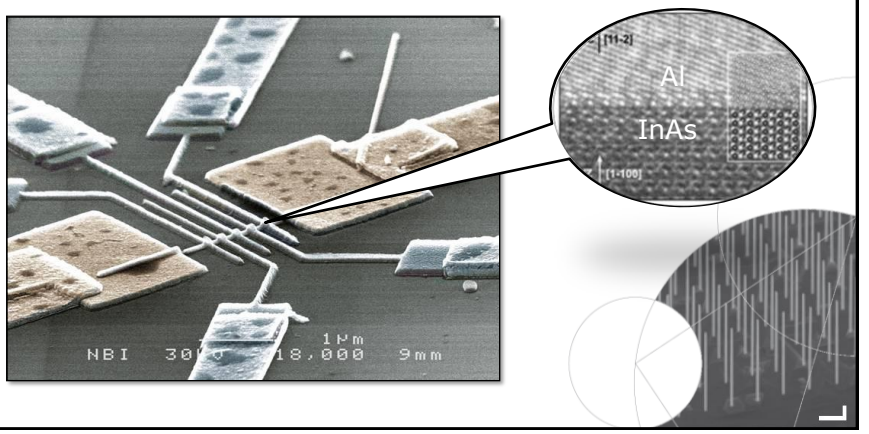
UNIVERSITY OF COPENHAGEN NIELS BOHR INSTITUTE

Faculty of Science

Jesper Nygård, Center for Quantum Devices, Niels Bohr Institute

Progress in the materials science of hybrid nanowires for topological devices



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Niels Bohr Institute

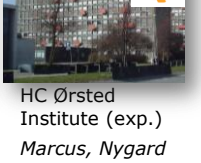
HC Ørsted Institute (exp.)

Marcus, Nygard

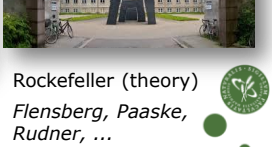
Rockefeller (theory)

Flensberg, Paaske, Rudner, ...

Niels Bohr Institute
... Nielsen



HC Ørsted Institute (exp.)
Marcus, Nygard



Rockefeller (theory)
Flensberg, Paaske, Rudner, ...

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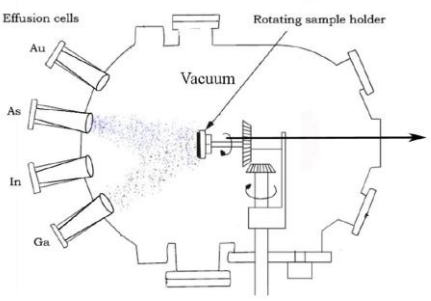
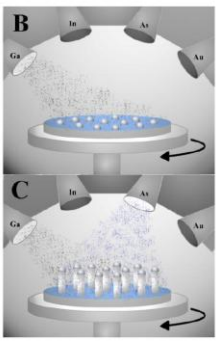
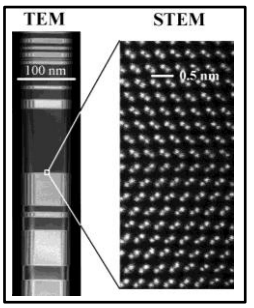
Growth of nanowires by molecular beam epitaxy

UHV

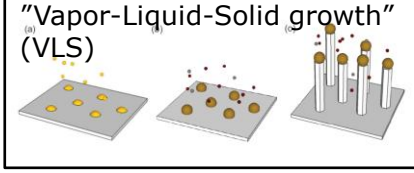


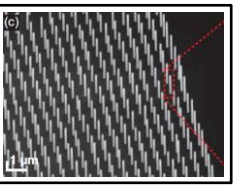
Directional beams



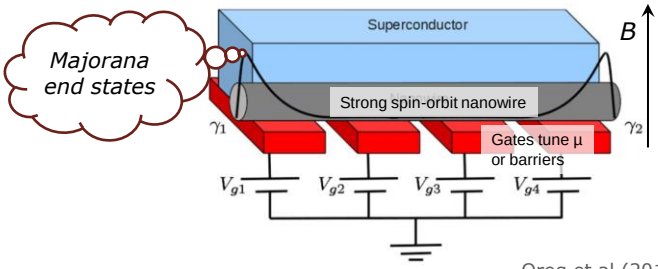


”Vapor-Liquid-Solid growth” (VLS)

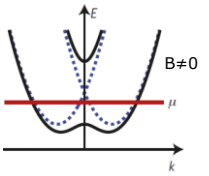




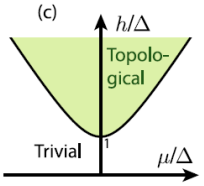
Semiconductor nanowires for topological systems



Topological superconductor



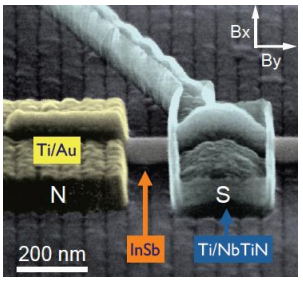
Oreg et al (2010), Lutchyn et al (2010)

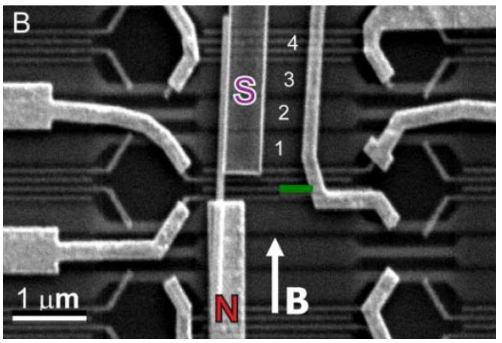


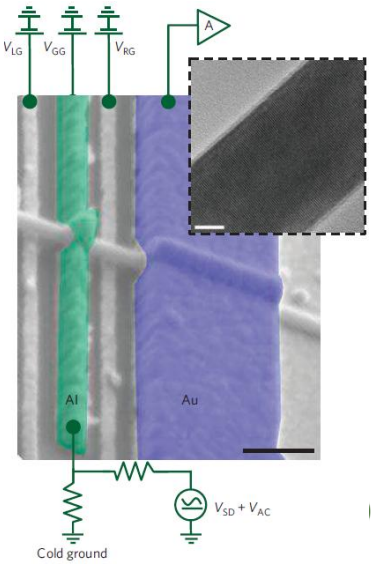
Topological phase in semiconductor nanowires:

1D tunable wire + spin-orbit interactions + superconductor

... SC with uniform interface, high critical field, ...

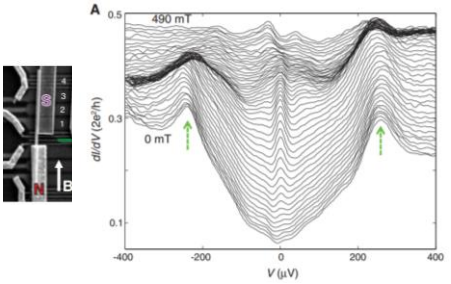




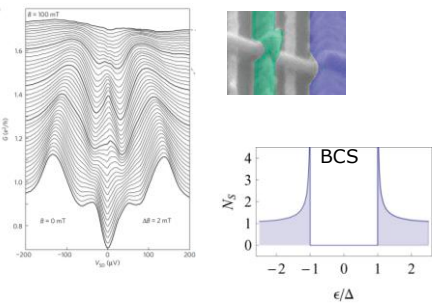


Tunneling experiments and the proximity induced gap

Mourik et al (2012) – **InSb + Nb** (long)



Das et al (2012) – **InAs + Al** (short)



Experimental observations in typical in Majorana-type experiments:

- "soft" proximity gap with $\Delta^* < \Delta_{bulk}$
- quasiparticle states in gap rather than suppressed sub-gap BCS
- complicates interpretation, allows resonances (Kondo), would potentially decohere (Majorana) qubits etc

THEORY

PHYSICAL REVIEW B **90**, 085302 (2014)

Soft superconducting gap in semiconductor-based Majorana nanowires

Tudor D. Stanescu
Department of Physics and Astronomy, West Virginia University, Morgantown, West Virginia 26506, USA

Roman M. Lutchyn
Station Q, Microsoft Research, Santa Barbara, California 93106-6105, USA

S. Das Sarma
Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742, USA

Inverse proximity effect of normal metal lead

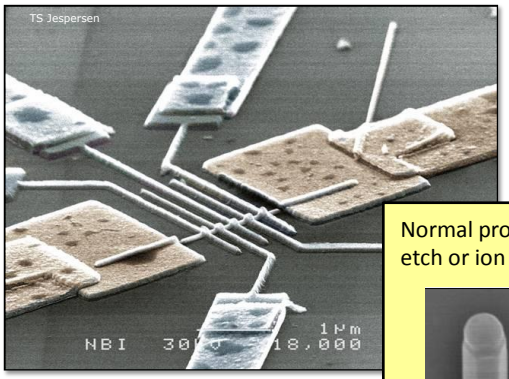
PRL **110,** 186803 (2013) PHYSICAL REVIEW LETTERS week ending 3 MAY 2013

Soft Superconducting Gap in Semiconductor Majorana Nanowires

So Takei, Benjamin M. Fregoso, Hoi-Yin Hui, Alejandro M. Lobos, and S. Das Sarma

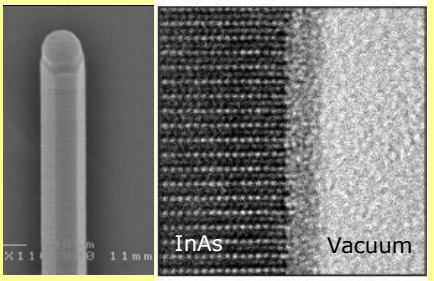
Interface inhomogeneity between SC and nanowire

Epitaxy of superconductor-semiconductor interfaces



- how MBE can improve the electrical contacts

Normal procedure: remove native oxide by etch or ion milling: damages, disorder

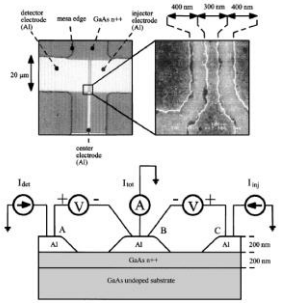


MBE grown SNS junctions (1990'ies)

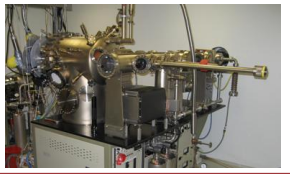
VOLUME 83, NUMBER 23 PHYSICAL REVIEW LETTERS 6 DECEMBER 1999

Observation of Supercurrent Enhancement in SNS Junctions by Nonequilibrium Injection into Supercurrent Carrying Bound Andreev States

Jonatan Kutchinsky,[1] Rafael Taboryski,[2] Claus B. Sørensen,[3] Jørn Bindslev Hansen,[1] and Poul Erik Lindelof[3]

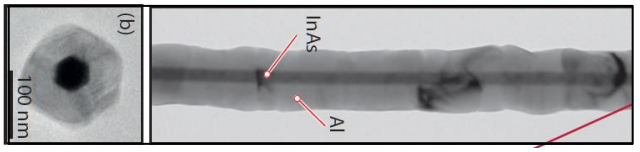


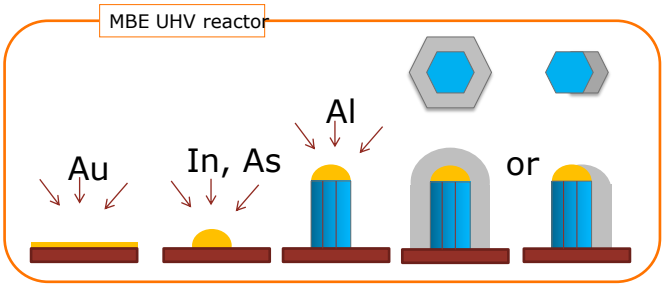
The samples were formed from a layered structure of GaAs and Al, grown in an MBE chamber. Here, 200 nm of highly doped *n*-GaAs were grown on an undoped/ insulating substrate. This was then capped with 150–200 nm Al. In order to reduce the Schottky barrier between GaAs and Al, five layers of δ doping with 5×10^{13} cm^{-2} Si were inserted in the GaAs just below the Al. The Al film was subsequently deposited without breaking the vacuum. This resulted in a contact resistance



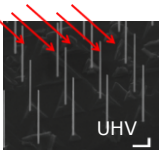
Claus B. Sørensen
MBE engineer

MBE grown aluminum shell on InAs nanowires





Evaporated Al



Al grown in-situ after cooling to -30 C, without breaking vacuum

NBI 2012

Ziino et al, arxiv 1309.4569; Krogstrup et al., Nature Mat. (2015)

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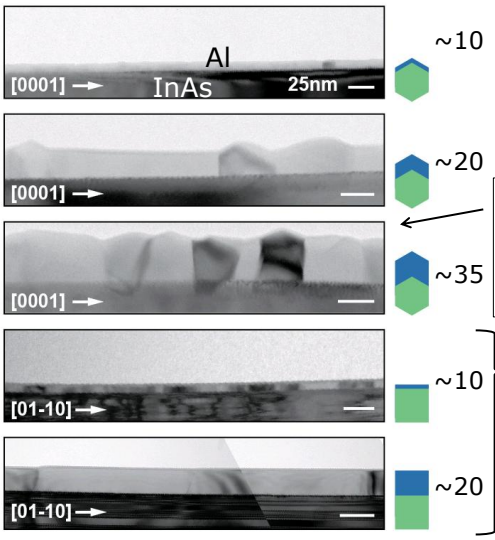
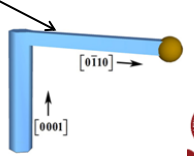
Shell morphology vs thickness and facets

Rotation disabled; half shell

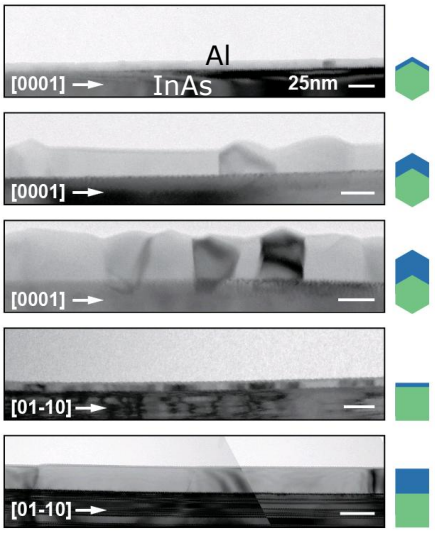


Reconstruction
- critical thickness ~25nm
- faceted, grain structure
- interface/surface energy minimization vs strain



Shell morphology vs thickness and facets

Rotation disabled; half shell



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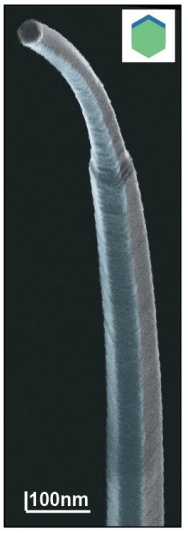
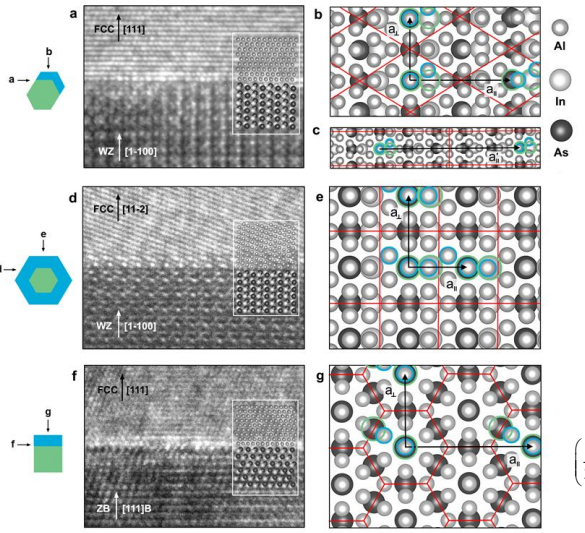


Strain

Epitaxial domain match



Typical mismatch for Al/InAs: 0.3%

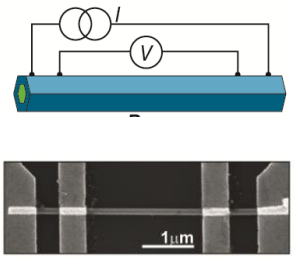
$$\left(\frac{7_{[11-2]}}{5_{[0001]}}, -0.5\%\right) \times \left(\frac{3_{[1-10]}}{2_{[11-20]}}, 0.3\%\right)$$

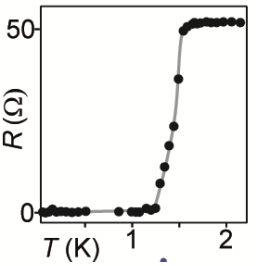
$$\left(\frac{1_{[111]}}{1_{[0001]}}, 0.3\%\right) \times \left(\frac{3_{[1-10]}}{2_{[11-20]}}, 0.3\%\right)$$

$$\left(\frac{3_{[11-2]}}{2_{[11-2]_{ZB}}}, 0.3\%\right) \times \left(\frac{3_{[1-10]}}{2_{[1-10]_{ZB}}}, 0.3\%\right)$$

Parallel perp.

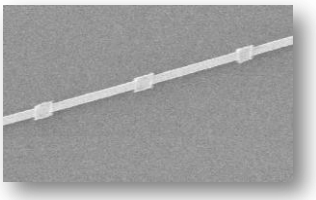
Electrical characterization: superconducting Al shell





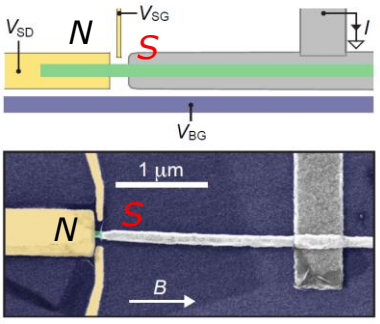
OK for reaching topological regime:
Critical magnetic field for 13nm Al film:
$\boldsymbol{B_c > 1.5\ T}$ (parallel) vs 0.1 mT in bulk

For InAs, topological phase reached at
$B = 2\Delta^*/g\mu_B \sim$ **0.5 T**



Electrical characterization: induced superconducting gap

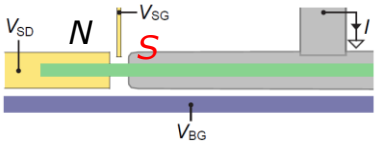
in the semiconducting nanowire



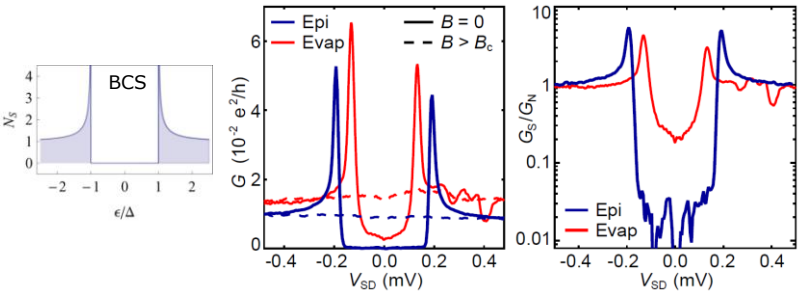
Spectroscopy of nanowire:

Tunneling from normal (Au) contact to proximitized wire

Electrical characterization: induced superconducting gap



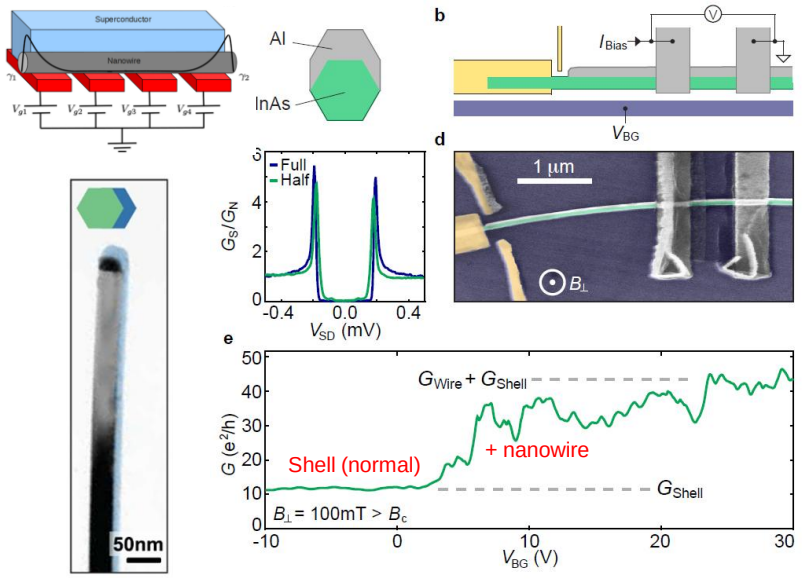
Subgap conductance
Epitaxial: 1:100
Control (evap.): 1:5



"Hard gap" - Indicates a transparent, uniform interface

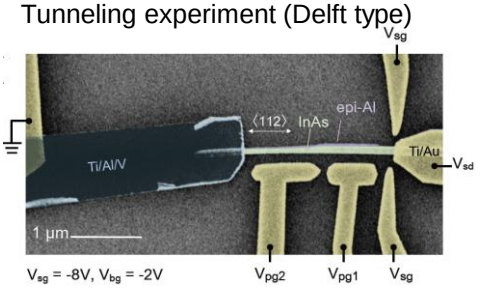
Chang et al., Nature Nanotechn. (Jan. 2015)

Gate tunability of proximitized segment



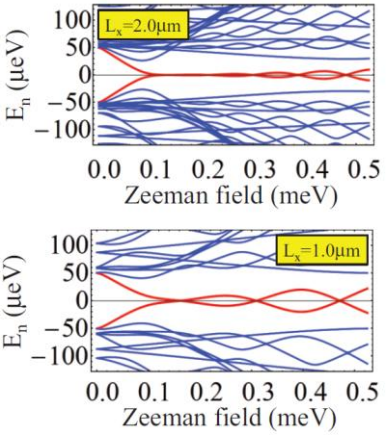
Finite wires and search for Majorana signatures

Tunneling experiment (Delft type)



V_{pg1} = 0V, V_{pg2} = 0V: "Longer Wire"
V_{pg1} = 0V, V_{pg2} < -3V: "Shorter Wire"

Predicted low-energy spectrum

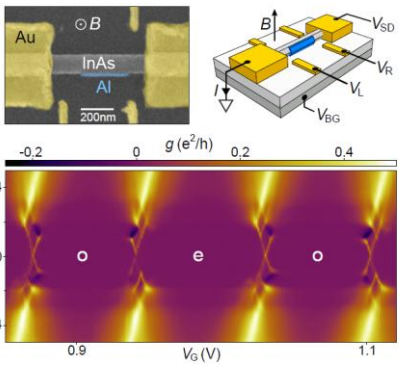


- split Majorana modes
- oscillating in field

Stanescu, Lutchyn, Das Sarma, PRB (2013)

Different device geometries

Superconducting quantum dots

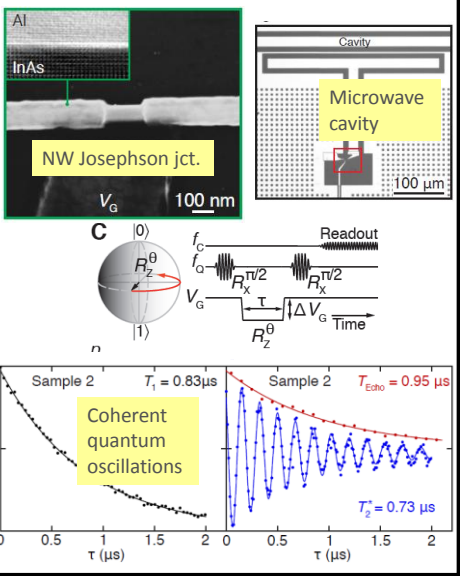


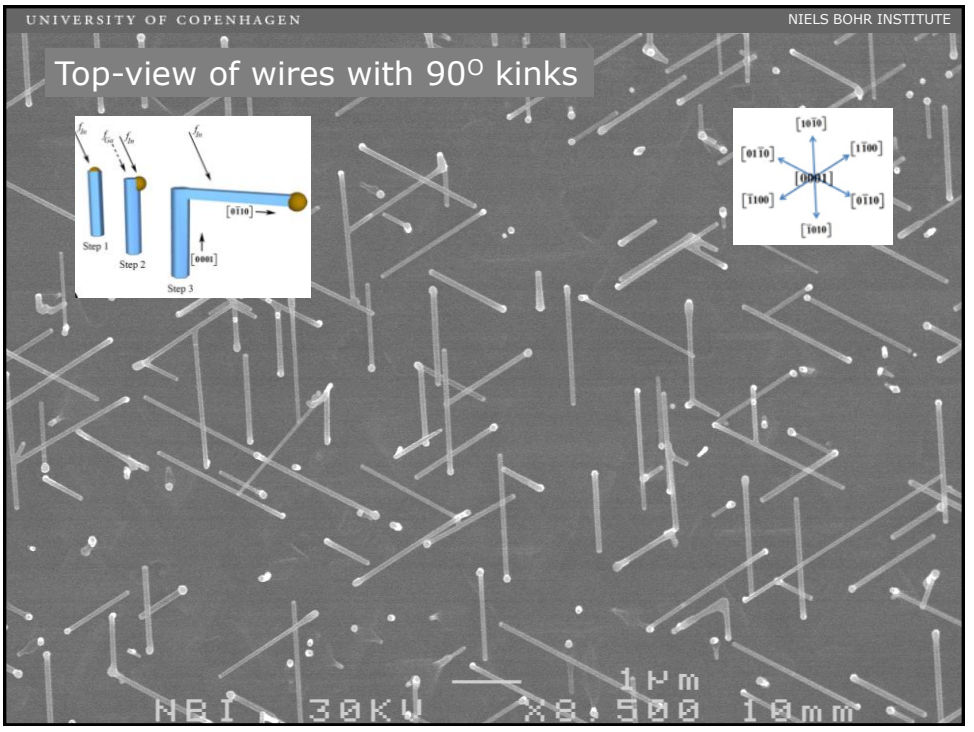
Basis for isolated Majorana system
Parity lifetime of bound states ~10 ms

A. Higginbotham et al (arXiv:1501.05155)

T.W. Larsen et al (submitted)

Tunable superconducting qubits (transmon devices)

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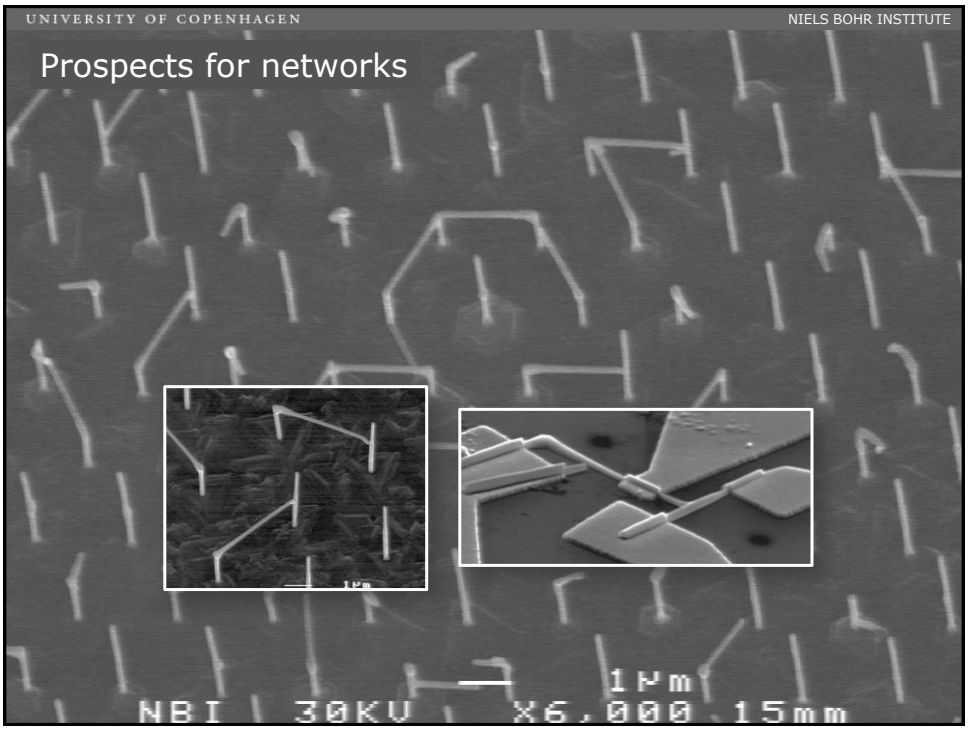
Top-view of wires with 90° kinks
Step 1
Step 2
Step 3
[0001]
1μm
NBI 30kV X8,500 10mm


UNIVERSITY OF COPENHAGEN
NIELS BOHR INSTITUTE
Prospects for networks
1μm
NBI 30kV X6,000 15mm


Thomas Sand Jespersen


Peter Krogstrup


Jessica Bolinsson


Caroline Lindberg


Claus Sørensen


Mingtang Deng


Andrew Higgenbotham


Sven Albrecht


Daniel Sherman


Thorvald Larsen


Karl Petersson


Ferdinand Kuemmeth


Charlie Marcus

Nanowire growth and design:
Thomas S Jespersen, Peter Krogstrup, Jessica Bolinsson, Caroline Lindberg, Morten H Madsen, Erik Johnson, Claus B Sørensen

Quantum devices: Charlie Marcus, Andrew Higgenbotham, Willy Chang, Sven Albrecht, Mingtang Deng, Daniel Sherman

+ Qubits: Ferdinand Kuemmeth, Karl Petersson, Thorvald Larsen

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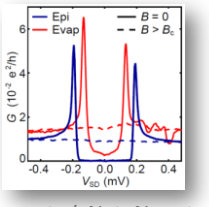
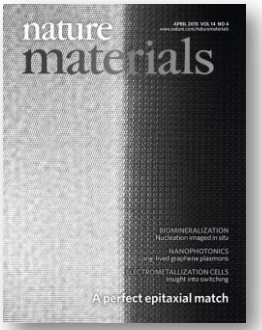


Chang *et al,* Nat. Nanotech. (2015)



Krogstrup *et al,* Nat. Materials (2015)

CONCLUSIONS

New concept for contacting of NWs
- MBE grown aluminum shells
- Epitaxial super-semi heterostructures
- Processing into segments, QPC, dots, ...
- Tunneling experiments

Hard gap induced superconductivity
- Critical field >1.5 T (parallel)
- Features consistent with Majorana
- Prospects for complex geometries, qubits, other materials (ultra-hard?)...

Carlsberg
Microsoft

Danmarks Grundforskningsfond
Danish National Research Foundation

Center for Quantum Devices