Imaging the Motion of Electrons in Nanostructures

R.M. Westervelt
Harvard University

Imaging Electron Motion in Nanostructures

- Quantum Materials and Devices
  - Science & Technology Center for Integrated Quantum Materials
- Imaging Techniques
  - Capacitance Spectroscopy – Ray Ashoori
  - Imaging Magnetic Fields with an NV Center – Amir Yacoby
  - Imaging Electron Charge with an SET – Amir Yacoby
- Imaging Electron Paths & Control of Quantum Dots
  - Flow from a Quantum Point Contact – Mark Topinka
  - Electron Interferometer – Brian LeRoy
  - Quantum Dot control – Ania Bleszynski & Parisa Fallahi
  - 2DEG Magnetic Focusing – Kathy Aidala
- Conclusions

Quantum Materials Vision

Extraordinary new quantum materials enable atomic-scale electronics and photonics that transform signal processing and computation.

1950 1960 1970 1980 1990 2000 2010 **future**

1971 Intel P4004
1st CPU by Intel.

QUANTUM MATERIALS

- **Topological Insulators**
- **Graphene**
- **NV Center Qubits in Diamond**

Science & Technology Mission

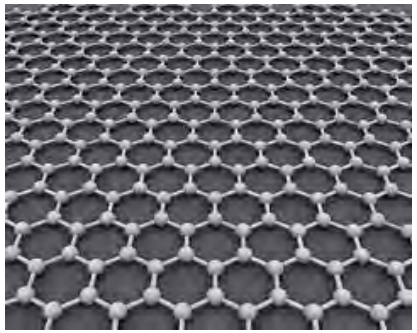
Integrated quantum systems made from atomic-scale devices, error-free data channels, and single-atom memory sites:

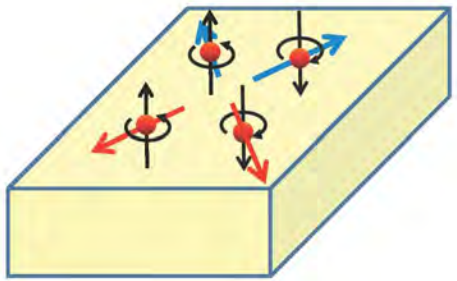
Quantum Materials

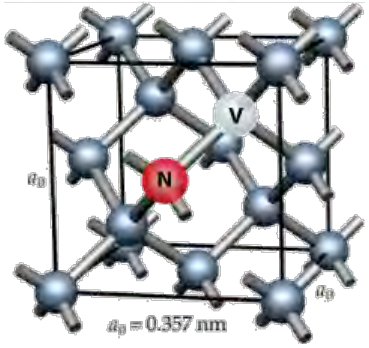
Atomic Layers: Graphene, BN, MoS_2 – *atomic scale devices*

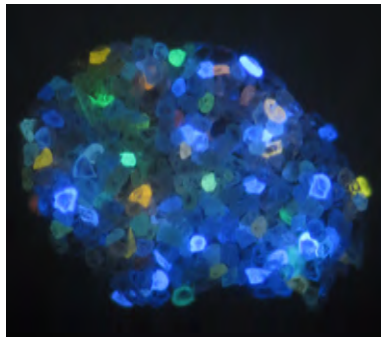
Topological Insulators – *topologically protect data*

NV Center Diamond – *1 atom memory sites, ultrasensitive magnetosensors*









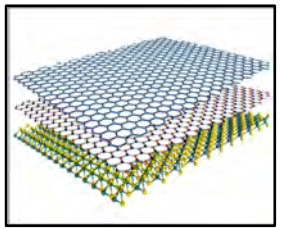
Quantum Materials → Research Thrusts

Atomic Layers

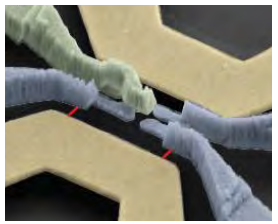
Topological Insulators

NV Center Diamond

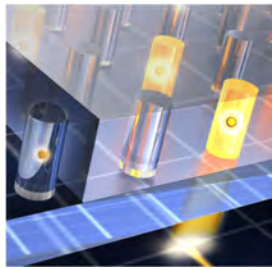
Quantum Materials by Design



Quantum Electronics and Photonics



Atomic Scale Networks

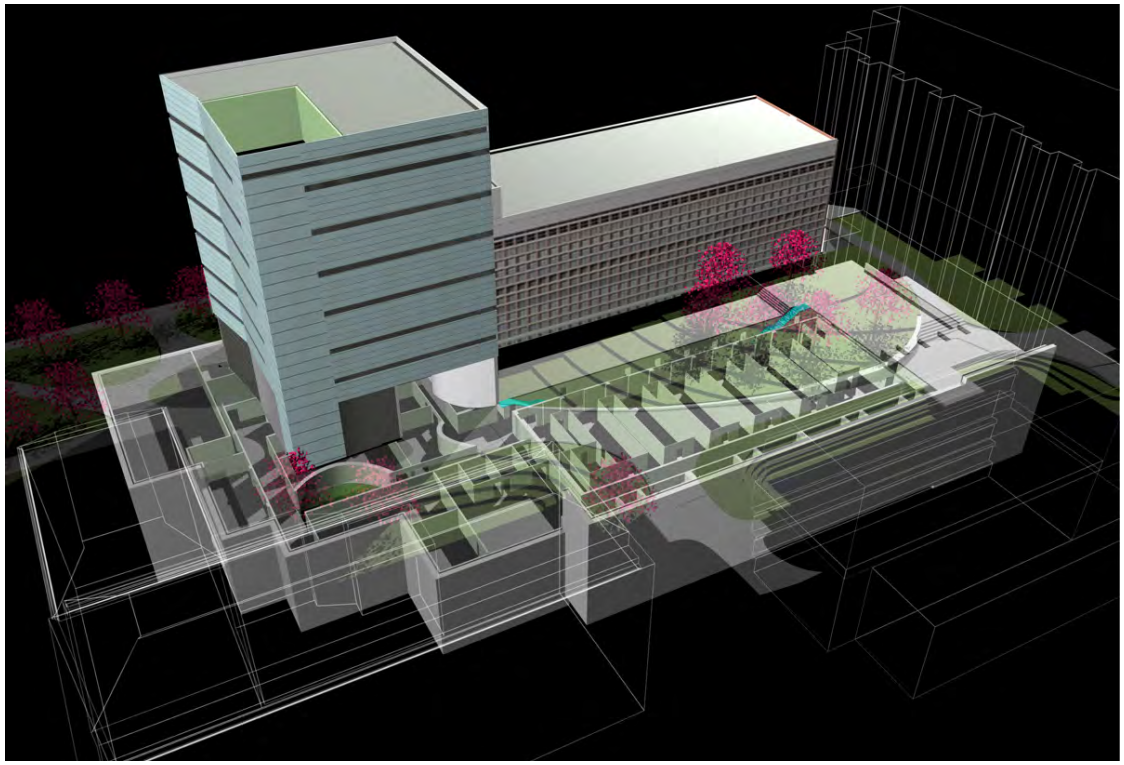


Material → **Device** → **System**

timeline


Kathy Aidala
Carol Lynn Alpert
Alan Aspuru Guzik
Ray Ashoori
David Bell
Robbie Berg
Naomi Brave
Tina BrowerThomas
Joe Checkelsky
R Christianson
Liang Fu
Silvina Gatica
Nuh Gedik
Fawwaz Habbal
B I Halperin
Donhee Ham
Gary Harris
Eric Heller
Jennifer Hoffman
Kathryn Hollar
Charles Hosten
Evelyn Hu
Tito Huber
P Jarillo Herrero
Philip Kim
Jing Kong
Joe Lassiter
JoDe Lavine
L Levitov
Marko Loncar
Mikhail Lukin
David Macaulay
J Moodera
Tomas Palacios
S Richardson
Paul Sabila
Scott Sinex
Robert Westervelt
Amir Yacoby

Center for Nanoscale Systems at Harvard



3 Story Building underground

10,000 sq ft Cleanroom for Quantum Materials

excellent imaging suite < 1 Å, TEM, STEM & Atom Probe

1500+ users

Bob Westervelt – CNS Director

Bill Wilson - new CNS Executive Director

previously led the Materials Research Lab at University of Illinois at Urbana Champaign

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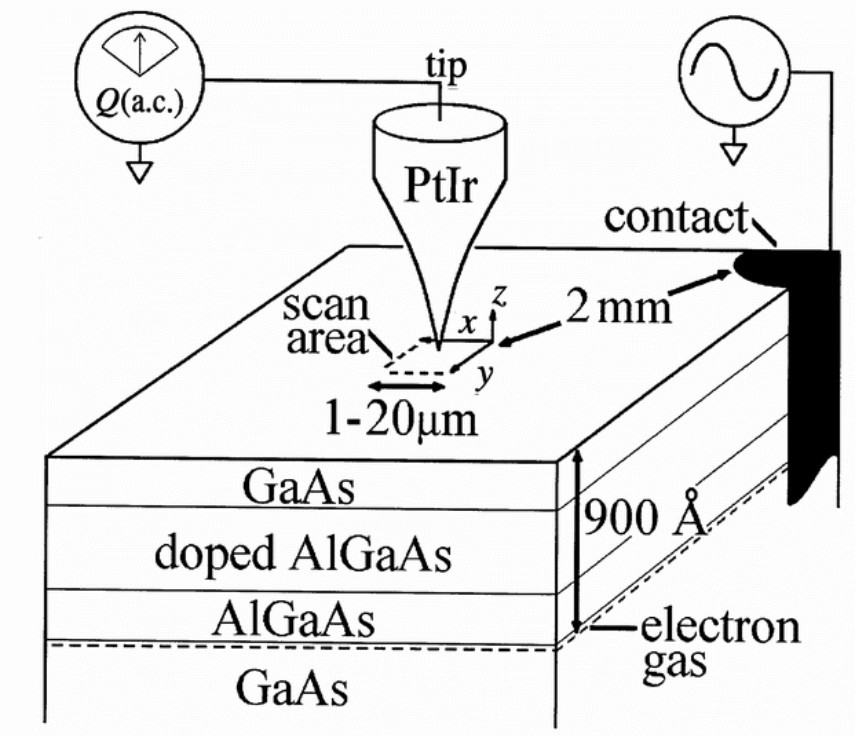
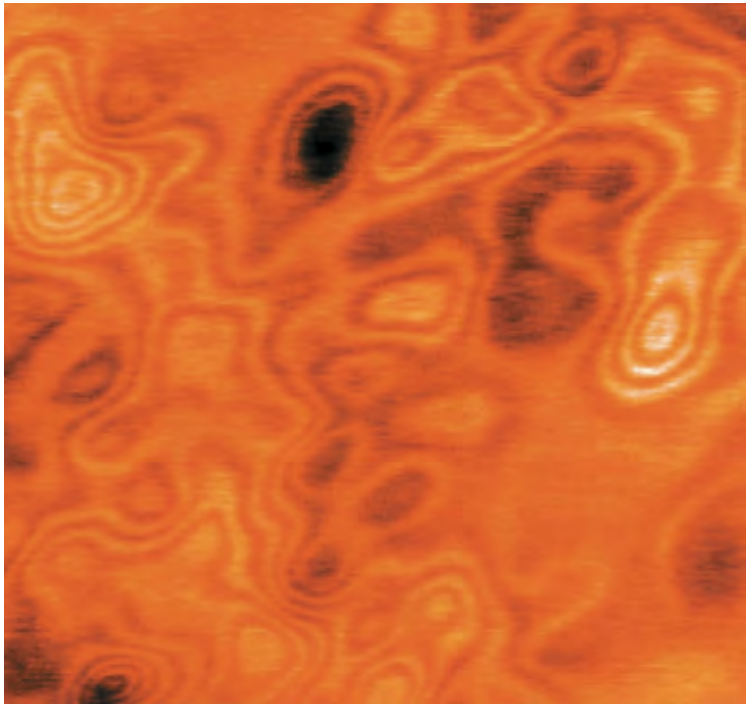
Subsurface Charge Accumulation Technique



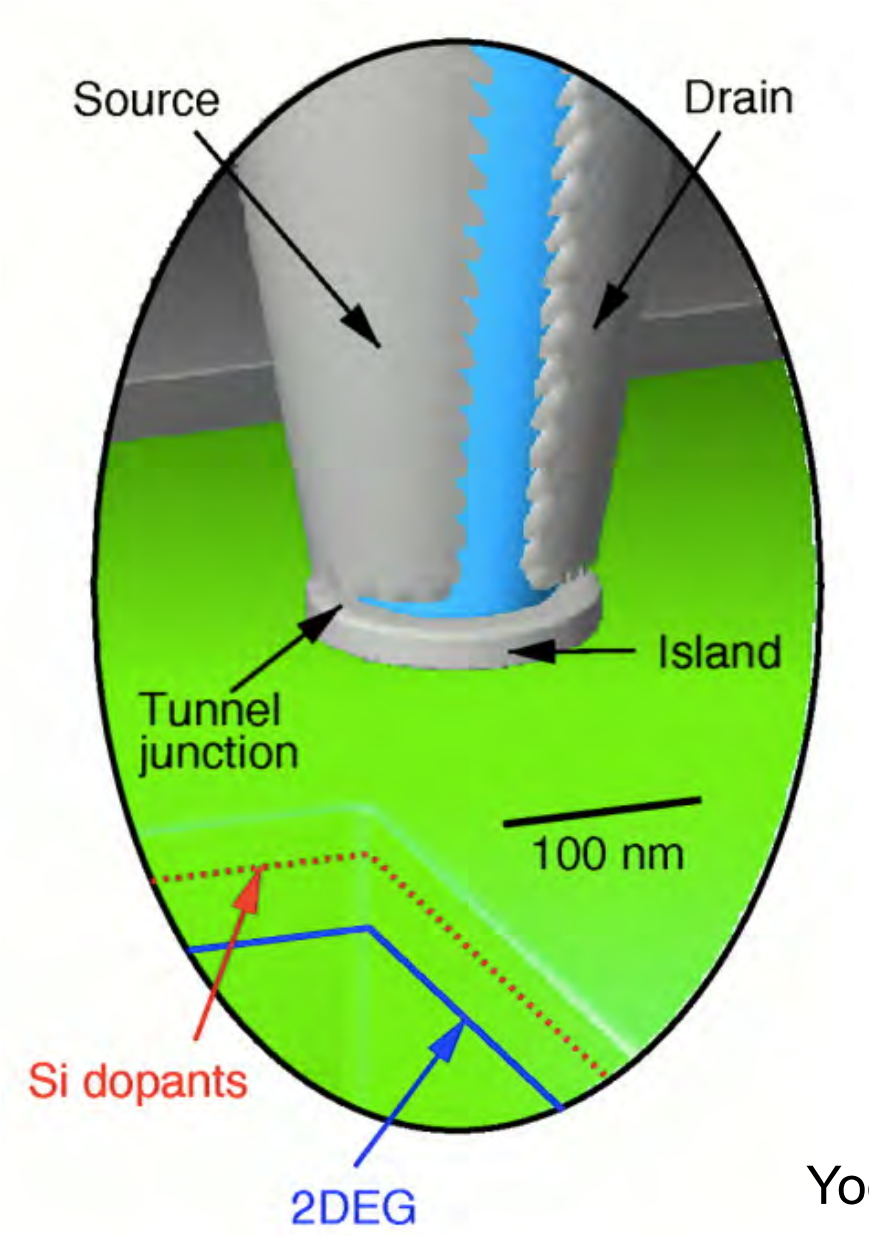
Capacitive imaging technique is based on the image charge induced in the electron gas by a scanned tip.



Subsurface Charge Accumulation image of quantum Hall liquid Landau level filling at low T in B.

Ashoori, Nature (1998); Science (2000).

Imaging Electron Charge with an SET

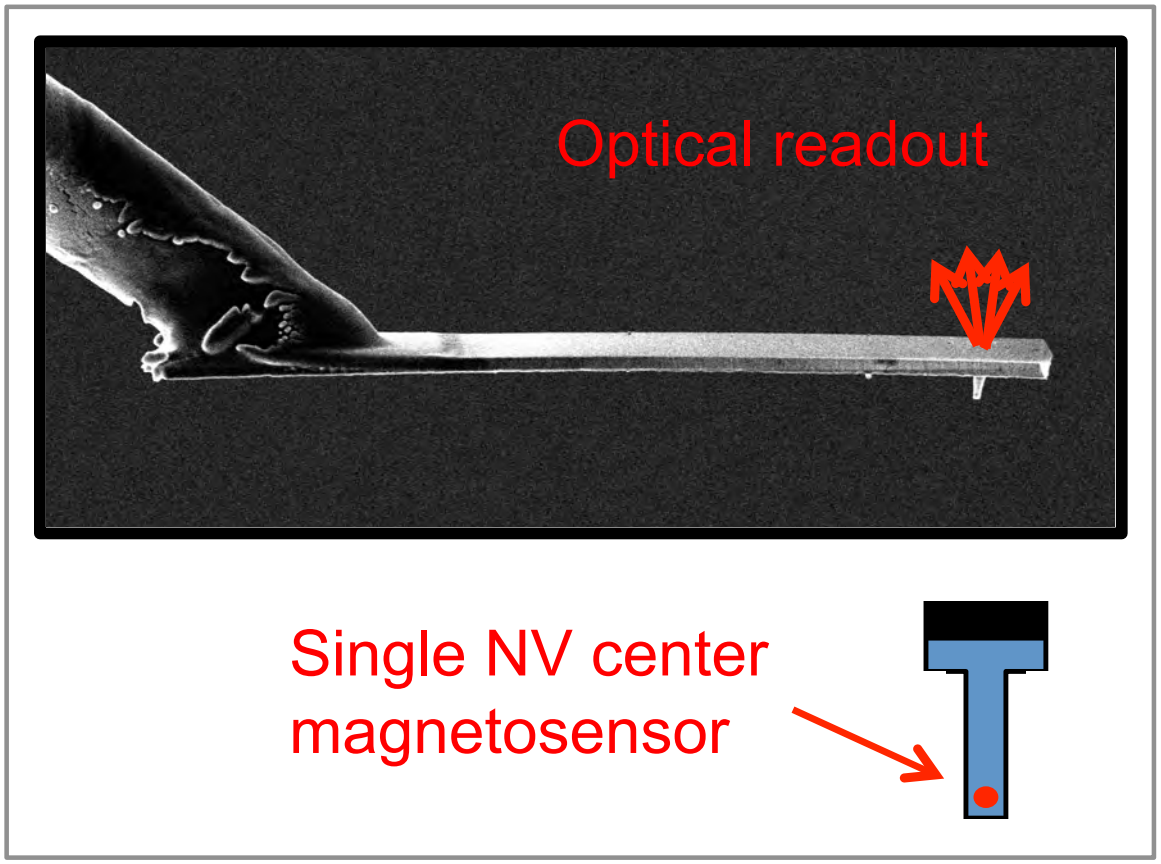


Ultra-sensitive single-electron transistor (SET) is fabricated on the end of an insulating probe via sequential metal evaporations.

The SET can sense a tiny fraction of an electron charge, and maps out the charge density as it is scanned acroos the sample.

Yoo, Fulton, Hess … Science (1997)

Ultrasensitive Scanned Magnetosensor based on a Diamond NV Center



A nitrogen vacancy (NV) center in a diamond nanowire has ultrahigh sensitivity and spatial resolution.

Yacoby, Nature Nano. (2012)

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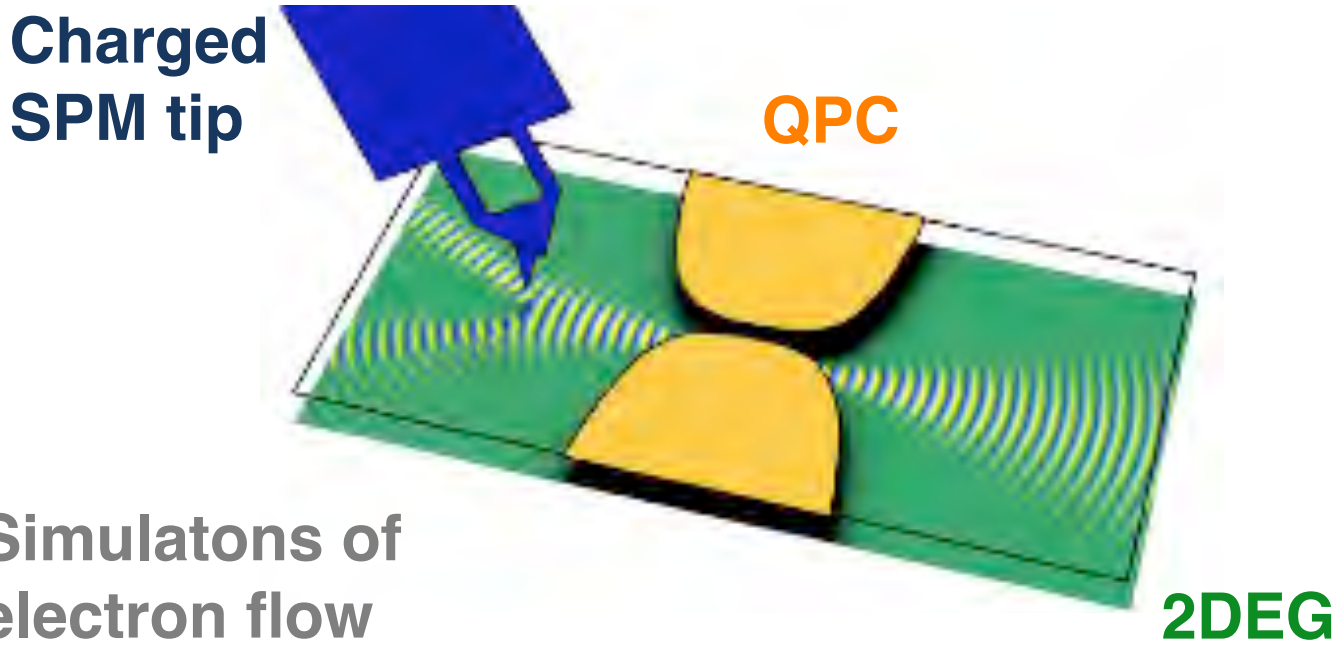
Imaging Electrons in a GaAs/AlGaAs 2DEG

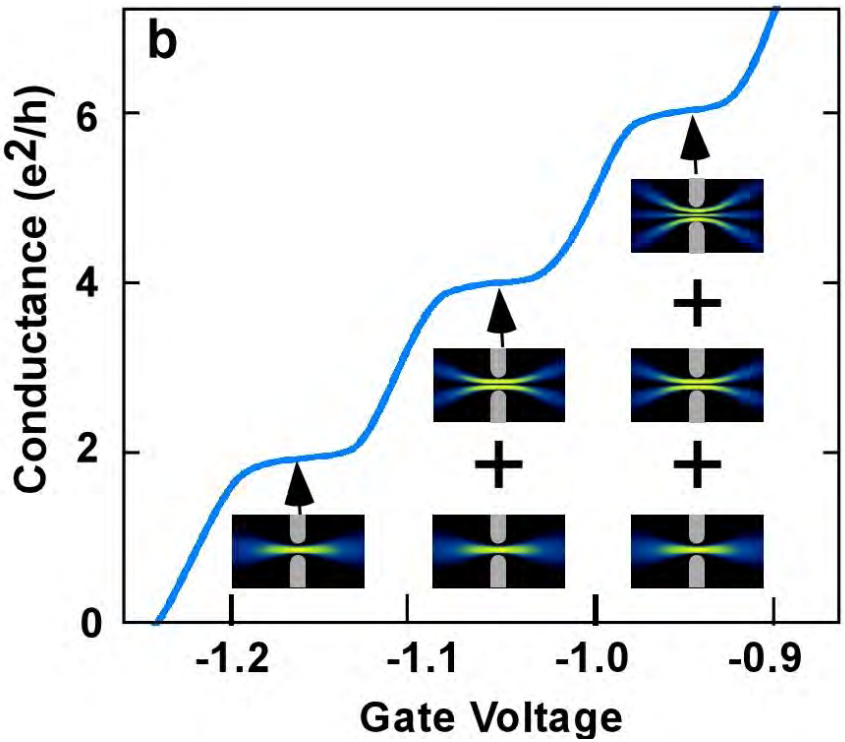


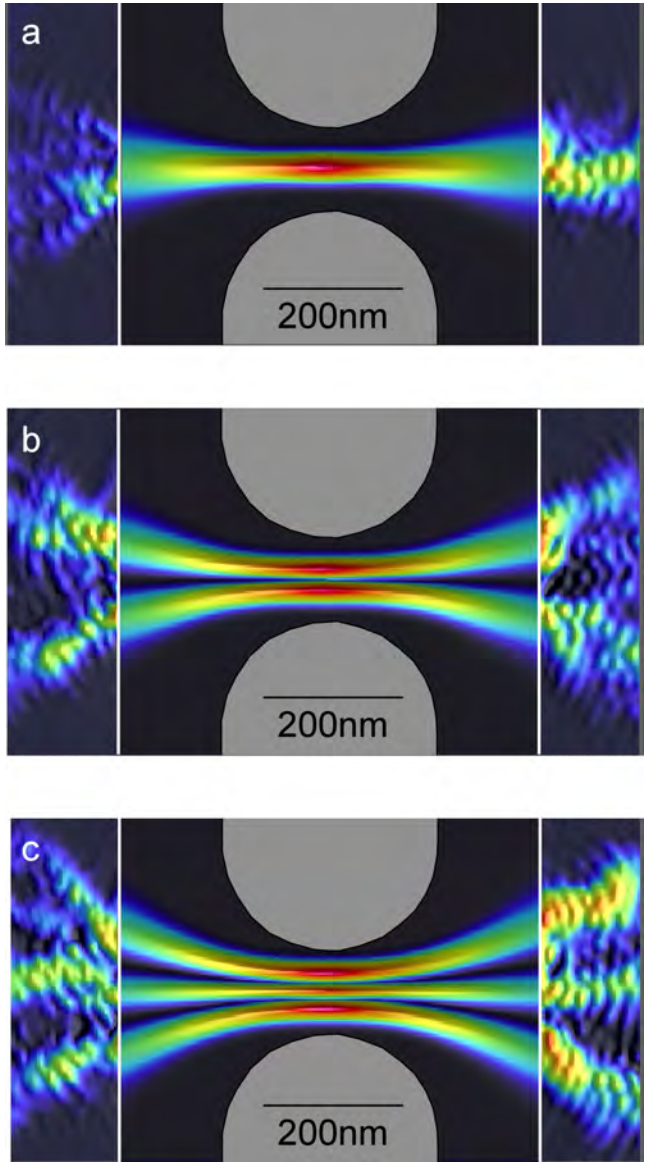
Electron waves flowing from a quantum point contact (QPC) are deflected by a charged SPM tip

Topinka *et al*. Nature **410**, 183 (2001)

Imaging Coherent Flow of Electrons from a Quantum Point Contact

Quantized Conductance Steps





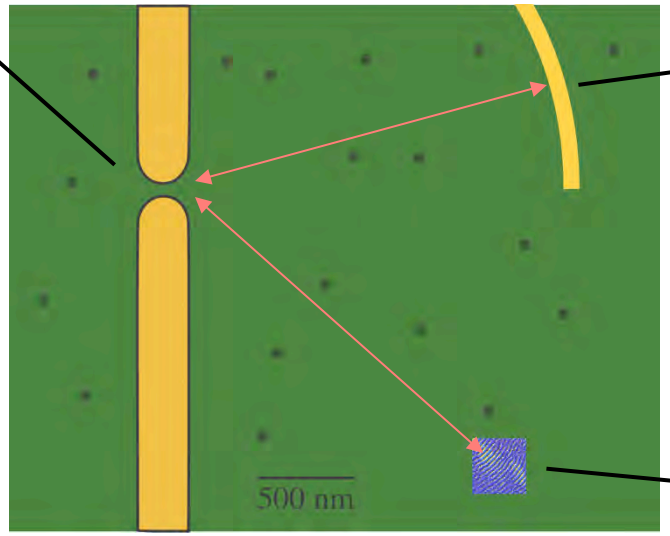
Fringes demonstrate coherence

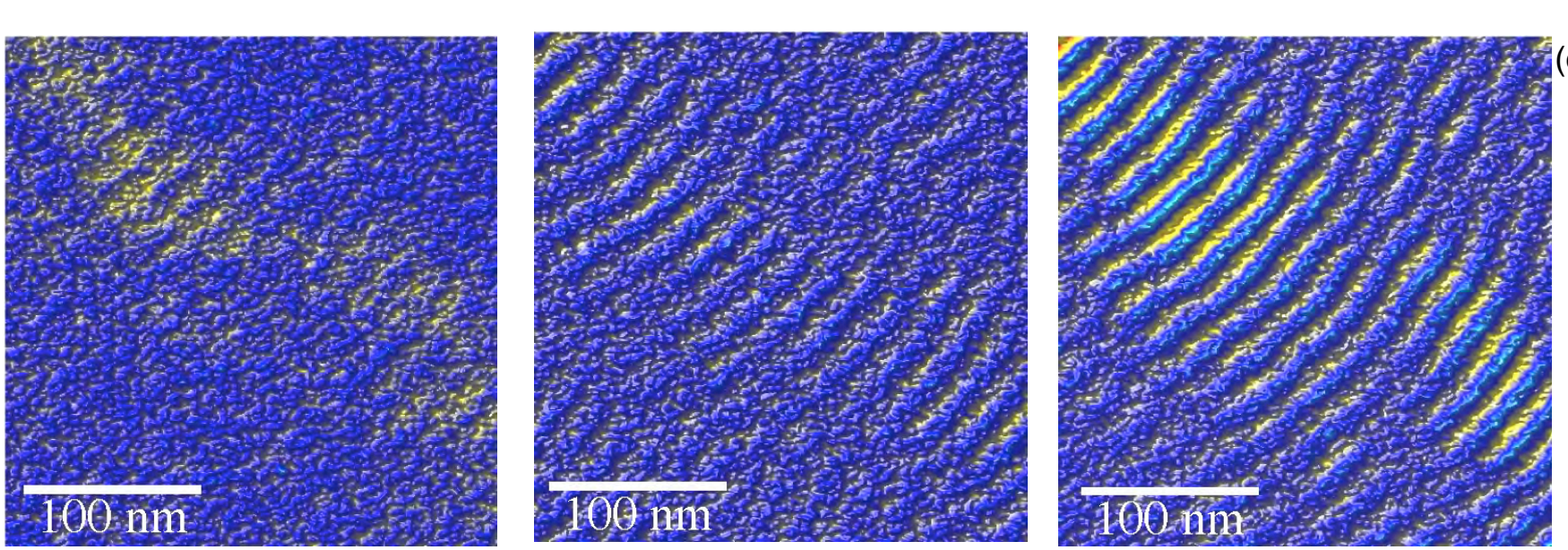
Topinka *et al. Physics Today* **56**, 47 (2003)

Imaging Electron Interferometer

LeRoy *et al* PRL(2005)

Turning on the reflector creates fringes on the other leg of the V-shaped path





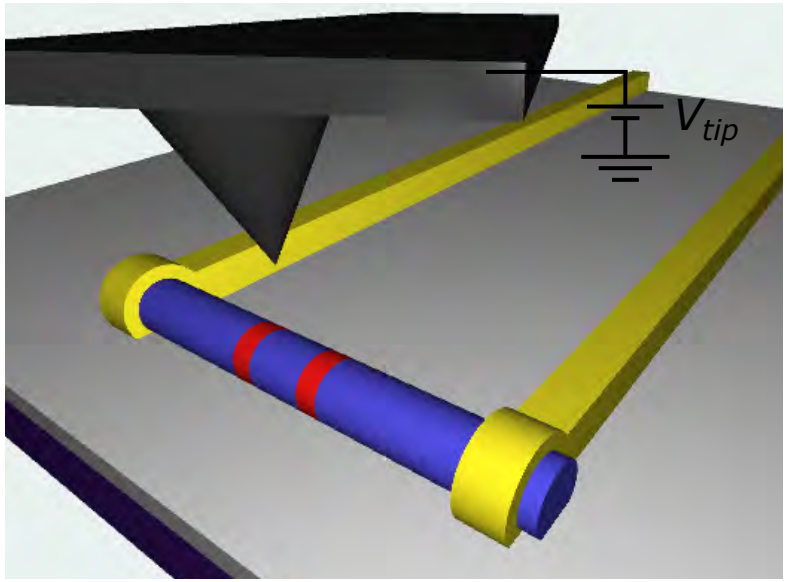
V_{refl} = 0 V V_{refl} = -0.4 V V_{refl} = -0.8 V

Imaging a Quantum Dot in a Nanowire

SPM tip

InAs/InP Nanowire

Conducting substrate

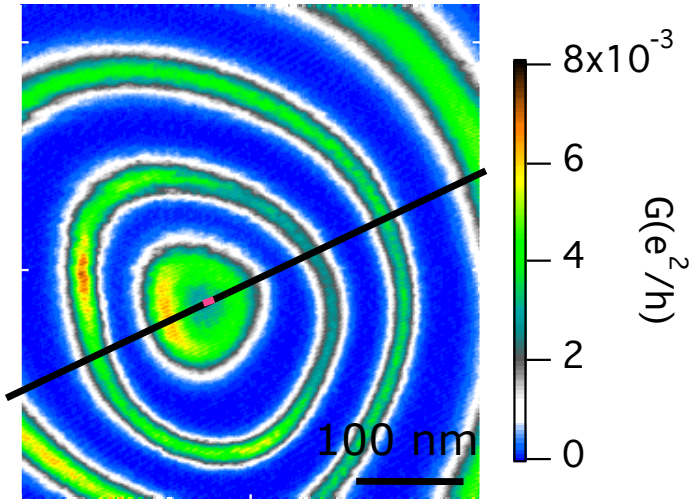


T = 4.2 K

Insulating SiO_2 layer

- Metallized tip is a movable gate
- Display dot conductance vs. r_{tip} for different V_{tip}
- Conductance 'bullseye' locates dot and measures Coulomb blockade conductance

SPM image of InAs/InP nanowire

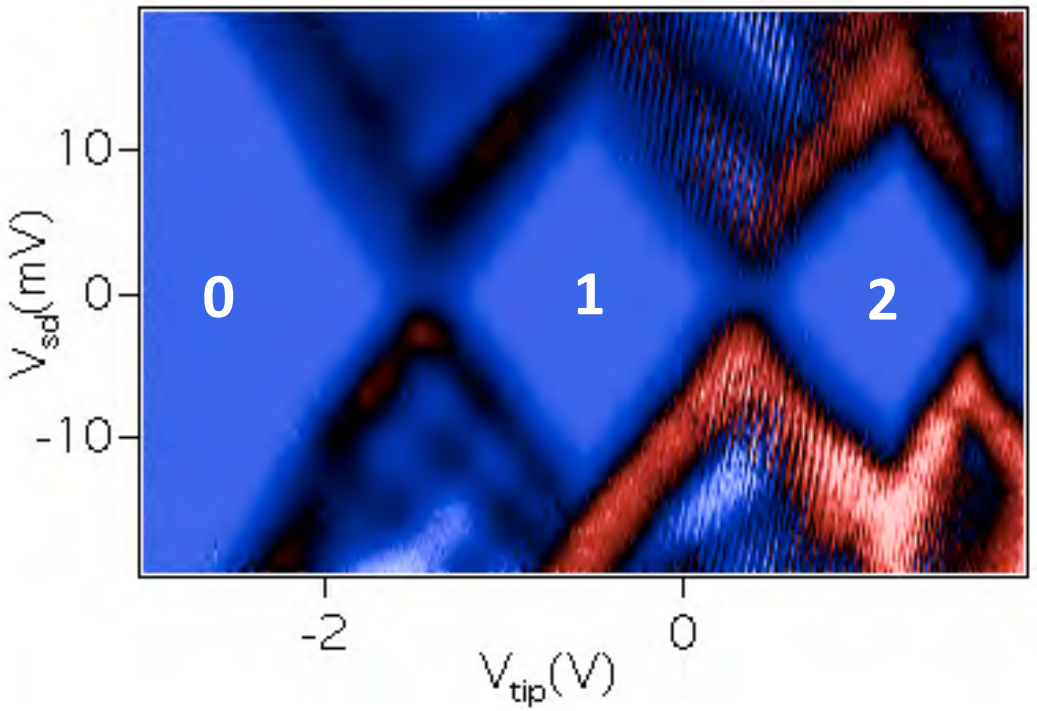


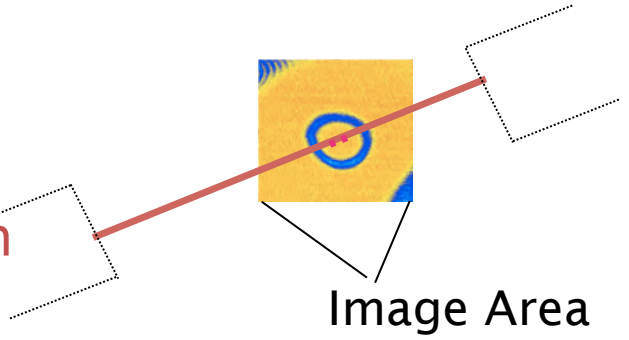
Ania Bleszynski and Linus Fröberg

Imaging the Nanowire Dot's Last Electron

V_{tip} steps from -2.5 V to 1.75 V

100nm

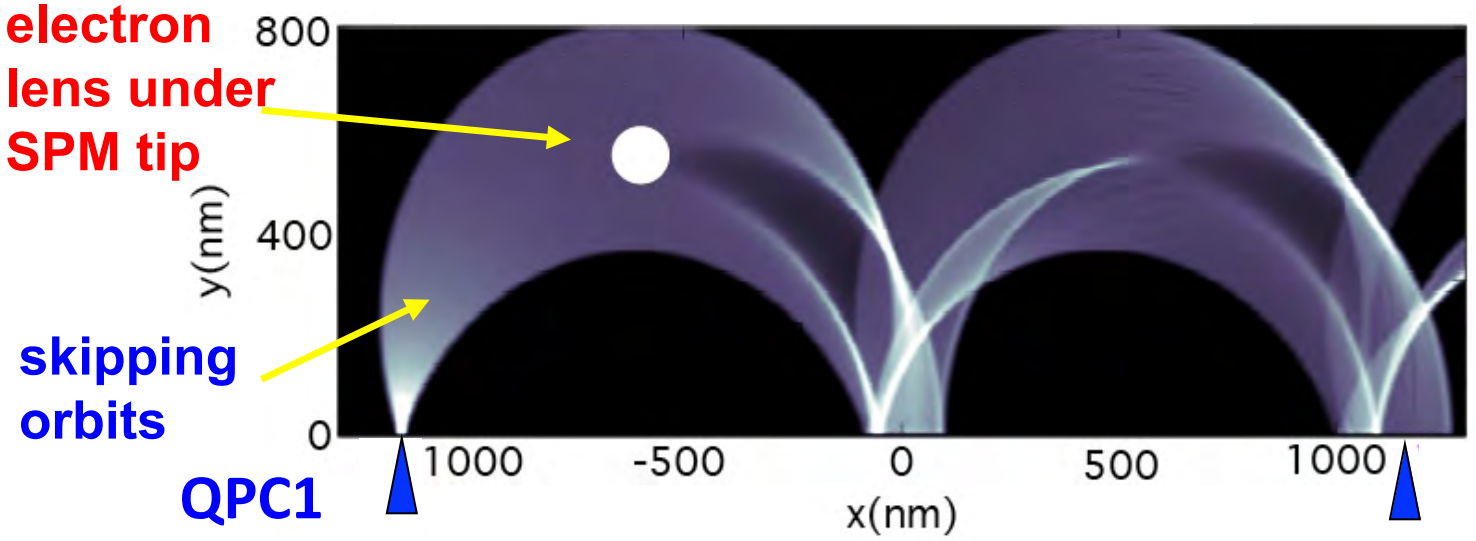




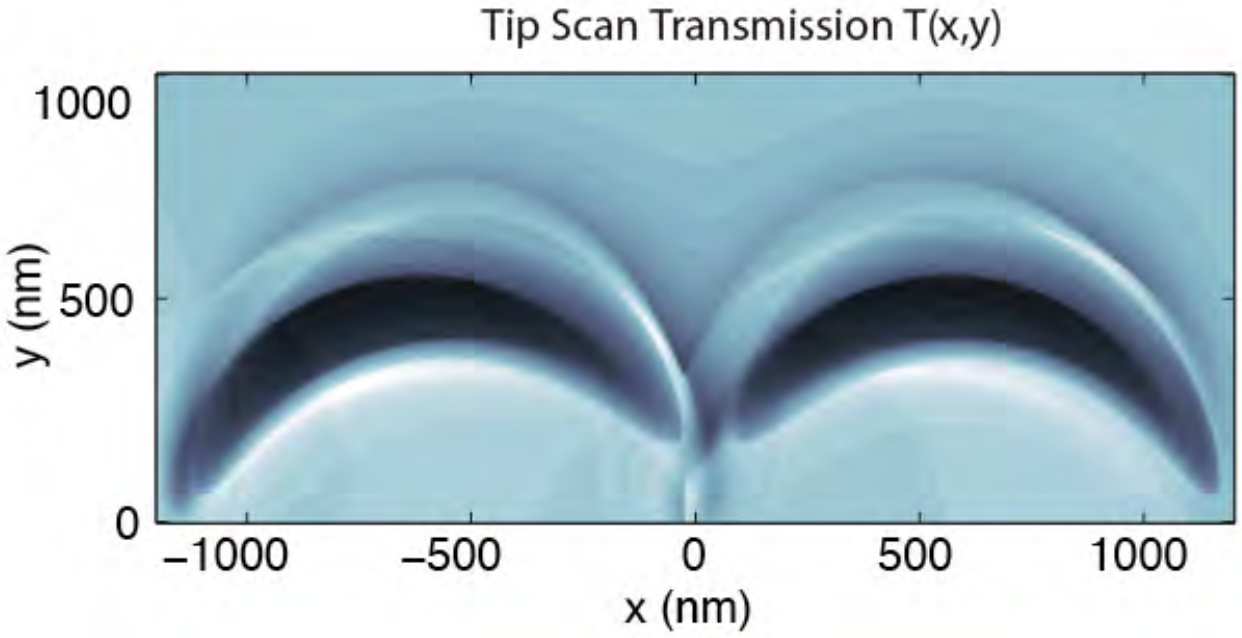
- Rings show addition of 1st and 2nd electron
- Rings shrink as V_{tip} increases

Bleszynski, Fröberg *et al.* (2007)

Image Magnetic Focusing with an SPM Tip



simulated electron trajectories



simulated tip scan transmission

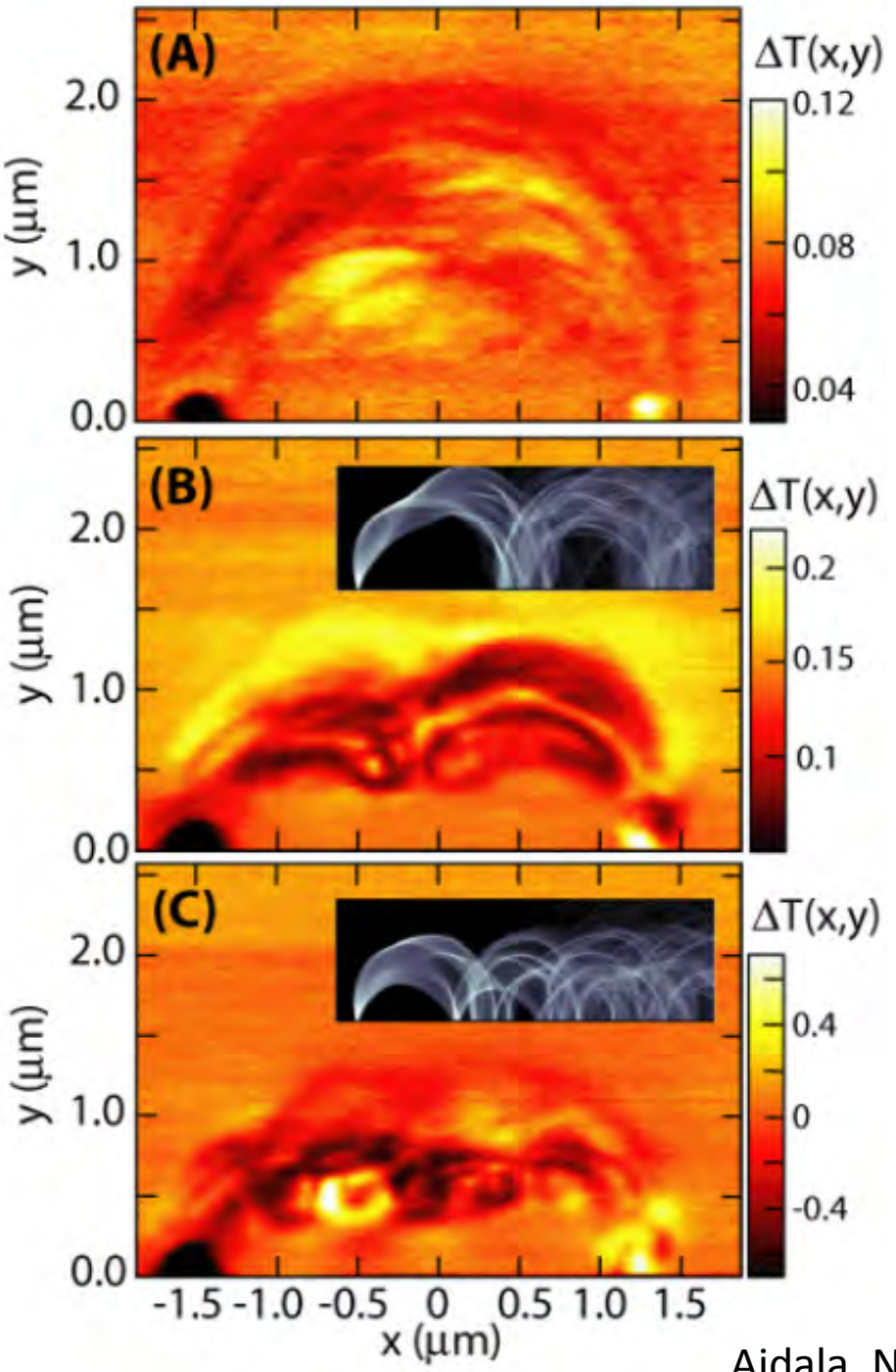
Rob Parrott

SPM Magnetic Focusing Images

1st peak

2nd peak

3rd peak



insets are simulated trajectories

Aidala, Nature Phys **3**, 464 (2007)

Frontiers in Quantum Materials & Devices

Atomic-scale Electronics & Photonics
Spintronics & Quantum Information

Science & Technology Center for Integrated Quantum Materials

Harvard Univ, Howard Univ, MIT, Museum of Science Boston

May 21-22, 2015
Harvard University
Cambridge, MA
ciqm.harvard.edu

National Science Foundation
WHERE DISCOVERIES BEGIN

CIQM CENTER for INTEGRATED QUANTUM MATERIALS

Speakers

David Bell (Harvard)
Marija Drndic (Univ Pennsylvania)
Donhee Ham (Harvard)
Yoshiro Hiroyama (Tohoku Univ)
Jennifer Hoffman (Harvard)
James Hone (Columbia)
Hiroyuki Isobe (Tohoku Univ)
Andras Kis (EPF Lausanne)
Jelena Klinovaja (Univ Basel)
Motoku Kotani (Tohoku Univ)
Marko Loncar (Harvard)
Hideo Ohno (Tohoku Univ)
Tomas Palacios (MIT)
Eiji Saitoh (Tohoku Univ)
Yoshinori Tokura (Univ Tokyo)
Tim Taminiau (Delft Univ Tech)
Daniel Twitchen (Element Six)
Qi-Kun Xue (Tsinghua Univ)
Amir Yacoby (Harvard Univ)