Weber-blockade view of magnetoresistance oscillations in superconducting strips
(*and related issues in nanosuperconductivity*)

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Experimental motivation:

Johansson, Sambandamurthy, Shahar, Jacobson, Tenne, PRL 95, 116805 (2005)

Theoretical ideas:

PMG, Pekker, Refael, BAPS.2009.MAR.W34.7
Atzmon, Shimshoni, arXiv:1010.0664v1
Pekker, Refael, PMG, arXiv:1010.4799v1

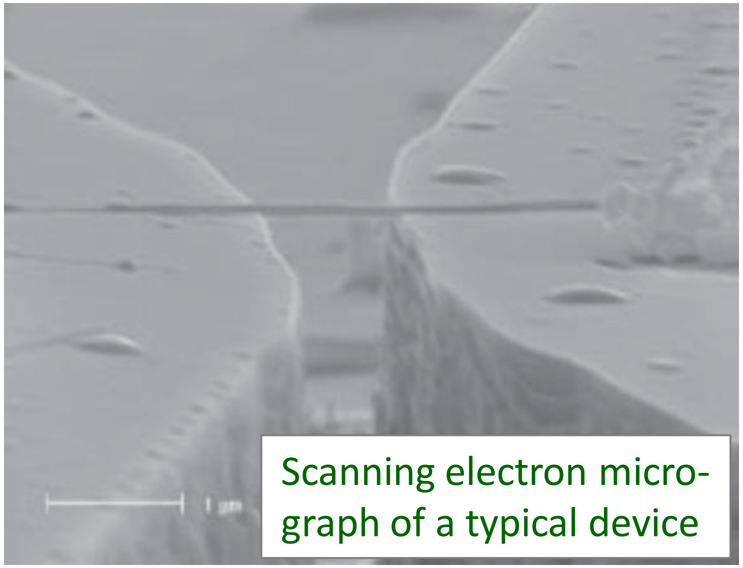
Talk outline

- Shahar group's experiments
  on narrow superconducting strips
- magnetoresistance data: oscillations
- proposed explanation:
  vortex analog of Coulomb blockade
- model and its implications

Magnetoresistance data

Shahar group, PRL 95, 116805 (2005)

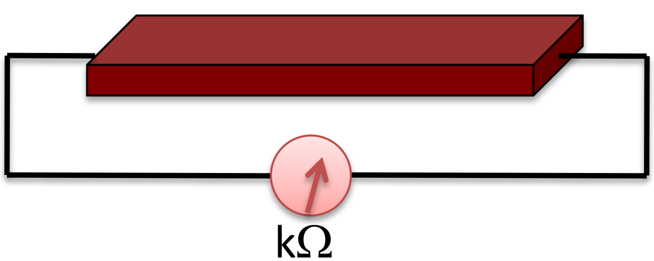
- **materials**
  - amorphous indium oxide superconducting nanowires
  - technique: molecular templating (Bezryadin et al. 2000)
- **wire geometries**
  - widths 40 to 120 nm
  - thicknesses ~20-30 nm
  - lengths 1.5 to 3.4 μm



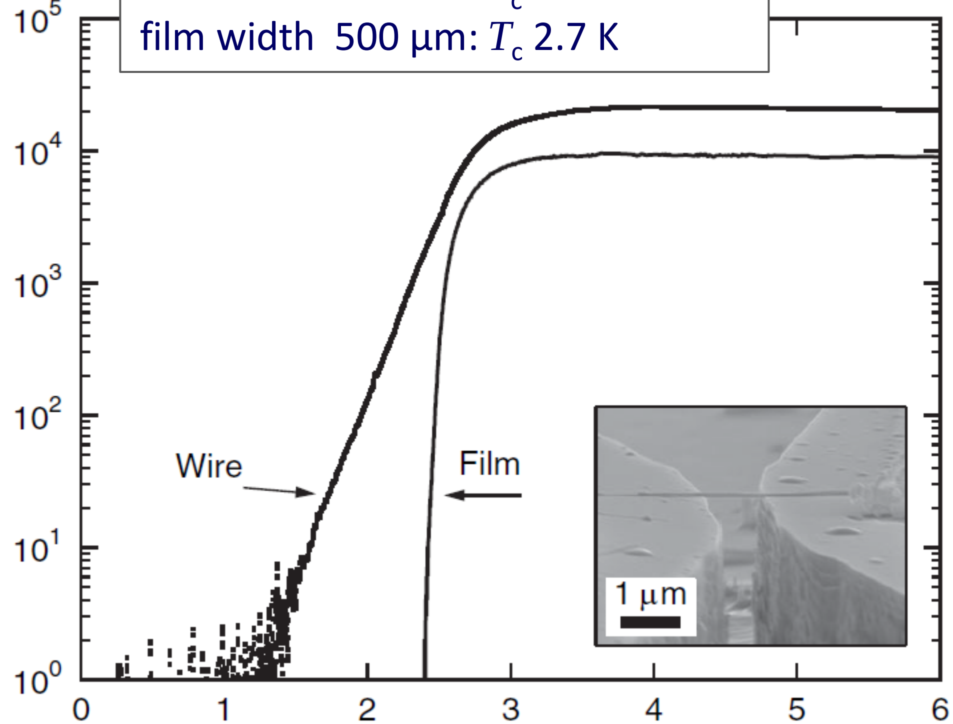
Scanning electron micro-graph of a typical device

Magnetoresistance data

- **measurements**
  - electrical resistance
  - vs magnetic field
  - at temperatures below T_c for superconductivity



Resistance (Ω) vs temperature (K)
wire width 100 nm: T_c 2.8 K
film width 500 μm: T_c 2.7 K



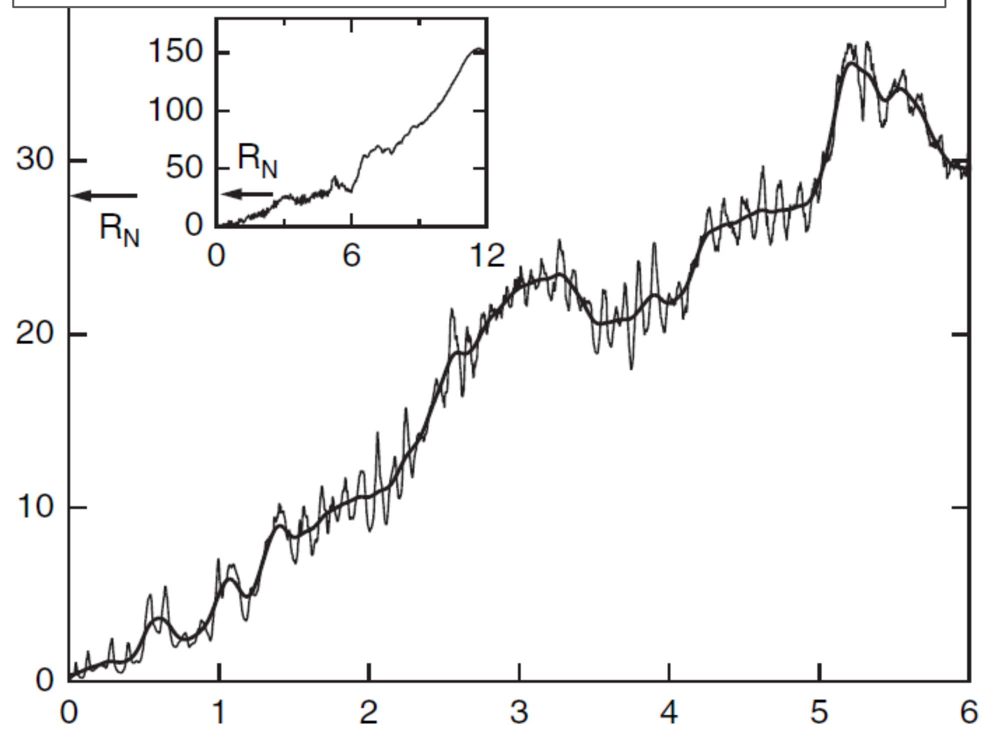
Shahar group
PRL 95, 116805 (2005)

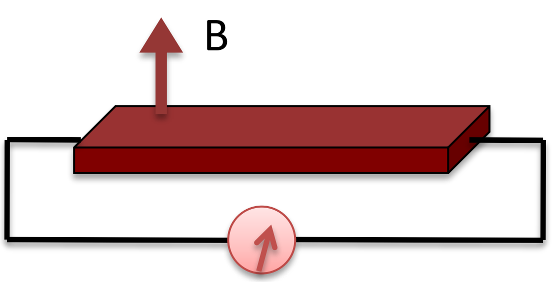
Magnetoresistance oscillations

- **observations**
  - nonzero along-strip electrical resistance
  - clear oscillations with magnetic field
  - reproducible, 5 samples reported, various geometries (*t*hickness, *w*idth, *L*ength)

Wire	*t* (nm)	*w* (nm)	*L* (μm)
39Ue	21	40	1.5
86Gc	30	94	1.0
86Gd	30	94	1.0
86Ge	30	94	1.0
99Nb	30	120	3.4

Resistance (kΩ) vs magnetic field (T) for wire 99Nb at temperature 12 mK. Inset: resistance to 12 T



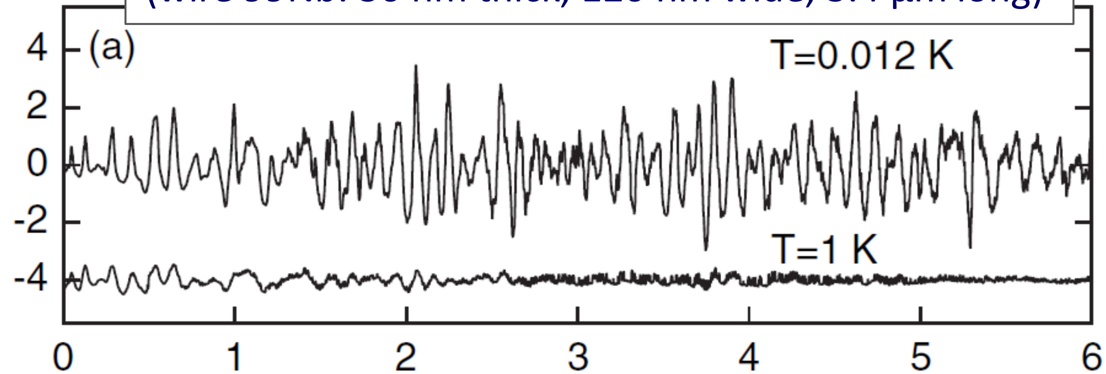


Shahar group
PRL 95, 116805 (2005)

Magnetoresistance oscillations

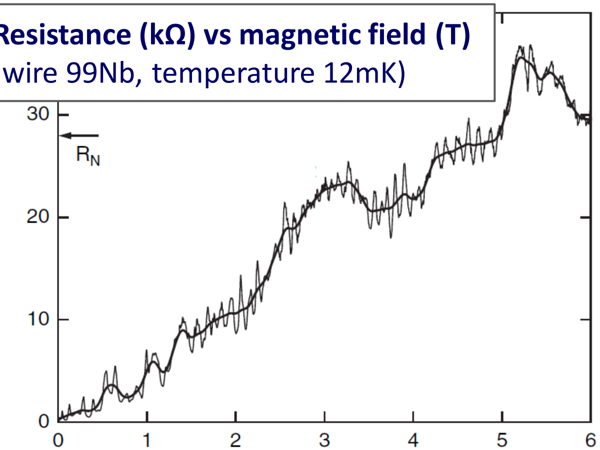
- **observations**
  - nonzero along-strip electrical resistance
  - clear oscillations with magnetic field
  - reproducible, 5 samples reported

Resistance oscillation (kΩ) vs magnetic field (T): background subtracted, temperatures 12 mK & 1 K (wire 99Nb: 30 nm thick, 120 nm wide, 3.4 μm long)



- **aim to explain**
  - origin of electrical resistance
  - mechanism for oscillations
  - oscillation period
  - oscillation amplitude
- **suggest new regimes of behavior**

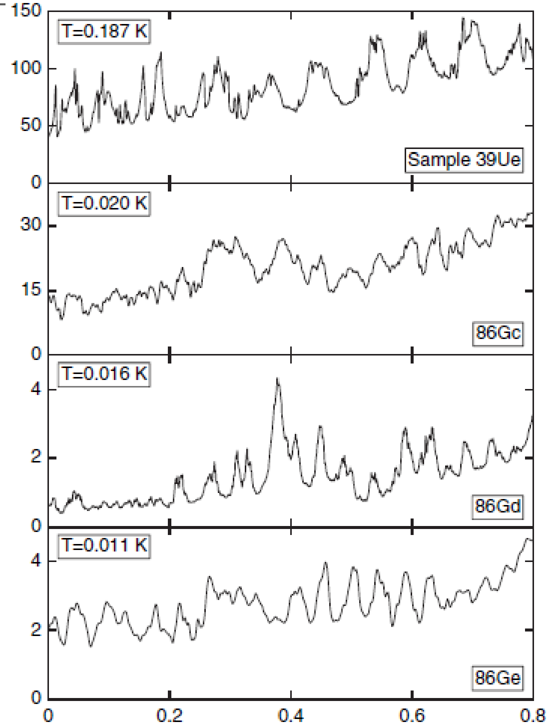
Resistance (kΩ) vs magnetic field (T)
(wire 99Nb, temperature 12mK)



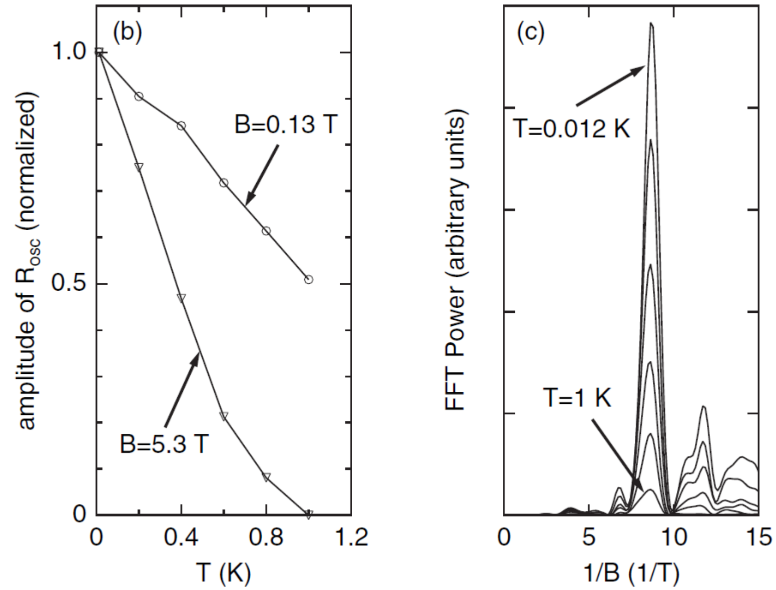
Shahar group
PRL 95, 116805 (2005)

Oscillations: reproducibility & characteristics

Resistance oscillation (kΩ) vs magnetic field (T): various samples & temps, narrow field range



Wire	t (nm)	w (nm)	L (μm)	rms R_{osc} (kΩ)	f_{osc} ($1/T$)
39Ue	21	40	1.5	15.5	12.1
86Gc	30	94	1.0	2.30	20.7
86Gd	30	94	1.0	0.36	21.6
86Ge	30	94	1.0	0.46	23.0
99Nb	30	120	3.4	0.90	8.6

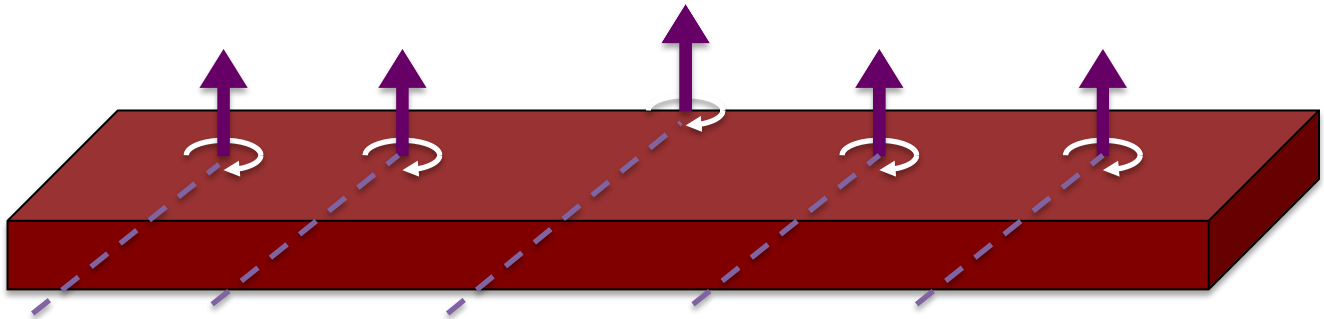


Resistance characteristics vs temperature & magnetic field: wire 99Nb oscillation amplitude & power spectrum

- **oscillations**
  - reproducible
  - weaken with T (quicker at large B)
  - main peak frequency fixed, height decreases with T

Shahar group
PRL 95, 116805 (2005)

Origin of electrical resistance of superconducting strip



- **supercurrent bias *<u>along</u>* strip**
- **vortex passage *<u>across</u>* strip**
  - unwinds end-to-end phase difference
  - reduces supercurrent along strip
  - voltage via Josephson-Anderson relation:

$$\frac{2eV}{\hbar} = \frac{d}{dt}\Delta\varphi = 2\pi \times \text{passage rate}$$

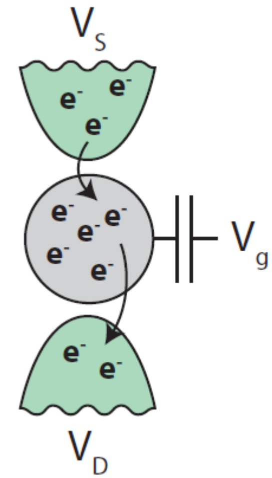
  - voltage/supercurrent → resistance (collective/GL/bosonic)

  - *useful notion*: sidewalks/pavements as vortex reservoirs

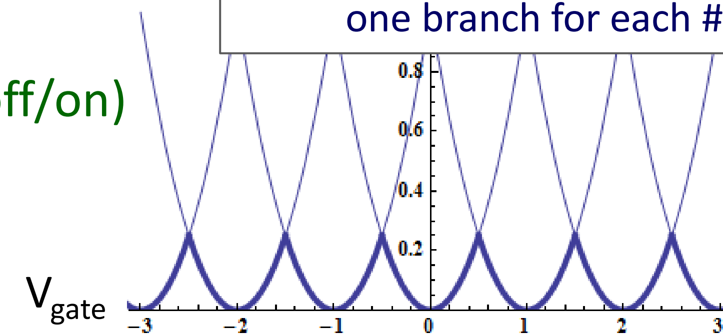
Coulomb blockade (zero bias)

- **almost closed quantum dot**
  - electrons: indivisible, repulsive
  - zero source/drain voltage
- **generic gate voltages**
  - a preferred # of electrons on dot
  - energy barrier to traverse dot (on/off or off/on)
  - low through-dot electrical conductance
- **special gate voltages**
  - two preferred #s of electrons on dot
  - no barrier to traverse dot, charge flucts
  - high through-dot electrical conductance
  - **except at periodic V_{gate} electrical transport Coulomb is blockaded**

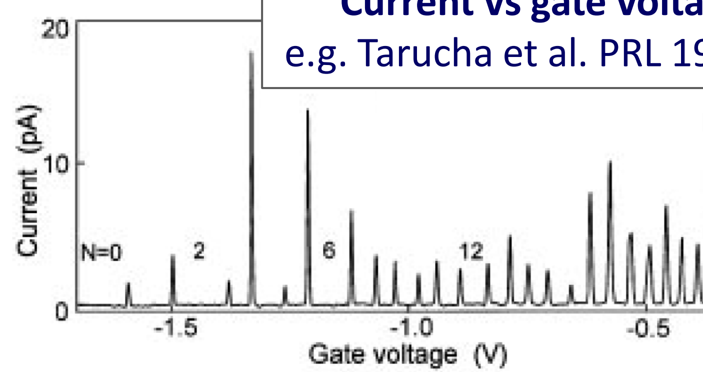
Quantum dot: controlled by source, drain & gate voltages



Dot energy vs gate voltage: one branch for each #



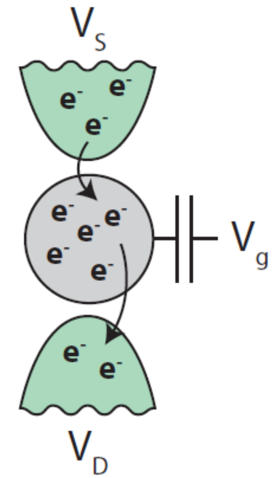
Current vs gate voltage: e.g. Tarucha et al. PRL 1996

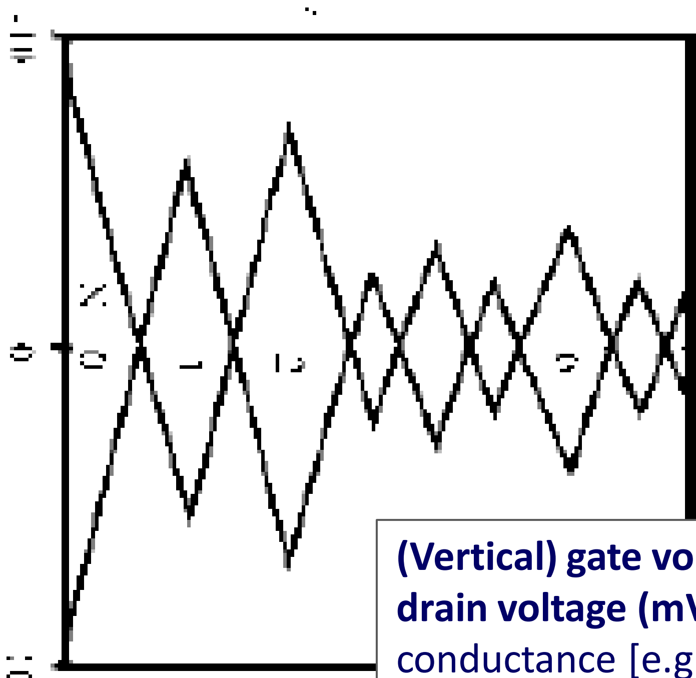


Coulomb blockade (nonzero bias)

- **almost closed quantum dot**
  - nonzero source/drain voltage
  - energy now available via source & drain
  - around conducting gate voltages
    "room to traverse" opens up
  - blockaded gate-voltage ranges shrink

Quantum dot: controlled by source, drain & gate voltages





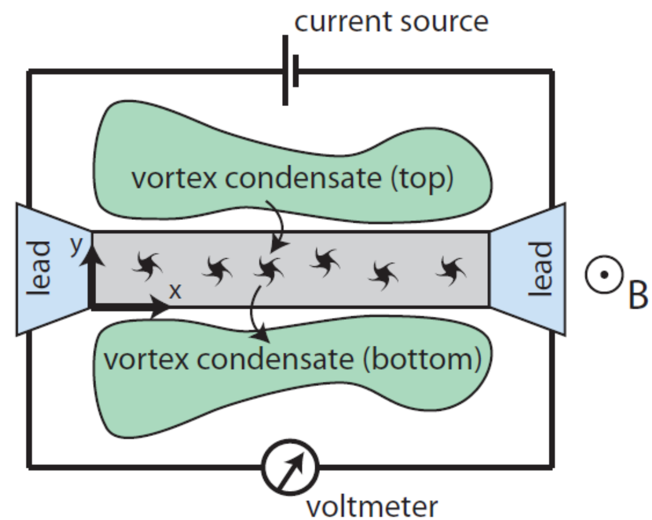
- ***inside* diamonds in gate vs source-drain voltage plane, Coulomb blockade of electrical transport remains**

(Vertical) gate voltage (arb. units) / (horizontal) source-drain voltage (mV) plane: diamonds of low electrical conductance [e.g. Kouwenhoven et al. (unpublished) 1996]

Mechanism for magnetoresistance oscillations

PMG, Pekker, Refael, APS 2009
Pekker, Refael, PMG, arXiv:1010.4799v1

- **vortices indivisible, mutually repelling**
- **generic magnetic fields**
  - a preferred # of vortices on strip
  - energy barrier for crossings (on/off or off/on)
  - low across-strip vortex conductance
  - low along-strip electrical resistance: ~~Coulomb~~ Weber blockade



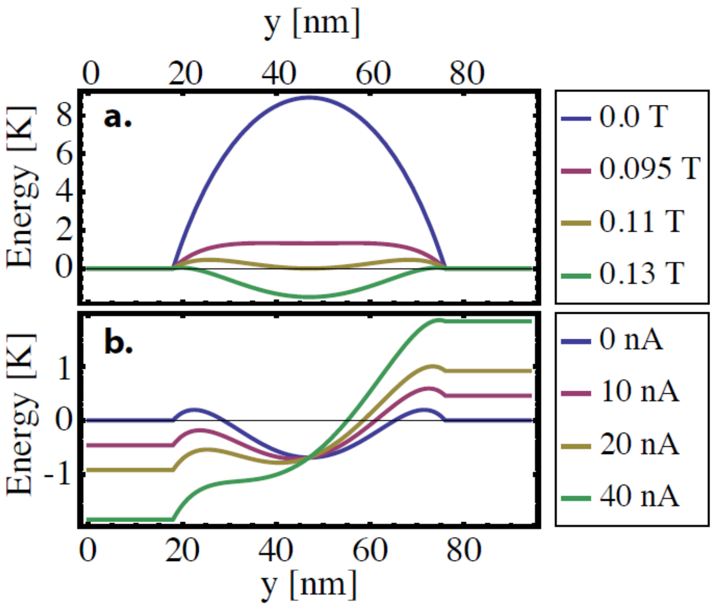
- **special magnetic fields**
  - two preferred #s of vortices on strip
  - no barrier for crossings (on/off or off/on), # fluctuations
  - high across-strip vortex conductance
  - high along-strip electrical resistance: magnetoresistance oscillations
- **add along-strip bias current**
  - energy now available, “room to traverse” opens up
  - blockaded magnetic-field ranges shrink: ~~Coulomb~~ Weber diamonds

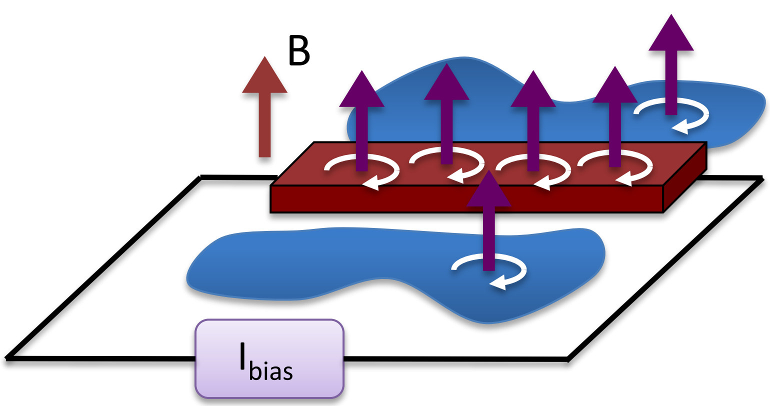
Ingredients of a model

PMG, Pekker, Refael, APS 2009
Pekker, Refael, PMG, arXiv:1010.4799v1

- **energetics of single vortices in strips**
  - Likharev (1971): phase model, conformal mapping, images,…
    - vortex core, vortex / image
    - vortex / B-field
    - vortex / current
- **multiple-vortex energetics**
  - effective reduction of area
  - period & diamonds
- **vortex kinetics**
  - fluid of vortices on strip
  - virtual vortex reservoirs adjacent to strip
  - Beenakker (1991) kinetic equation approach

Vortex potential across strip:
for various magnetic fields &
along-strip currents (at 120 mT)
(width 94 nm, length 1 μm,
ξ of 18nm superfluid density 5 K)



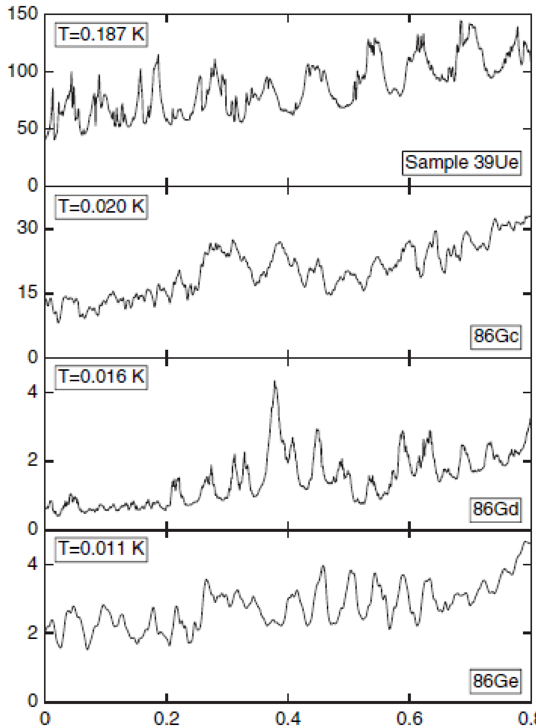


Implications I

- **MR oscillations: reflecting underlying Weber blockade?**
  - generic B: low along-strip electrical resistance
  - special B: high along-strip electrical resistance
  - model gives period ΔB as adding 1 SC flux quantum though roughly half the area of strip
  - due to vortex-vortex & vortex image interactions

sample	width (nm)	length (μm)	geom. period (mT)	obs. period (mT)	fit ξ (nm)
39Ue	40	1.5	34	83	10
86Gc	94	1.0	22	48	17
86Gd	94	1.0	22	46	16
86Ge	94	1.0	22	43	15
99Nb	120	3.4	5.1	116	too wide?

Resistance oscillation (kΩ) vs magnetic field (T): various samples & temps

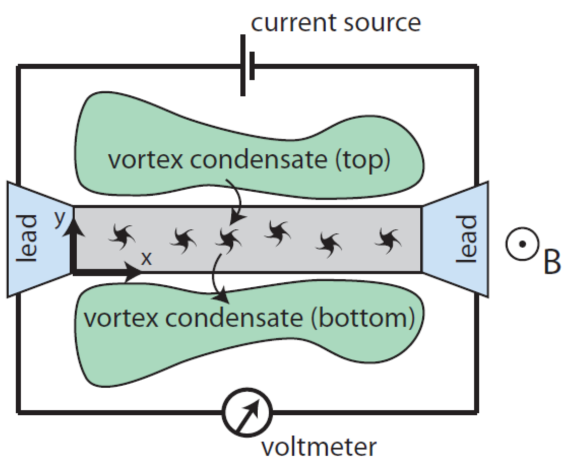


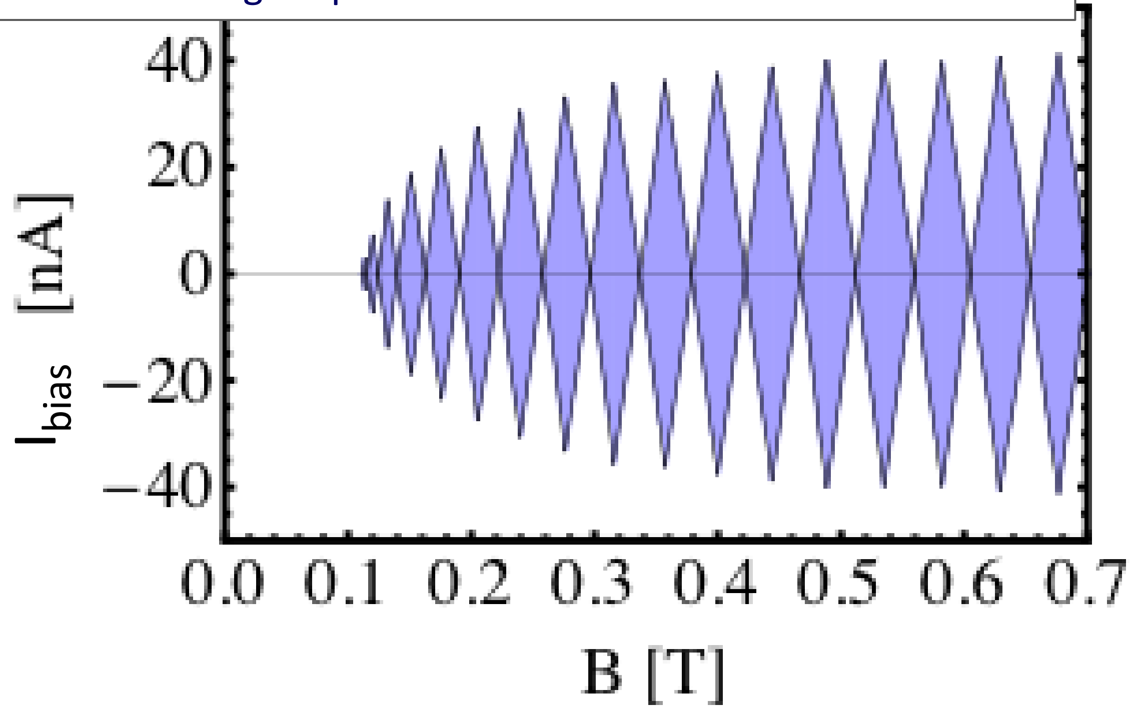
PMG, Pekker, Refael, APS 2009; Pekker, Refael, PMG, arXiv:1010.4799v1

Implications II

- **Weber diamonds**
  - along-strip bias current enables across-strip vortex motion
  - vortex-blockaded magnetic-field ranges shrink

Weber diamonds in the along-strip current vs magnetic field plane:
(prediction for width 94 nm, length 1 μm, ξ of 18nm, superfluid density 5 K)
inside the diamonds the along-strip electrical resistance is low

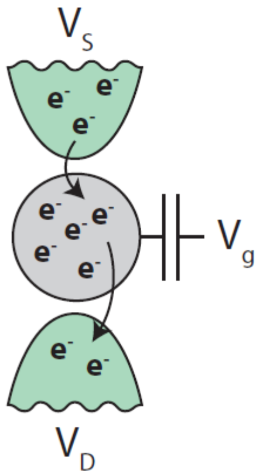


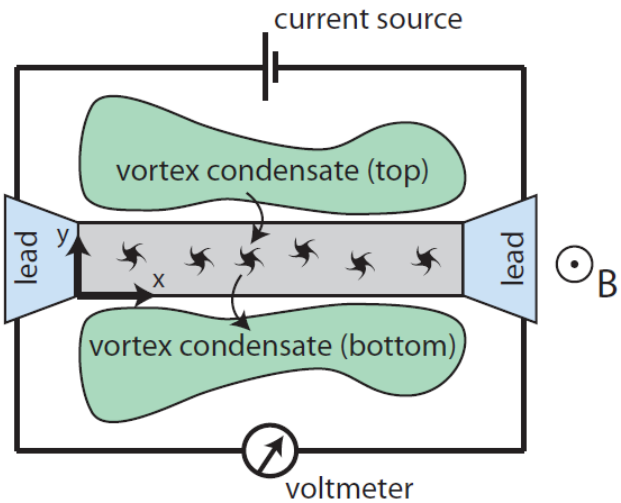


PMG, Pekker, Refael, APS 2009
Pekker, Refael, PMG, arXiv:1010.4799v1

Summary: Blockade correspondence

Element	Coulomb	Weber
system	quantum dot	superconducting strip
particle	electron	vortex
number controlled by…	gate voltage	magnetic field
blockaded current	electron	across-strip vortex
what drives this current	source-drain voltage	along-strip supercurrent
generic conductance implications	low s-d electrical	low across-strip vortex; high along-strip electrical
diamonds of…	high electrical resistance	low electrical resistance





Future

- **Narrow strips**
  - lower temperatures, sharper peaks?
  - observing diamonds?
- **Wide strips**
  - vortex line vs lattice & diamonds from transitions in structure?
  - role of disorder?
  - connection between resistance & critical current?