Imaging Electrons in Nanoscale Structures

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Outline

Imaging the flow of electron waves

Quantum point contact
  flow through individual quantum modes
  branches formed by small-angle scattering

Electron interferometer

Imaging a single-electron quantum dot
Electron waves flowing from a quantum point contact (QPC) are deflected by a charged SPM tip (Topinka et al, *Nature*, 2001)
Two-Dimensional Electron Gas

GaAs/AlGaAs Heterostructure

Quantum Point Contact Sample

$\mu = 1.0 \times 10^6 \text{ cm}^2/\text{Vsec}$

$l = 11 \mu\text{m}$

$n = 4.2 \times 10^{11} \text{ cm}^{-2}$

$\lambda_F = 39 \text{ nm}$

2DEG 57nm below surface
Quantum Point Contacts

Electrons flowing through a narrow constriction

Classical

Quantum

Tunneling Regime

1st Mode

2nd Mode

conductance plateaus

conductance (e²/h)

Width

Vg (Volts) ~ Width
Imaging Coherent Flow of Electrons from a Quantum Point Contact

Quantized Conductance Steps


Fringes demonstrate coherence
STM tip depletes the 2DEG below

Stopa
How the Tip Images Flow

Unperturbed electron flow and depleted disc beneath the tip

Tip moves down through electron flow

High spatial resolution
QPC conductance changed by the backwards 'glint' from the disc in the electron gas depleted by the tip.
Coherent Electron Flow far from the QPC

Branches of electron flow formed by small angle scattering
Coherent fringes occur throughout image. (Topinka et al, Nature, 2001)
Modal Patterns Far Away from QPC

1st Mode

2nd Mode

3rd Mode

4th Mode

$\Delta G$: $0.0 \ e^2/h$ to $-0.4 \ e^2/h$
Small angle scattering by ionized donors creates curved electron paths.

- Si donor layer
- 2DEG
- Potential from ionized impurities
- Curved electron path
Branches formed by dips in the electron potential

Effect of one donor ion on electron flow

Small angle scattering from many donor ions

Electron lens created by donor ion

Branches produced by folding in phase space

Shaw and Heller
Simulations of Electron Flow
Scot Shaw and Eric Heller

Electron flux
Superposition
Small-angle scattering potential
Simulations of quantum flux density of electron flow from a quantum point contact.

Simulations of the change in conductance by electron waves that are backscattered from the SPM tip - interference fringes are created.
Theoretical simulations fit the image cusp produced by one potential dip

Simulation of the image for scattering by one potential dip

Heller
Electron Interferometer

with a V-shaped path

Area imaged at the *same* distance $R$ from QPC as the mirror

Area imaged at *twice* the distance $R$ from QPC as the mirror
Interference Fringes created by the Mirror

Mirror Off
\((V_G = 0V)\)

Mirror On
\((V_G = -0.8V)\)

Image at the same distance from the QPC as the mirror

Image at twice the distance from the QPC as the mirror

Fringes spaced \((1/2)\lambda_F\)

Fringes spaced \((1/2)\lambda_F\)
Fringes in interferometer simulations

Mirror Off

Mirror On

Same distance as the mirror

Twice the distance as the mirror

Heller
Fringes phase shifted by reflector voltage

Fringes move twice as fast at twice the distance from the QPC
Fringes appear at the same distance from the QPC as the mirror.

Ensemble average over the thermal distribution of electrons destroys fringes over the thermal length.

\[ l_t = \frac{\hbar v_F}{\pi k_B T} = 530\text{nm} \]

Reflector position - interference maintained
Fringes destroyed by thermal average

fringe strength $\propto \cos[2k_F(r'_i - r'_t)] \exp[-(r'_i - r'_t)^2 / l_t^2] / r_ir_t$

Thermal length $l = \frac{\hbar^2 k_F \sqrt{\pi}}{4mk_BT} = 530\text{nm} @ 1.7\text{K}$

Reflectator position - interference maintained
V-shaped Electron Interferometer
Electron Interferometers

- Quantum phase shifter (3 terminal device)
  - Mirror motion via gate voltage shifts electron phase
- Spectroscopy
  - Direct measurement of wavelength, long scans give spectrum
- THz speed via spatial imaging:
  - Fermi Energy $E_F/h \sim 3$ THz
  - Sense time differences as small as $\Delta t \sim 50$ fsec
- Electronic analogs of femtosecond laser physics
Quantum information processing

Entangled spins on single electron quantum dots can be used to perform quantum information processing

Loss and DiVincenzo (1998)
Using a charged SPM tip to image a quantum dot
Single-electron quantum dot

Sachrajda geometry
Imaging with the Coulomb Blockade

The dot potential is shifted as the tip is scanned above the dot shifting the energy of the ground state by $\Delta_{\text{tip}}$.

An image of the energy shift $\Delta$ relative to the Fermi energy of the leads can be made from an image of the Coulomb blockade conductance of the dot:

$$G = G_0 / \cosh^2(\Delta/2k_B T)$$
Coulomb-blockade diamonds of a single-electron quantum dot

\[ T = 1.7K \]
Coulomb-blockade diamonds obtained by varying the SPM Tip Voltage

$T = 1.7K$
Coulomb-blockade image as the first electron enters the quantum dot

Fixed tip voltage + 40 mV as the SPM tip is scanned above the dot.

The ring is the first Coulomb blockade peak that occurs as the number of electrons on the dot is changed from 0 to 1.
As the tip voltage is made more positive, the ring shrinks to a spot directly over the dot, where the first electron is allowed to pop on.
Line shape of Coulomb blockade rings

\[ G = \frac{G_0}{\text{Cosh}^2\left(\frac{\Delta}{2k_B T}\right)} \]

\[ \Delta = 2k_B T \text{Cosh}^{-1}\left(\sqrt{\frac{G_0}{G}}\right) \]

G image

G(path)
Map of the energy shift $\Delta$ of the dot ground state

Energy shift $\Delta(X,Y)$ extracted from the line shape in the Coulomb blockade images above
A method to image the wavefunction

**Tip divot wider than wavefunction**

In images above, the tip perturbation is wider than ground state wavefunction, that maintains it shape.

**Tip divot narrower than wavefunction**

Tip dents the wavefunction and shifts it's energy.
Extracting information about the wavefunction

1st order perturbation theory:

\[
\Delta(r_{tip}) = \langle \Psi | \Phi_{tip}(r, r_{tip}) | \Psi \rangle = \text{conv} \left( \Phi_{tip}(r, r_{tip}), |\Psi(r)|^2 \right)
\]

Information about the wavefunction over distances larger than the tip pivot can be obtained by deconvolving \( \Delta \) with respect to \( \Phi_{tip} \).
Coulomb Blockade Imaging

• **Image spin inside quantum dots**
  – Spin to charge conversion

• **Manipulate charges and spins in double dots and quantum dot circuits**

• **Image electron wavefunctions in quantum dots**
  – Excited states

• **Interference fringes for electron spectroscopy**