Majorana Fermion Experiments in Nanowires

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Lecture 1

Kitaev Model mapped on to superconductor-semiconductor hybrids

Experimental signature: zero-bias peaks

Lecture 2

Modern state of the field

Andreev states in quantum dots

Boulder Summer School, 2016
Majorana recipe for nanowires:

1. One-dimensional wire
2. Spin-orbit interaction
3. Superconductivity
4. Magnetic field

\[ \mathcal{H} = \left[\frac{p^2}{2m} - \mu(y)\right] \tau_z + u(y)p \sigma_z \tau_z + B(y)\sigma_x + \Delta(y)\tau_x. \]

Lutchyn, Sau, Das Sarma, PRL 2010
Oreg, Refael, von Oppen, PRL 2010
$E_z < \Delta$

$E_z = \Delta$

$E_z > \Delta$

Trivial Superconductor
“positive gap”

Majorana
“zero gap”

Topological Superconductor
“negative gap”
Tunneling into a Majorana bound state: Resonant Andreev current!

gray: $T = 0$
### Which nanowire? Which superconductor?

<table>
<thead>
<tr>
<th>Need:</th>
<th>Need:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• strong spin-orbit coupling</td>
<td>• large gap</td>
</tr>
<tr>
<td>• large g-factor</td>
<td>• withstand high B-fields</td>
</tr>
<tr>
<td>• ballistic 1D transport</td>
<td>• small work function mismatch</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>InAs nanowires:</th>
<th>Aluminum contacts:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g = 6\text{--}10$, $l_{so}=100$ nm</td>
<td>Gap $\sim 100$ ueV</td>
</tr>
<tr>
<td>Disorder is high (low mobility)</td>
<td>Critical field $\sim 100$ mT</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>InSb nanowires:</th>
<th>NbTiN contacts:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larger $g$, similar $l_{so}$, “cleaner”</td>
<td>Gap $\sim 3$meV</td>
</tr>
<tr>
<td></td>
<td>Critical field $&gt; 10$ T</td>
</tr>
</tbody>
</table>
Growth dynamics

1: Precursor transport
2: Precursor dissociation
3: Diffusion through Au
4: Crystal growth
5: Adsorption on substrate
6: Film deposition on substrate
7: Surface diffusion
8: Film deposition on nanowire sides
Why InSb?

1) High mobility
2) Large spin-orbit
3) Large g-factor
4) Easy ohmic contact

Nanowires grown by S. Plissard and E. Bakkers
Plissard et al, Nano Letters 2012
Dilution refrigerator: 5-10 mK
Cooling electrons down

Electron temperature ≠ Lattice T!
Si$_3$N$_4$ dielectric

Device Fabrication

following e.g. Fasth PRL 07
1 micron

1 micron

Ti/Au

Ti/Au

InSb nanowire

InSb nanowire

NbTiN

NbTiN

500 nm

500 nm
First Majorana ingredient: one-dimensional system

\begin{align*}
\text{B}=0\text{T} & \quad \text{FG(V)} \\
\begin{array}{c}
\text{FG(V)} \\
\text{B}=4\text{T}
\end{array}
\end{align*}

Voltage(mV)

\begin{align*}
\text{dI/dV/(2e}^2/\text{h)} & \quad \text{FG(V)} \\
\text{Magnetic field(T)} & \quad \text{Voltage(mV)}
\end{align*}

Data: Jun Chen, Peng Yu (Pitt)
Multi-subband topological superconductor

\[ g\mu_B B(\theta) > \sqrt{\Delta_{k=0,N}^2 + \mu^2(x)} \]
Spin-orbit strength in InSb nanowires

Nadj-Perge et al. PRL 2012

\[ \Delta_{so} = 0.3 \text{ meV} \]

\[ \Delta_{so}/g\mu_BB = 0.06 \text{ and } g = 43 \]

\[ l_{so} = 200 \text{ nm} \]
Majorana recipe:

1. One-dimensional wire
2. Spin-orbit interaction
3. Superconductivity
4. Magnetic field

InAs NW, C. Fasth et. al, PRL 2007; Pfund, PRB 2007;
InSb NW, H. A. Nillson et. al, Nano Lett. 2010

Nadj-Perge et al. PRL 2012

Not the subband spin-orbit splitting!
Observation of zero bias peak

\[ \frac{dI}{dV} \left( \frac{2e^2}{h} \right) \]

\[ B = 0 \]

\[ 490 \text{ mT} \]

\[ \Delta = 250 \text{ eV} \]

Data: Delft
Temperature dependence

$\frac{dI}{dV} (2e^2/h)$

$V (\mu V)$

$G G (e^2/h)$

$0 - \Delta V 0 \Lambda$

$=>$ Temperature scale is 0.3-0.4 Kelvin

Data: Delft
Gate dependence: under the superconductor

Data: Delft
Gate dependence: barrier gate

Data: Delft
Majorana recipe:

1. One-dimensional wire ✔
2. Spin-orbit interaction
3. Superconductivity
4. Magnetic field ✔
Third device in a 3D vector magnet

Data: Delft
Majorana recipe:

1. One-dimensional wire ✔
2. Spin-orbit interaction ✔
3. Superconductivity

4. Magnetic field ✔

No robust zero bias peaks observed
Zero-bias Zoo

Disorder (WAL, Reflectionless tunneling)

Kondo

Josephson

Majorana

Unknown effect

Andreev Bound States
\[ g^* > 50 \]

in InSb

...so, 1 Tesla = 1.5 meV
EJH Lee et al, PRL 2012
How would Kondo effect look?

Data: Delft
July 2011: Two Superconducting Contacts

Deng et al, Nano Letters 2012
“Observation of Majorana Fermions in a Nb-InSb Nanowire-Nb Hybrid Quantum Device”

Finck et al, PRL 2012
“...while considering more mundane explanations.”

Josephson
Supercurrents surviving to 2 Tesla.
Contact spacing = 900 nm

(Dark regions near zero bias = supercurrent)
Play with gates – make ZBP due to Josephson effect appear at finite field!

Data: Delft
Zero-voltage conductance peak from weak antilocalization in a Majorana nanowire

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(Dated: August 2012)

\[ G \left[ \frac{e^2}{h} \right] \]

\[ V \left[ \frac{E_{so}/e}{E_{so}} \right] \]

\[ E_Z \left[ \frac{E_{so}}{E_{so}} \right] \]

Data: Delft
BG1(V)

Data: Jun Chen, Peng Yu (Pittsburgh)
2012 signatures of Majorana

Zero bias peak (ZBP) onsets at $B \sim 100$ mT
$E_z \sim 150$ $\mu$eV, so $E_z \sim \Delta$

ZBP remains stuck to zero bias over significant range of $B$
(peak width 30 $\mu$eV, $\Delta E_z \sim 0.5$-$1.5$ meV)

ZBP persist over large gate ranges for all gates, but gate tuning is required!

ZBP vanishes when $B$ is aligned with $B_{SO}$

ZBP robust in both gate and magnetic field NOT OBSERVED
in three N-NW-N devices (superconductivity is important)

Trivial alternative scenarios ruled out easily (Kondo, Josephson, WAL…)
Where we are now

Is that a UFO???

Mourik Science 2012

CERN $5\sigma$
ZBP splitting: coupled Majoranas?

Data: Jun Chen, Peng Yu (Pittsburgh)

Sim: Aguado group
Where is the second Majorana?
SN1 N2

=> correlation in peak onset

N1-S

N2-S

B-field

Data: Delft
Nanowire networks for topological qubits

Plissard et al.
“Formation and electronic properties of InSb nanocrosses”
Nature Nanotechnology (2013)

Alicea et al.
Nature Physics 2011

Stanescu et al, PRB 2012