Transport Signatures of Quasiparticle Poisoning in a Majorana Island


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We investigate effects of quasiparticle poisoning in a Majorana island with strong tunnel coupling to normal-metal leads. In addition to the main Coulomb blockade diamonds, “shadow” diamonds appear, shifted by 1e in gate voltage, consistent with transport through an excited (poisoned) state of the island. Comparison to a simple model yields an estimate of parity lifetime for the strongly coupled island (~1 μs) and sets a bound for a weakly coupled island (> 10 μs). Fluctuations in the gate-voltage spacing of Coulomb peaks at high field, reflecting Majorana hybridization, are enhanced by the reduced lever arm at strong coupling. When converted from gate voltage to energy units, fluctuations are consistent with previous measurements.

LETTER

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Exponential protection of zero modes in Majorana islands

Device Layout

Sample:
- [0001] wurtzite InAs nanowire
- MBE Al on 2 of 6 faces (hard gap)
- Chemical etch to remove Al shell at ends
  → L=400nm Al island
- Ti/Au contacts
- Gates near 50nm exposed segment to form dot

B-field:
- perpendicular to wire
- Thin film Al (10nm) → high critical field:
  \( B_{\text{crit}} = 0.7 \text{ T (perp. substrate)} \)
  \( B_{\text{crit}} = 0.2 \text{ T (in plane)} \)

Measurements: Lockin 5µV, 314Hz, 50mK (fridge)

Charge states of island (no poisoning)

Number of charges on island: \( N = 2N_{cp} + N_0 \)
- \( N_{cp} \): Cooper pairs on island
- \( N_0 \): \((0/1)\) occupation of subgap state

State energies \( E(N_{cp}, N_\Delta, N_0) = E_C/2*(N_G-N)^2 + N_0*E_0 \)
Gate induced charge \( N_G = C_G V_G/e \)
Capacitance \( C_G \) (island – side gate)
Charging energy \( E_C = e^2/C_{tot} \)

Even \( N \): \((N_{cp},0)\) lowest state: condensate
Odd \( N \): \((N_{cp},1)\) 1 particle in subgap state

Charge transport @degeneracies
- \( E_0 > E_C \) Transport through cooper pairs => 2e spacing
- \( E_0 < E_C \) Alternating peak spacing \( S_o, S_e \) (\( E_0 \) lowered by Zeeman energy)
- \( E_0 = 0 \) Transport through Majorana zero modes => 1e spacing

S.M. Albrecht et al., Nature 531, 206 (2016)
Charge states of island

Number of charges on island: \( N = 2N_{cp} + N_{\Delta} + N_0 \)
- \( N_{cp} \): Cooper pairs on island
- \( N_{\Delta} \): Quasiparticles in BCS continuum
- \( N_0 \): \((0/1)\) occupation of subgap state

State energies \( E(N_{cp}, N_{\Delta}, N_0) = \frac{E_C}{2} (N_G - N)^2 + N_{\Delta} \Delta + N_0 E_0 \)
Gate induced charge \( N_G = C_G V_G / e \)
Capacitance \( C_G \) (island – side gate)
Charging energy \( E_C = e^2 / C_{tot} \)

Even \( N \):
- \((N_{cp}, 0, 0)\) lowest state is pure condensate, **black**
- \((N_{cp}, 1, 1)\) 1st excited state, **green**

Odd \( N \):
- \((N_{cp}, 0, 1)\) 1 particle in subgap state, **red**
- \((N_{cp}, 1, 0)\) 1st excited state, **blue**

Charge transport @\( T=0 \) (no poisoning):
- Island in ground state
- Tranport @ degeneracies

\[
\begin{align*}
(N_{cp}, 0, 0) &\Rightarrow (N_{cp}, 0, 1) \\
(N_{cp}, 0, 1) &\Rightarrow (N_{cp} + 1, 0, 0)
\end{align*}
\]
Transport with poisoning

Poisoning: Presence of quasiparticles (relaxe in energy down to BCS peak @ $\Delta$)

Transport at degeneracies with $N_\Delta=1$ (green squares)

Returning to unpoisoned state:
• Cooper pair recombination $(N_{cp},1,1) \rightarrow (N_{cp}+1,0,0)$ (possible due to lack of transl. invariance)
• Quasiparticle relaxation to subgap state: $(N_{cp},1,0) \rightarrow (N_{cp},0,1)$
• Quasiparticle tunneling to lead $(N_{cp},1,N_0) \rightarrow (N_{cp},0,N_0)$

Visibility of “excited state transport”:
• Relaxation rate
• Poisoning rate
• $\Gamma_{SD}$

Appearance: Same as ground state, but shifted by 1e in gate voltage
Coulomb blockade diamonds

Without subgap state:
1 set of diamonds with 2e peak spacing

Subgap state:
Alternating peak spacing \( S_o, S_e \)
2 sets of diamonds
• Small strong
• Faint large

Nearly vanishing odd diamonds
\( \Rightarrow E_0 \) only slightly smaller than \( E_c/2 \)
• Weak lines within large diamond
  \( \rightarrow \) quasiparticle transport

Extracted parameters:
\( E_c=210\mu eV, E_0=75\mu eV, \eta=6meV/V, \)
\( \Delta=140\mu eV \) (induced gap, onset negative diff. cond.)
\( \Gamma_s=1GHz, \Gamma_D=6GHz \) (peak height, width), previously \( \approx 0.5GHz \)
\( \tau_{qp}=0.1\mu s \) (relaxation quasiparticle to subgap state, previously meas. in similar devices)

Numerical simulations (using above parameters):
Best match using \( \tau_p=1.2\mu s \) (poisoning time)
• Electron like \( (N_{cp},0,N_0) \rightarrow (N_{cp},1, N_0) \)
• Hole like: \( (N_{cp},0,N_0) \rightarrow (N_{cp}-1,1, N_0) \)
Evolution to Majorana modes

Emergence of zero energy mode:
- Increasing $B_{\text{perp}}$ lowers state energy of $E_0$:
  $E_0 = 75 \mu\text{eV} - E_z$
- Uniform spacing $S_o = S_e$ for $B_{\text{perp}} > 0.16 \text{T}$
  =>$\text{zero energy state}$
- For $B > 0.16 \text{T}$: state remains at zero
  with small oscillations
  =>$\text{hybridized Majorana modes}$

Simulations use same parameters as for CBP

Shadow diamond & poisoning rate:
- Clearly split Coulomb peaks at finite field
- Strongly suppressed shadow peaks
- Peak height depends strongly on $\tau_p$
  =>$\text{Poisoning rate } \tau_p = 1.2 \mu\text{s}$

Parity lifetime of $\tau_p = 1.2 \mu\text{s}$ (obtained from ration $g_m/g_s$)
- Here, not ideal tuning for long lifetimes
  (large source drain coupling)
- Estimate $g_m/g_s$ for devices without shadow diamond
  ($g_s$ = noise floor) => conservative estimate $\tau_p > 10 \mu\text{s}$
Hybridized Majorana modes

B-field evolution of subgap state:
• spacing $S_o(S_e)$ increases (decreases) with growing field, both $B_{\text{perp}}, B_{\text{inplane}}$
• Strong and faint peaks merge $\Rightarrow$ Uniform peak spacing $\Rightarrow$ zero energy state
• Small oscillations for $B_{\text{perp}}$ consistent with hybridizing Majorana modes in finite length device:

$A = A_0 e^{-L/\xi} = 64 \mu eV$
$L = 400 \text{nm}$
$A_0 = 300 \mu eV$
$\xi = 260 \text{nm}$

No oscillations for $B_{\text{inplane}}$?
• Merging happens at higher field, close to gap closing
• $\Rightarrow$ expect “trivial” 1e period, no Majorana modes
Observation of merging (oscillating) subgap states

consistent with hybridizing Majorana modes in finite length samples

Observation of shadow Coulomb diamond => quasiparticles

Intensity of shadow diamond => quasiparticle poisoning rates

Majorana parity lifetime of 10µs (1.2µs) in weakly (strongly) coupled devices