Semiconductor Research Corporation

Towards Sub-10 nm Diameter III-V VNW Transistors

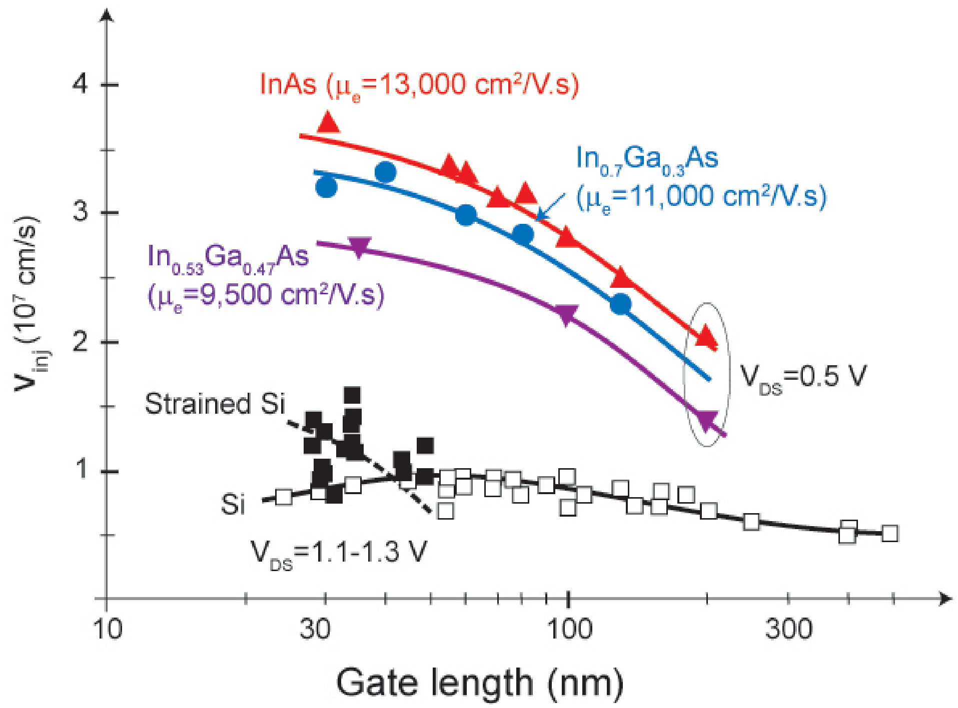
Wenjie Lu, Xin Zhao, Jesús A. del Alamo

Massachusetts Institute of Technology
wenjie@mit.edu

Task/Theme: 2655.001

Contents

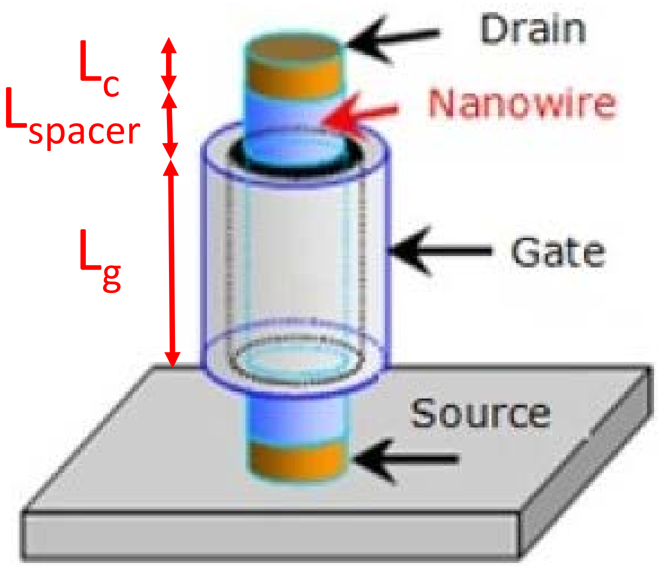
Motivation – Why III-Vs?



del Alamo, Nature 2011

- Exceptional carrier transport properties
- Rich band structure engineering

Motivation – why vertical nanowire?



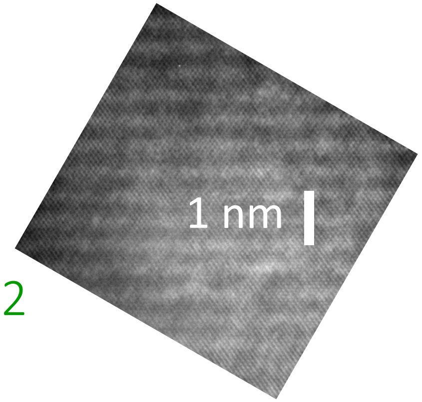
Vertical NW FET:

→ uncouples footprint scaling

Top-down

Lam Research

Leverage existing dry etch infrastructure



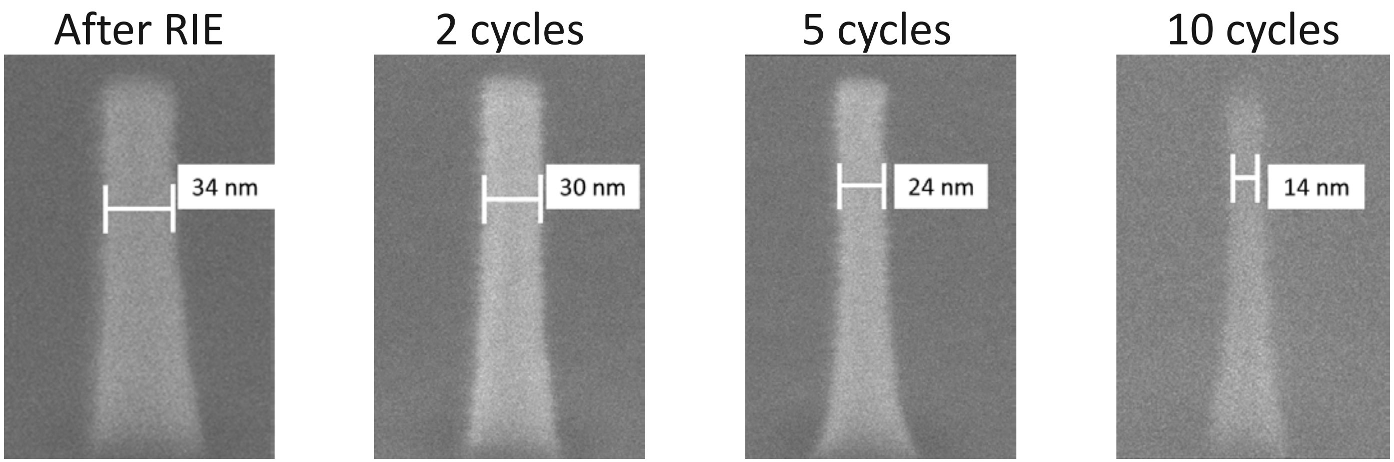
Iutzi 2012

Advanced epitaxial growth technology

VNW RIE & digital etch – 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



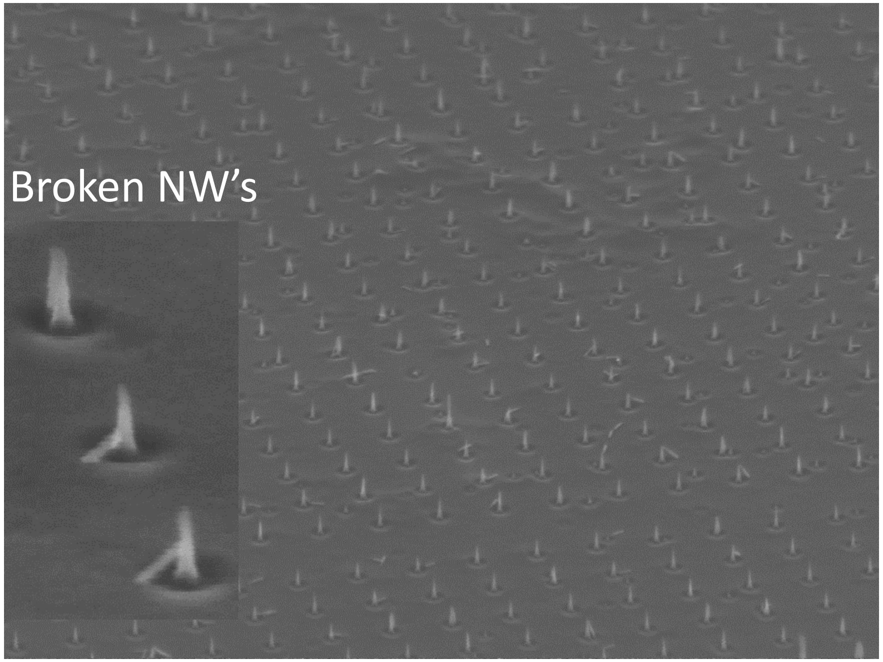
- Radial etch rate = 1 nm/cycle
- Can reach sub-20 nm NW diameter
- Aspect ratio > 10
- Smooth sidewalls

Zhao, IEDM 2013
Lu, EDL 2017

Digital Etch – Problem I

8 nm InGaAs VNWs after 7 DE cycles:

10% HCl in DI water
Yield = 0%



Water-based acid is problem:

Surface tension (mN/m):

- Water: 72
- Methanol: 22
- IPA: 23

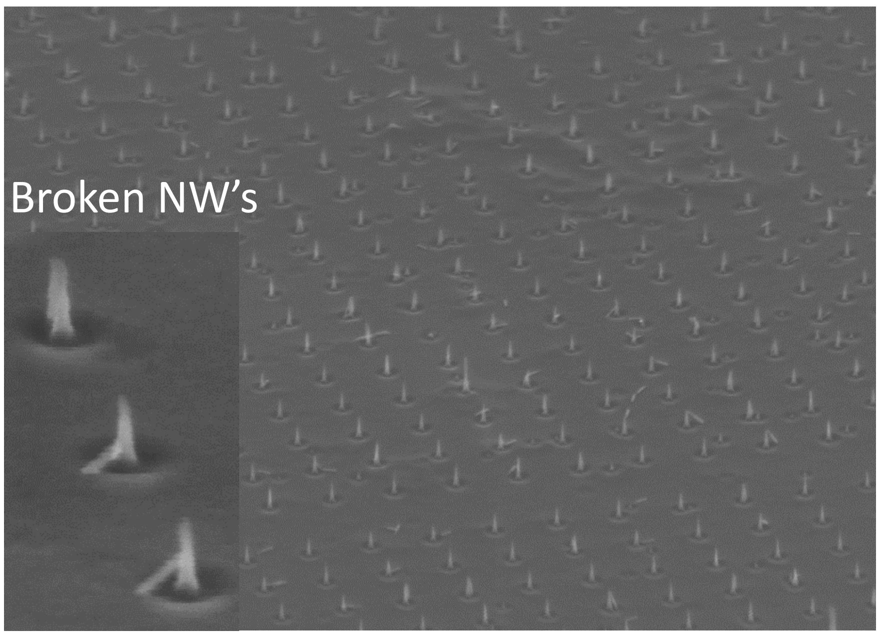
Lu, EDL 2017

Difficult to reach 10 nm VNW diameter due to breakage

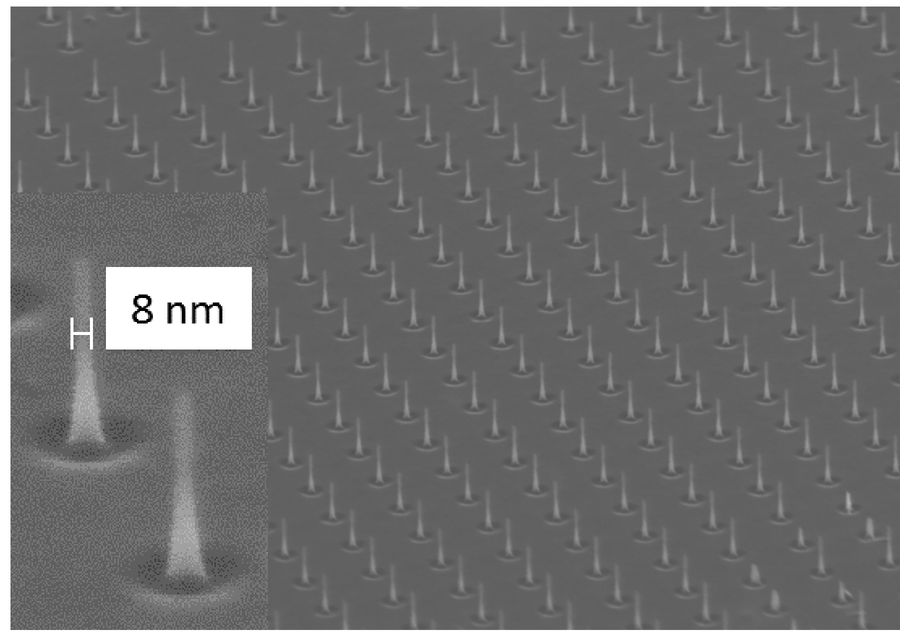
Alcohol-based Digital Etch - InGaAs

8 nm InGaAs VNWs after 7 DE cycles:

10% HCl in DI water
Yield = 0%

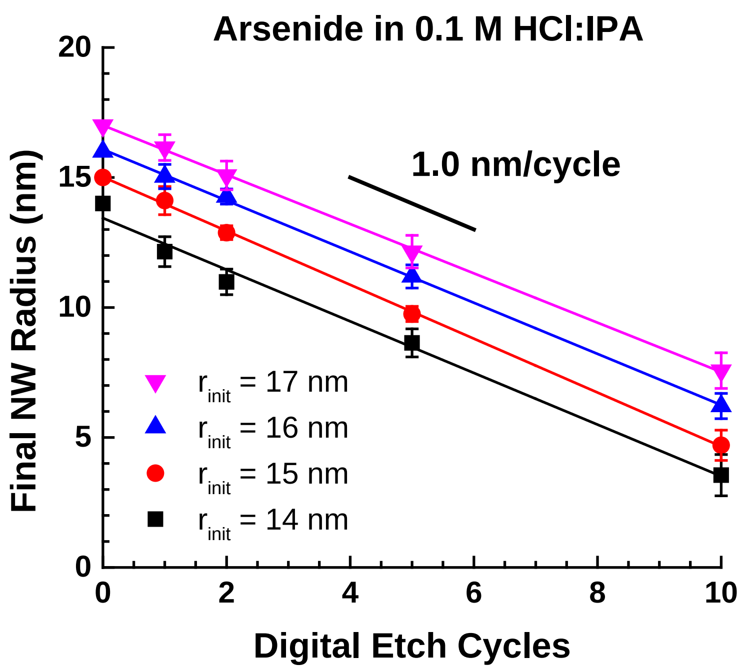


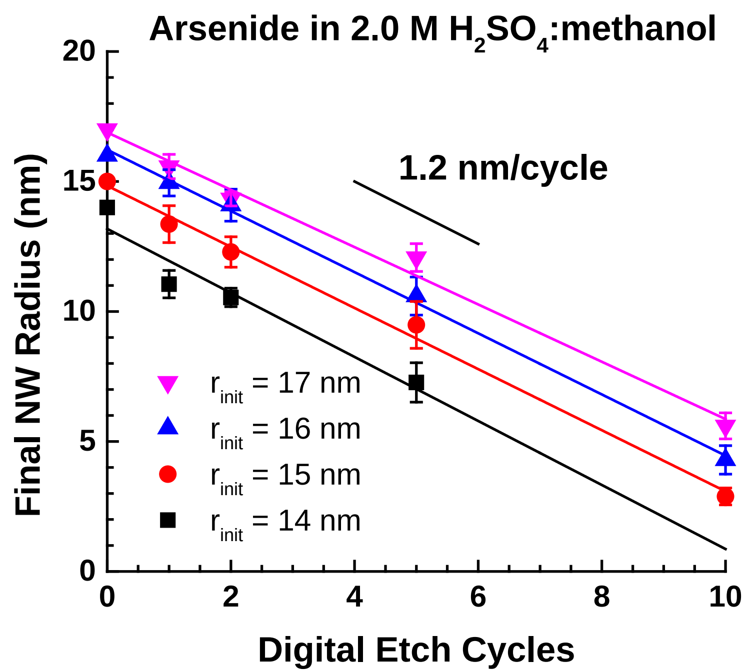
10% HCl in IPA
Yield = 97%



Alochol-based DE enables D < 10 nm

Radial Etch Rate

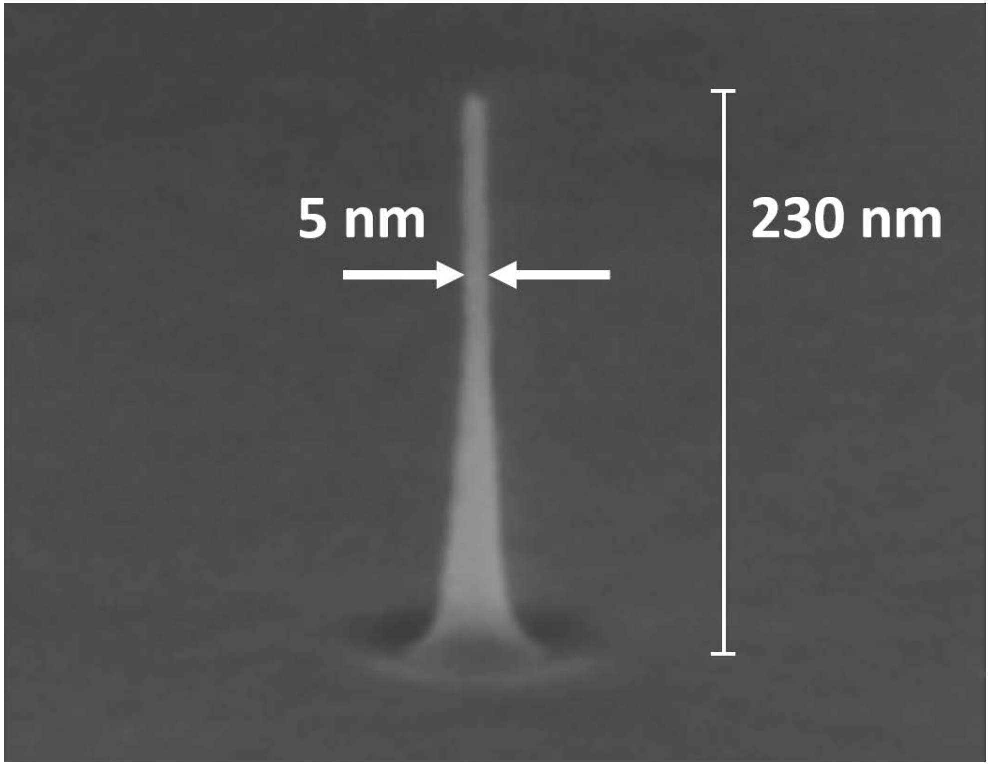




- About same etch rate as water-based DE → oxidation step sets etch rate
- Etch rate in H_2SO_4:methanol > HCl:IPA → different surface conditioning?

D = 5 nm VNW

10% H_2SO_4 in methanol



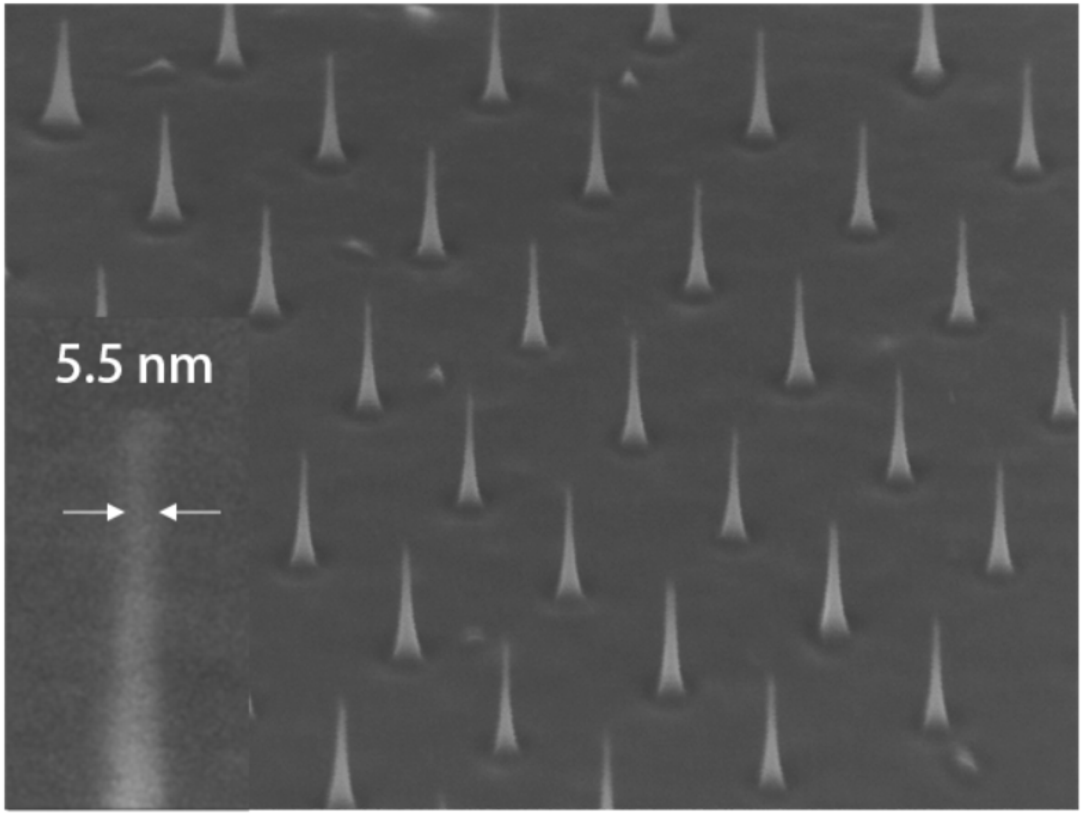
Lu, EDL 2017

First demonstration of D=5 nm diameter InGaAs VNW
(Aspect Ratio > 40)

D = 5.5 nm VNW Arrays

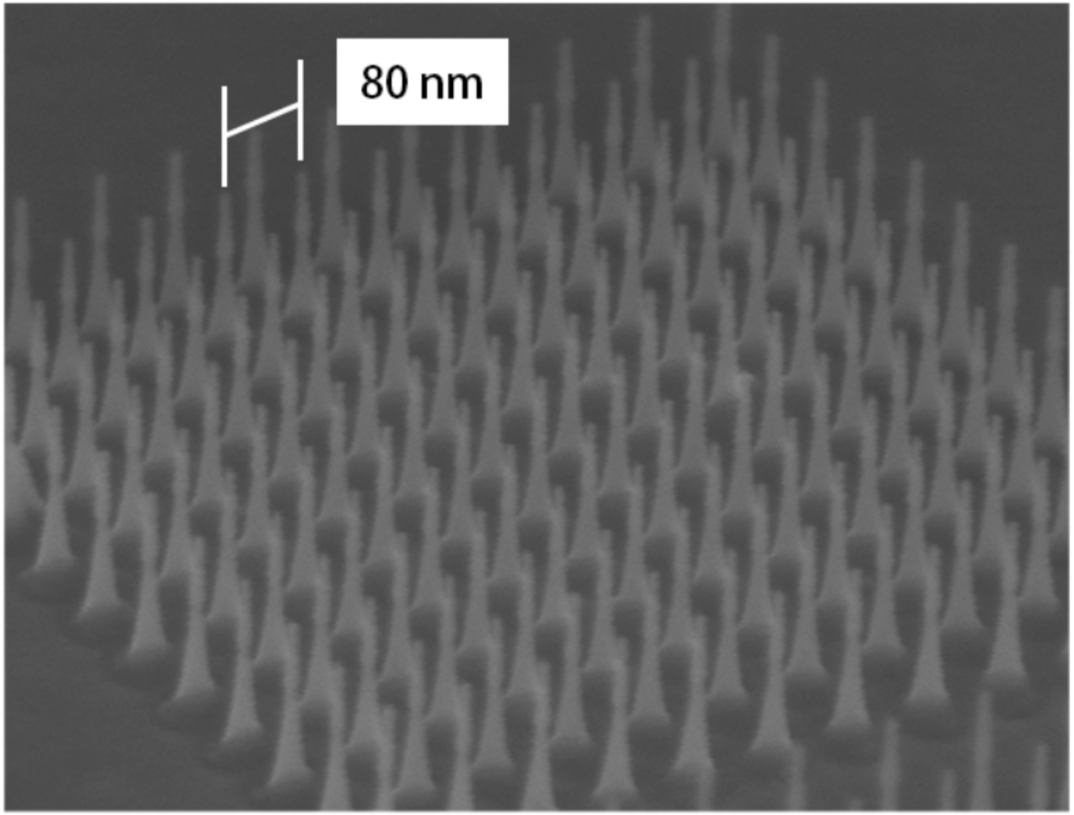
D=5.5 nm VNW arrays with 90% yield

10% H_2SO_4 in methanol



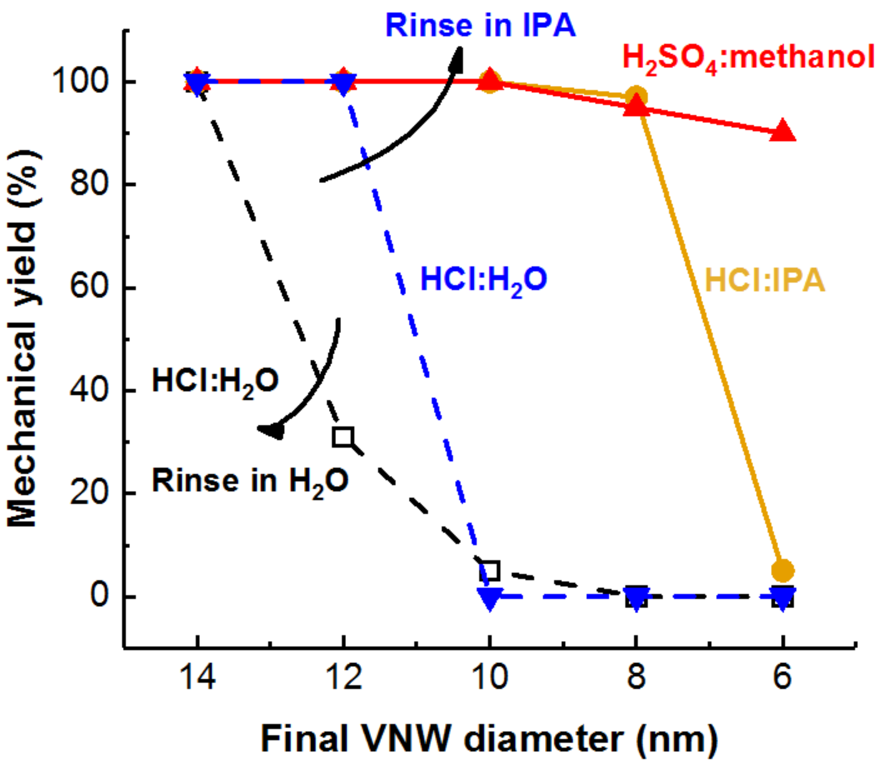
Close-packed VNW arrays

10% HCl in IPA



D=10 nm, pitch=80 nm, 100% yield

Role of Rinsing

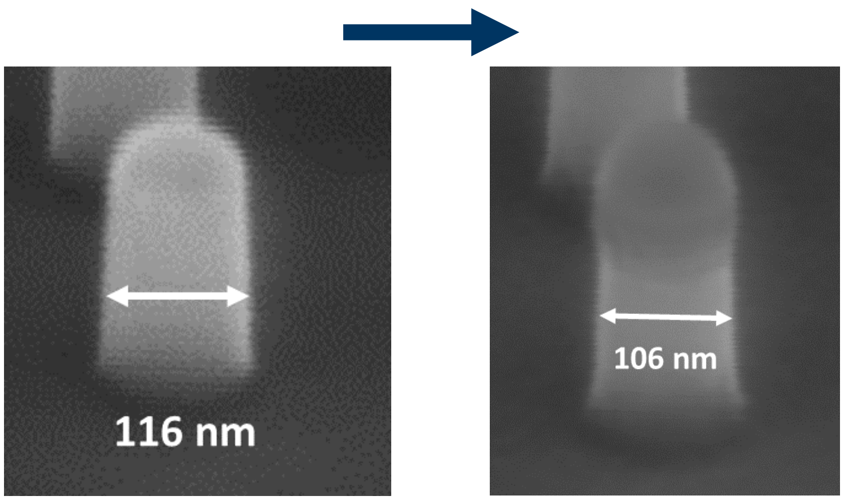


- H_2SO_4:methanol yields 90% at D=6 nm!
- Viscosity matters: methanol (0.54 cP) vs. IPA (2.0 cP)
- Rinse in alcohol improves DE yield at D=12 nm but not below → oxide removal is most aggressive step

Digital Etch – Problem II

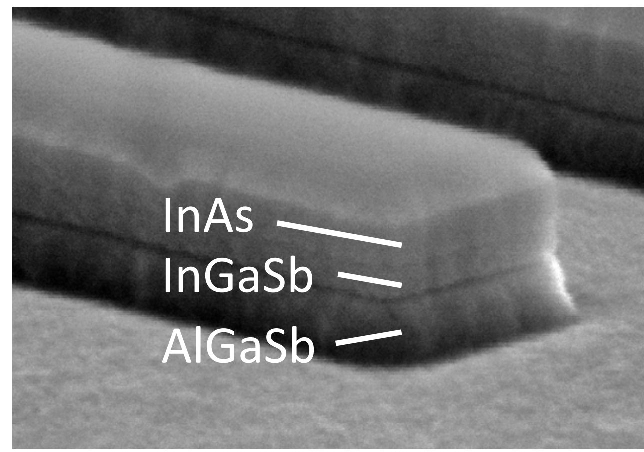
III-Sb very reactive: unable to perform digital etch on III-Sb

1% $HCl:H_2O$ 30 s



Lu, IEDM 2015

Dip in DI water for 2 min



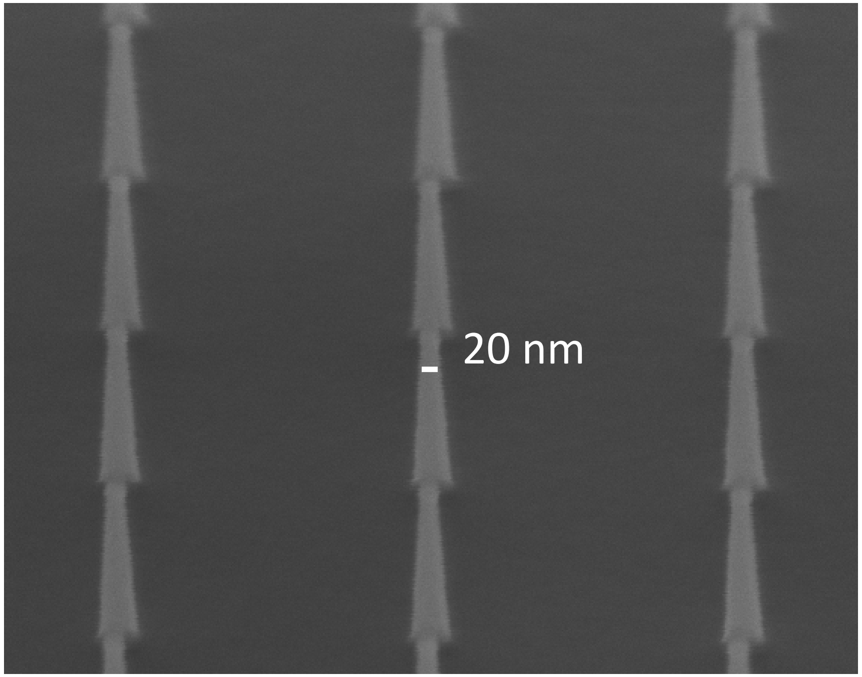
Lu, EDL 2017

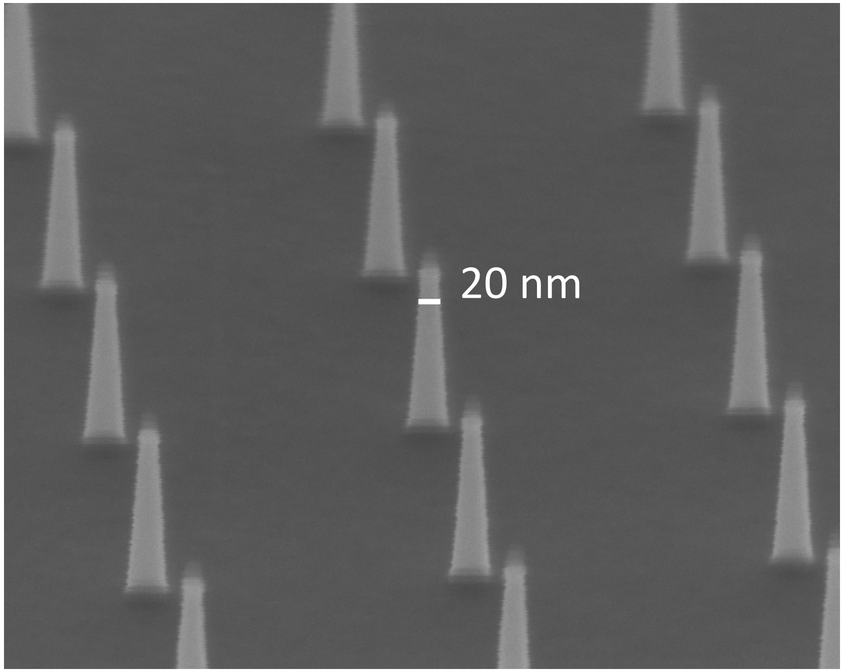
- Conventional HCl treatment damages III-Sb vertical sidewalls
- Aqueous solution not suitable for vertical III-Sb

Alcohol-based Digital Etch – InGaSb

RIE (BCl_3/N_2)

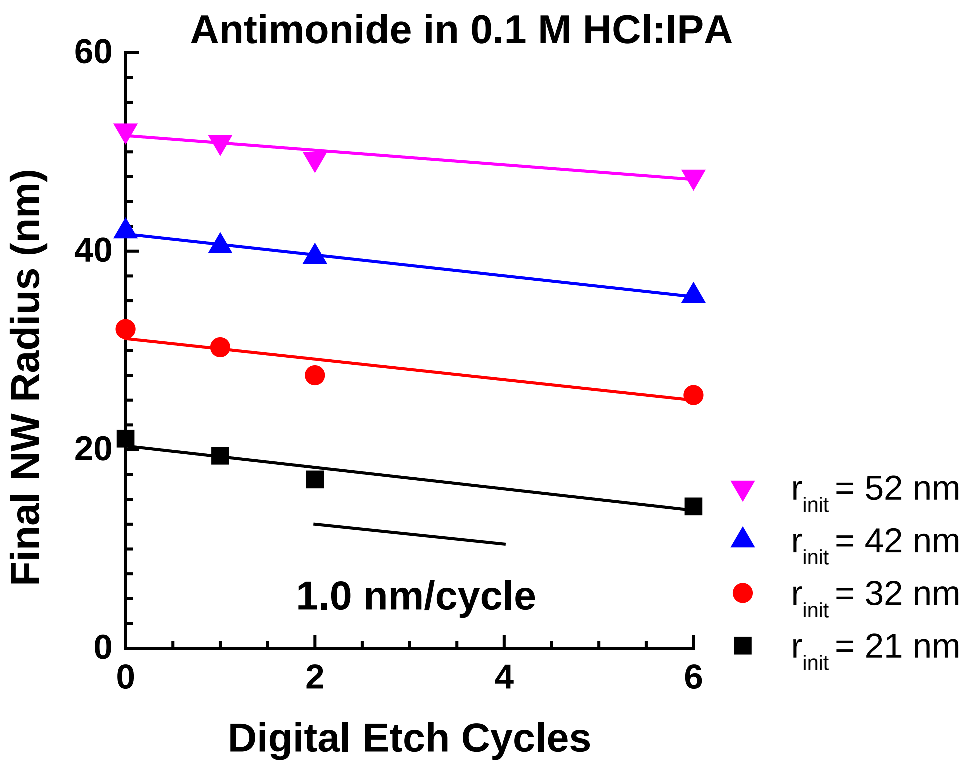
10% HCl:IPA 2 min



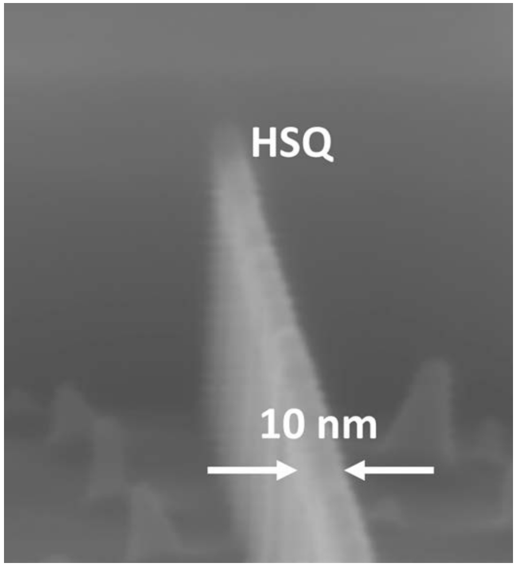


Alcohol-based HCl treatment does not damage III-Sb sidewall

Alcohol-based Digital Etch – InGaSb



10 nm InGaSb fin
after 5 cycles DE in HCl:IPA



First demonstration of InGaSb DE with radial etch rate = 1.0 nm/cycle

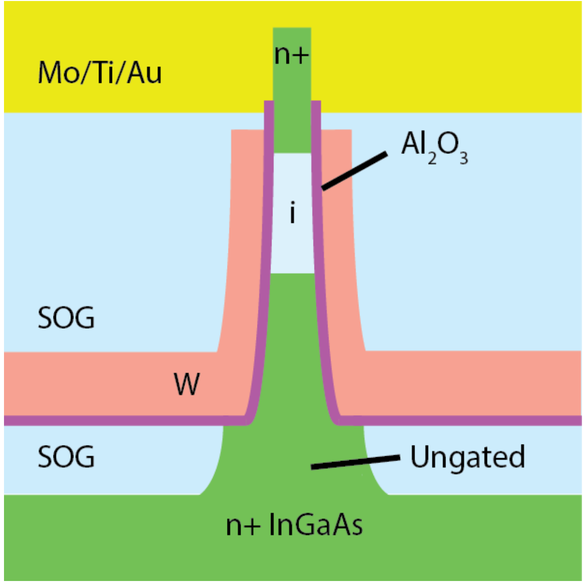
InGaAs VNW MOSFETs

MIT pursuing *top-down approach* for VNW fabrication

Starting heterostructure:

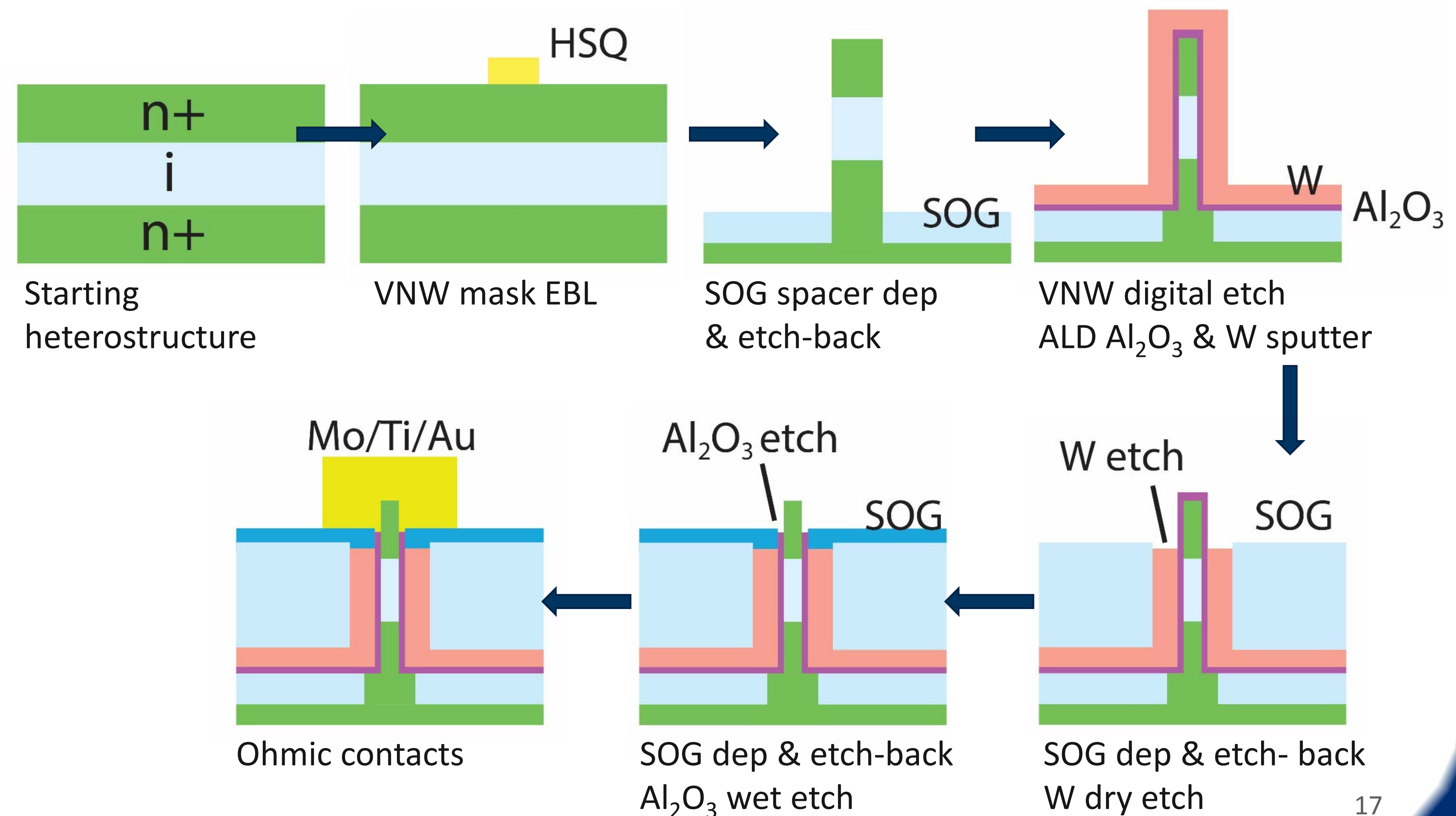
n^+ InGaAs, 70 nm
i InGaAs, 80 nm
n^+ InGaAs, 300 nm

n^+: 6×10^{19} cm^{-3} Si doping



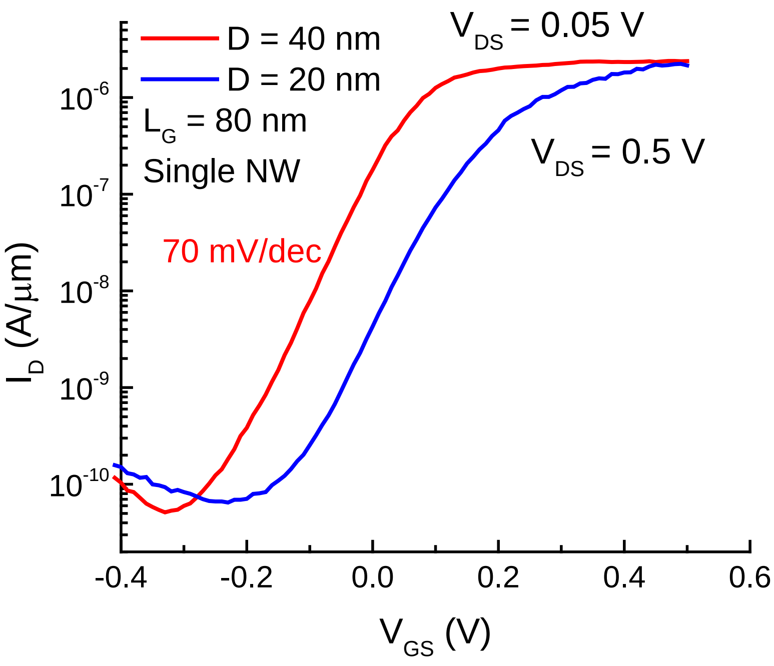
- 5 DE cycles in H_2SO_4:methanol
- Al_2O_3 = 2 nm (EOT = 1 nm)
- W gate, Mo ohmic contacts
- D = 20 – 40 nm

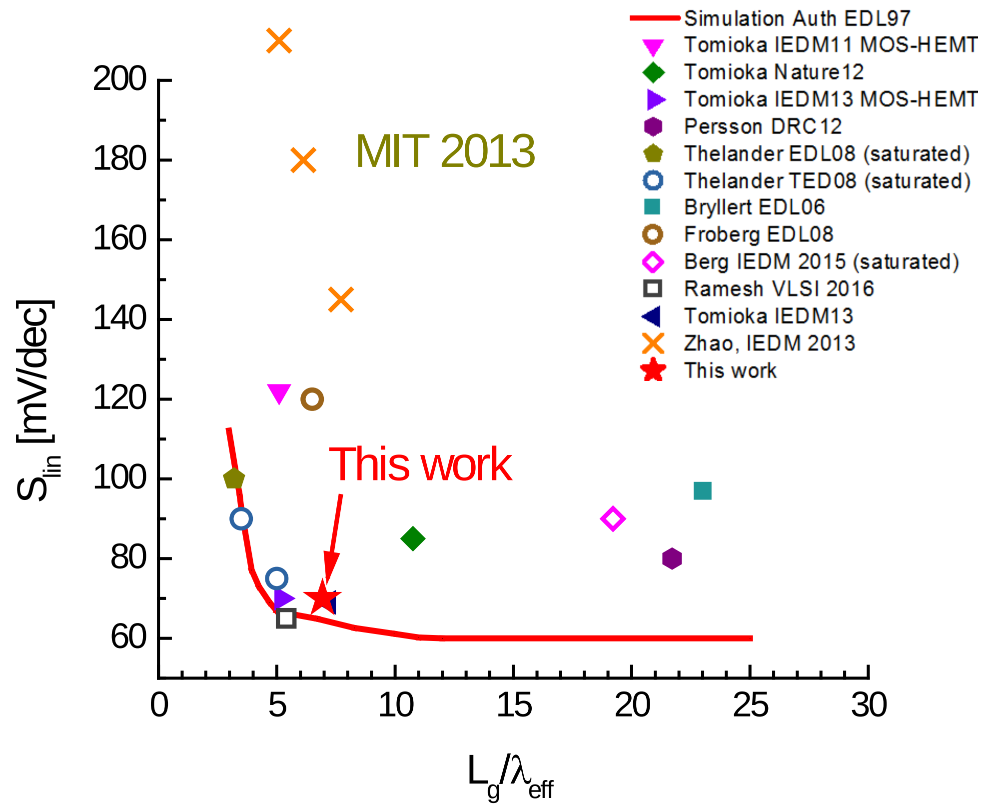
InGaAs VNW MOSFETs – Process flow



InGaAs VNW MOSFETs - Characteristics

Single VNW devices





- Minimum S_{lin} = 70 mV/dec for D = 40 nm
- $D_{it} \approx 3.9 \cdot 10^{12}$ $eV^{-1}cm^{-2}$

Conclusions

- Novel digital etch scheme using alcohol-based etchants:
  - High mechanical yield at sub-10 nm diameter
  - Record VNW with D = 5 nm and AR > 40
  - First demonstration of DE on InGaSb
- InGaAs VNW MOSFETs fabricated using alcohol-based DE with excellent subthreshold characteristics