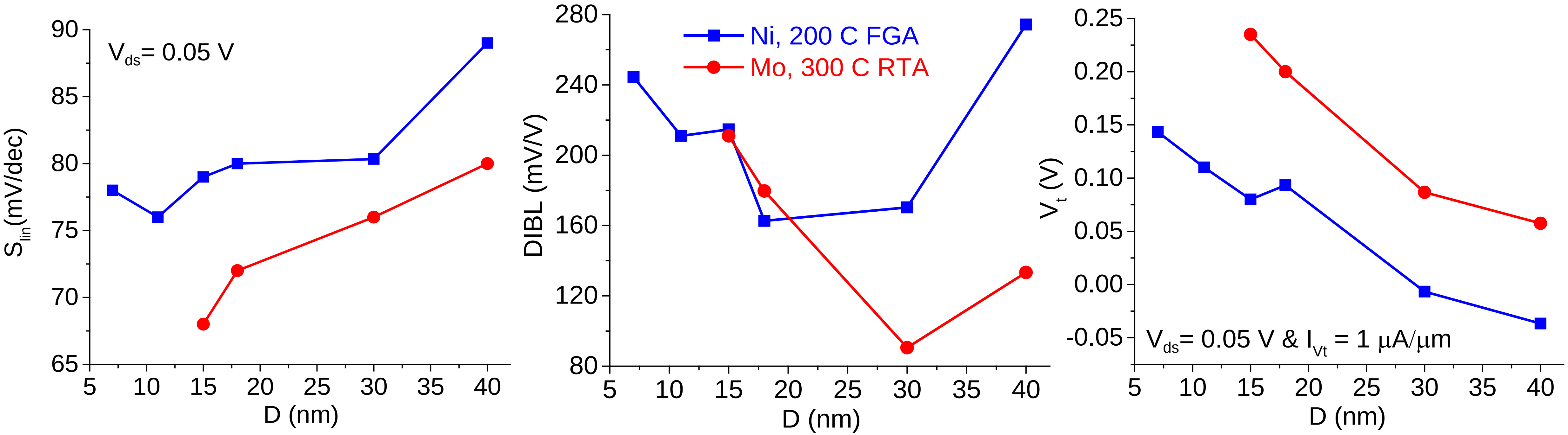


Single nanowire MOSFET:

- D = 30 nm & L_{ch}= 80 nm
- 2.5 nm Al_2O_3 (EOT = 1.25 nm)
- 300 °C N_2 RTA, 1 min
- S_{lin}= 66 mV/dec

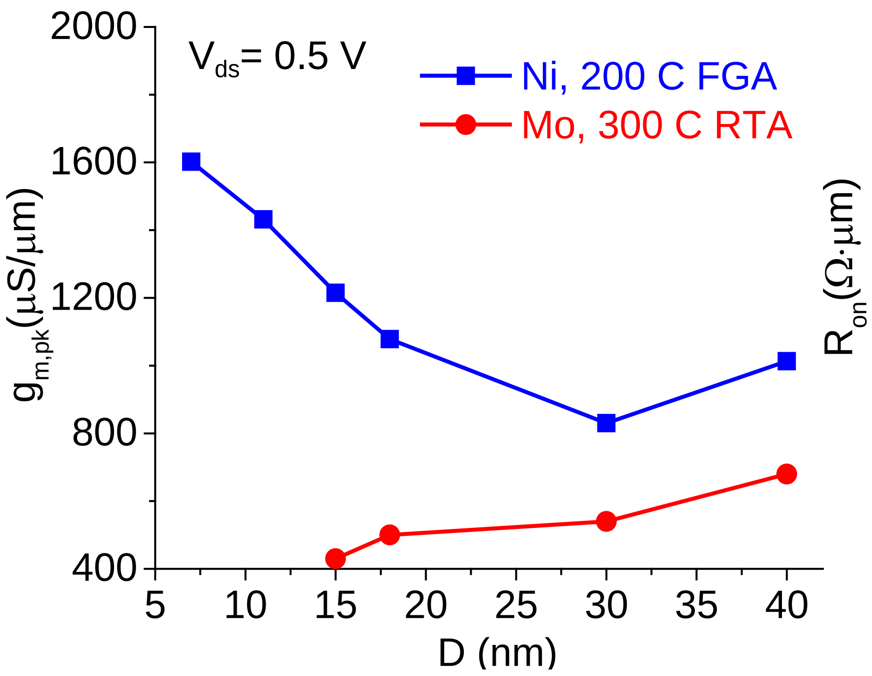


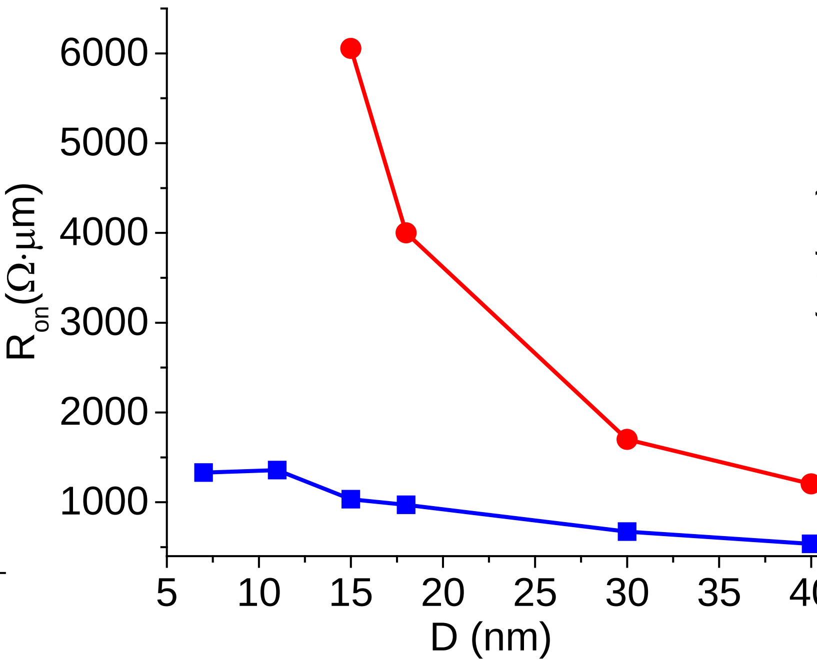
Diameter scaling: electrostatics

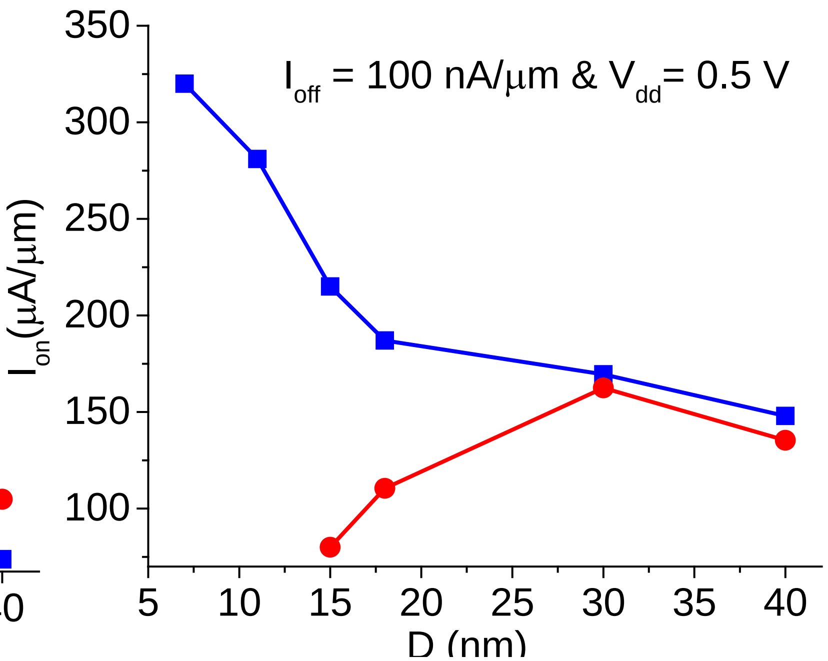


- DIBL degradation likely due to top contact
- Narrowest working device is 15 nm for Mo

Diameter scaling: performance







Excellent g_m & I_{on} scaling with D for Ni devices

Acknowledgement

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- Fabrication facility at MIT labs: MTL, SEBL
- MIT colleagues: W. Chern, T. Yu, L. Xia, D. Antoniadis, J. Hoyt
- E3S colleagues: E. Yablonovitch, M. Wu, M. Eggleston, A. Lakhani