Oxide Nanoelectronics:
A New Platform for Developing Quantum Information Technology

Jeremy Levy, Univ. Pittsburgh

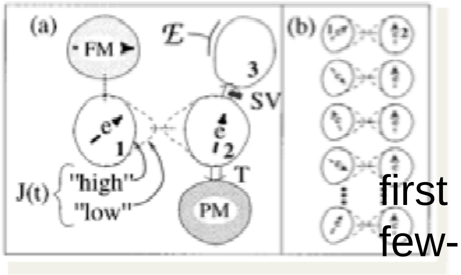
December 9, 2009

KITP Quantum Information Science

Timeline for spin qubits

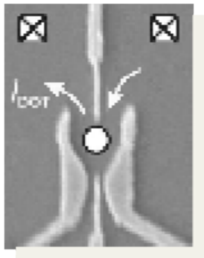
1998

Loss-DiVincenzo proposal



2000

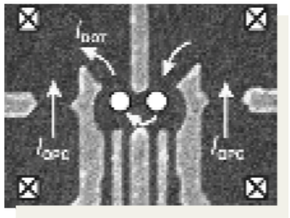
first
few-electron
lateral dot



Ciorga, et al.

2003

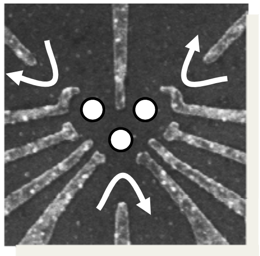
first
few-electron
double dot



Elzerman, et al.

few-electron
triple dot

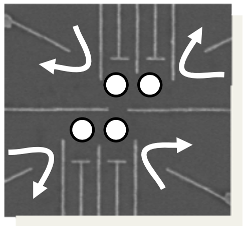
2009



Laird, Folleti, et al.

2010

few-electron
double
double dot



Laird, et al.

PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

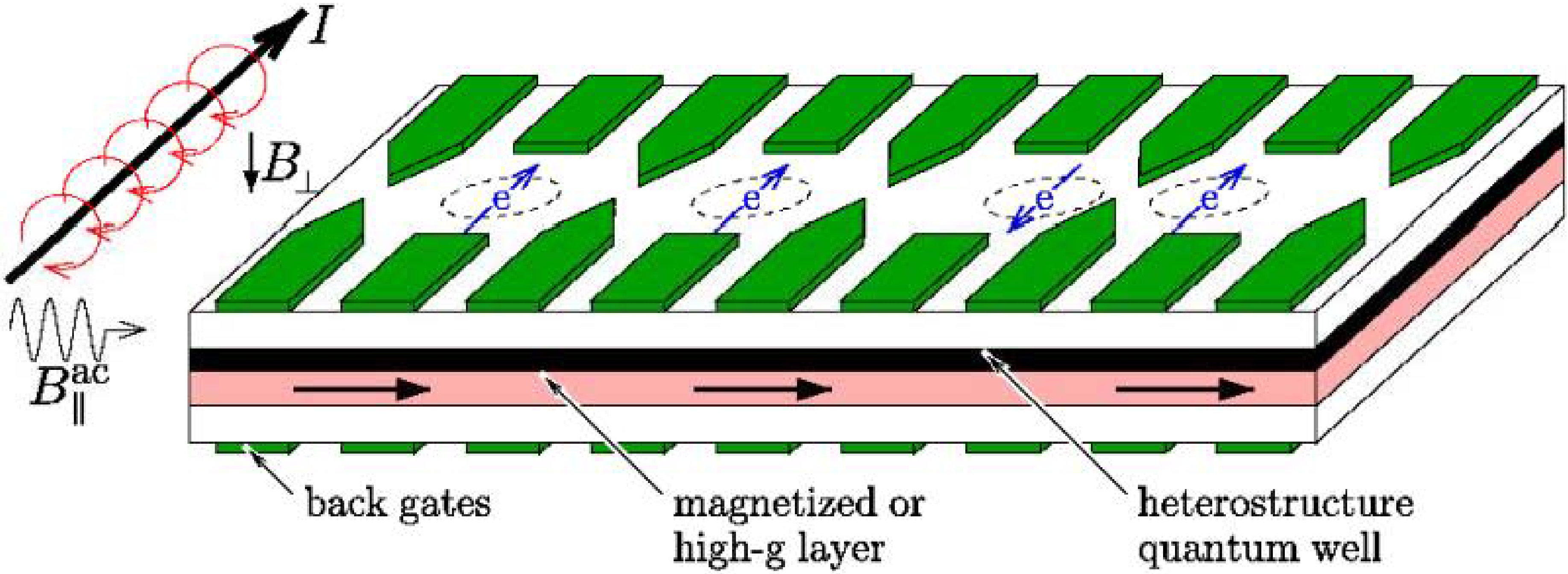
Quantum computation with quantum dots

Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]
[1]Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106-4030
[2]Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland
[3]IBM Research Division, T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598

(Received 9 January 1997; revised manuscript received 22 July 1997)

We propose an implementation of a universal set of one- and two-quantum-bit gates for quantum computation using the spin states of coupled single-electron quantum dots. Desired operations are effected by the gating of the tunneling barrier between neighboring dots. Several measures of the gate quality are computed within a recently derived spin master equation incorporating decoherence caused by a prototypical magnetic environment. Dot-array experiments that would provide an initial demonstration of the desired nonequilibrium spin dynamics are proposed. [S1050-2947(98)04501-6]

PACS number(s): 03.67.Lx, 89.70.+c, 75.10.Jm, 89.80.+h

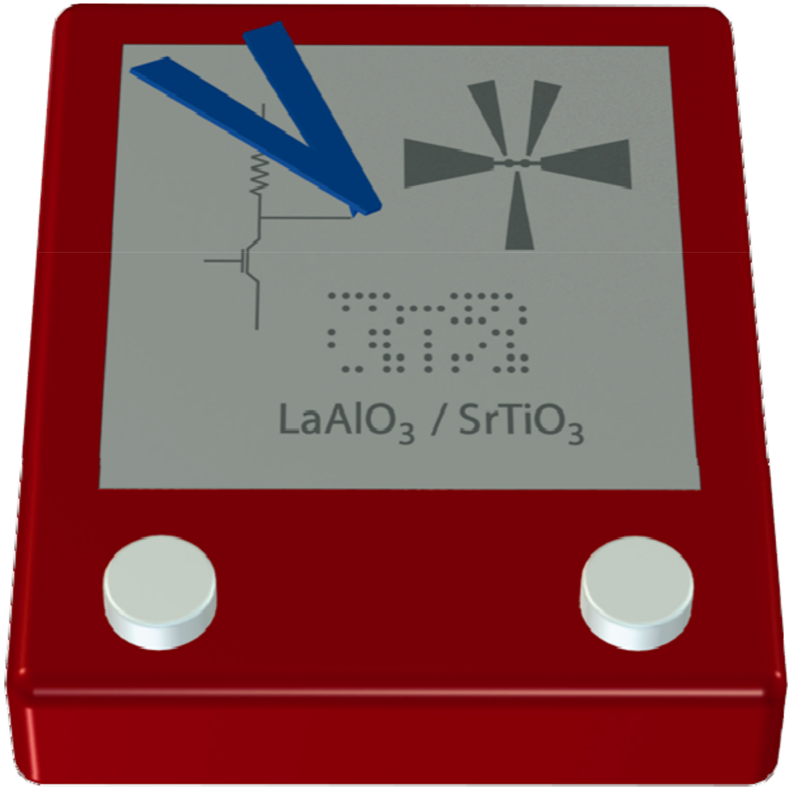


OXIDE NANOELECTRONICS

Jeremy Levy
University of Pittsburgh

qinfo2009
KITP

9 December 2009



Support:

Acknowledgements

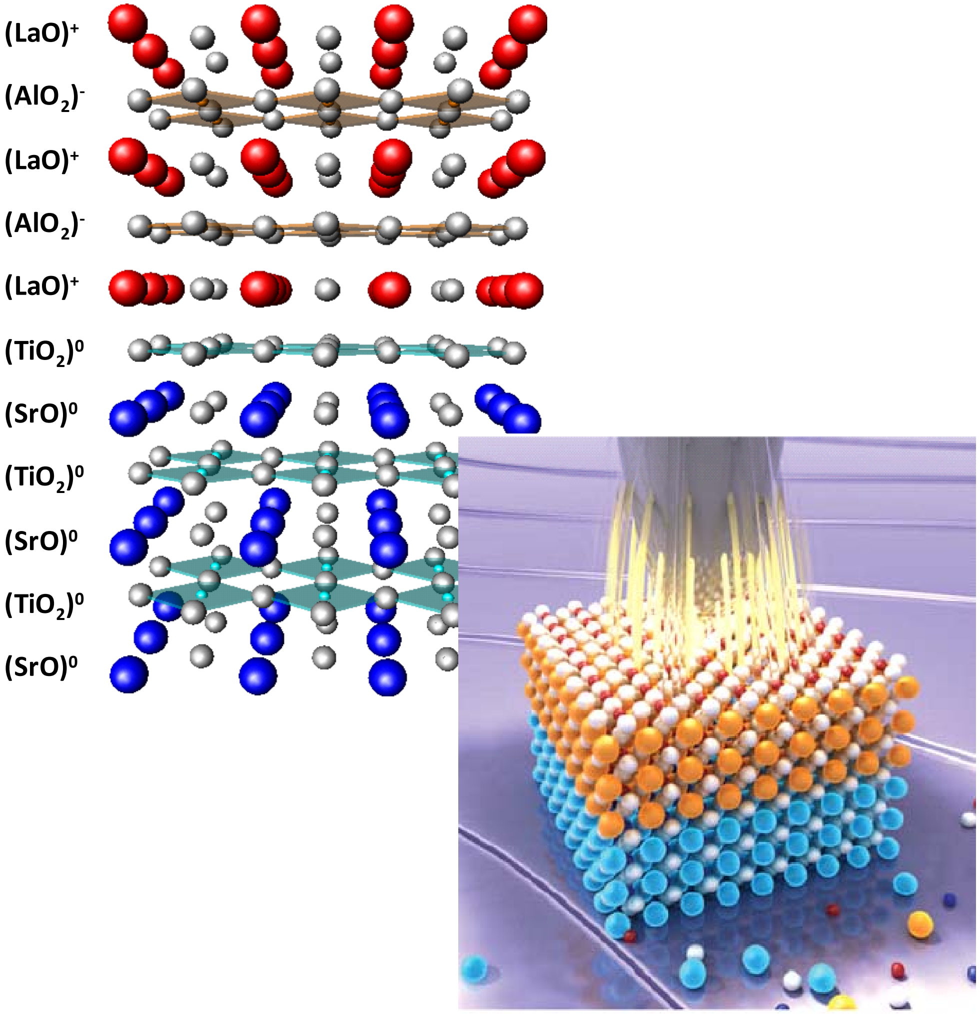
Cheng Cen Daniela F. Bogorin Shan Hu		U. Pittsburgh
Jochen Mannhart Stefan Thiel Christof W. Schneider		U. Augsburg
Jae-Wan Park Chang-Beom Eom		U. Wisconsin
Kris Andersen		Northern Arizona U.
C. Stephen Hellberg		NRL

Support:

Emergent Phenomena at Oxide Interfaces

- High-mobility 2DEG
  - Ohtomo and Hwang, Nature (2004)
- Metal-insulator transition
  - Thiel et al, *Science* (2006)
- Superconductivity
  - Reyren et al, *Science* (2007); Caviglia, *Nature* (2008)
- Magnetism
  - Brinkman et al, *Nature Materials* (2007)
- Nanostructures
  - Cen et al, Nature Materials (2008)
- Nanodevices
  - Cen et al, Science (2009)

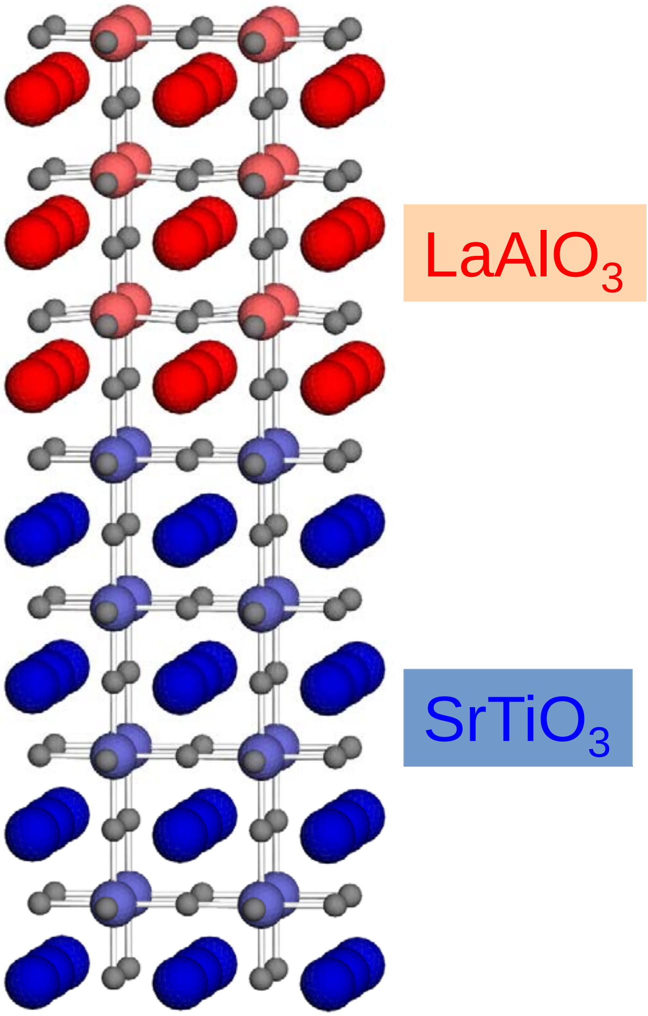
$LaAlO_3/SrTiO_3$

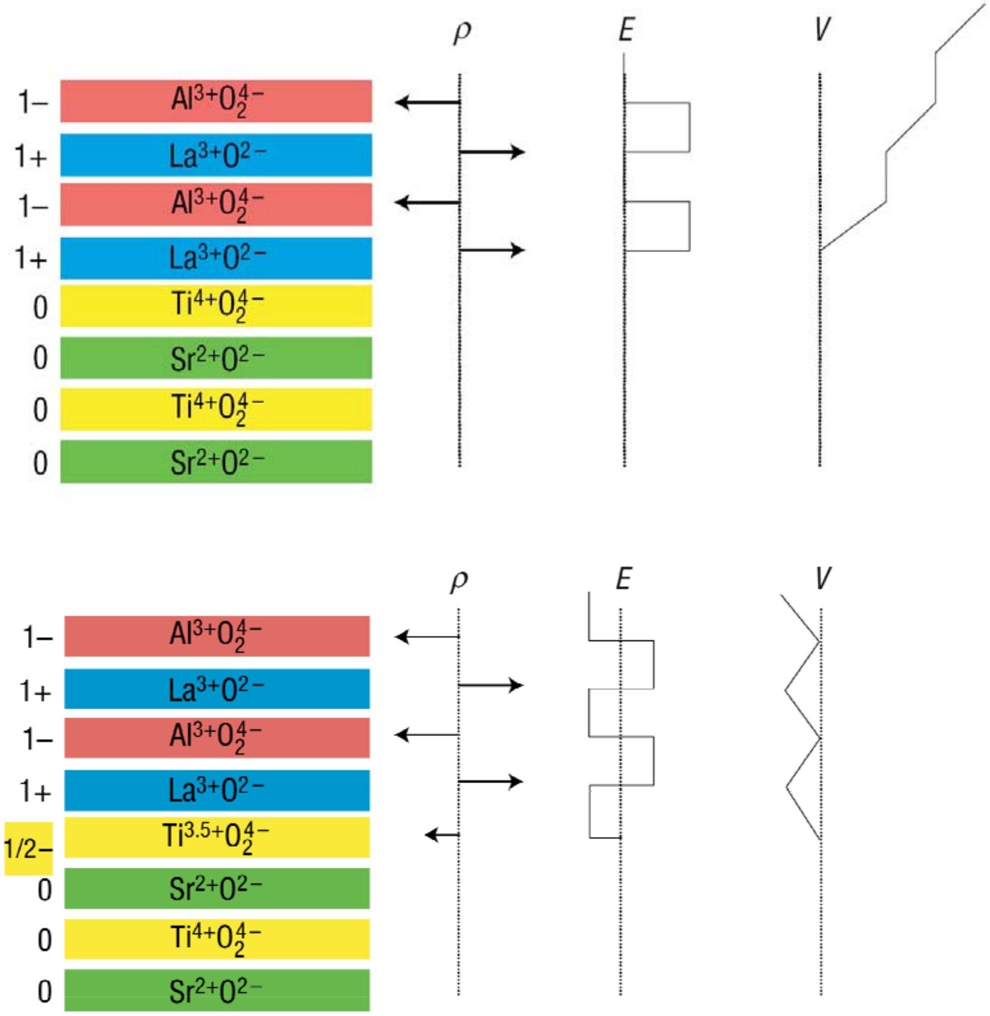


"The complexities of the crystal structure, lattice waves, band structure, transport properties, impurity electrons and superconductivity have inspired the comment: 'If SrTiO3 had magnetic properties, a complete study of this material would require a thorough knowledge of all of solid state physics.' "

Marvin L. Cohen, in *Superconductivity* vol. 1, Robert Parks, Ed. (New York, 1969).

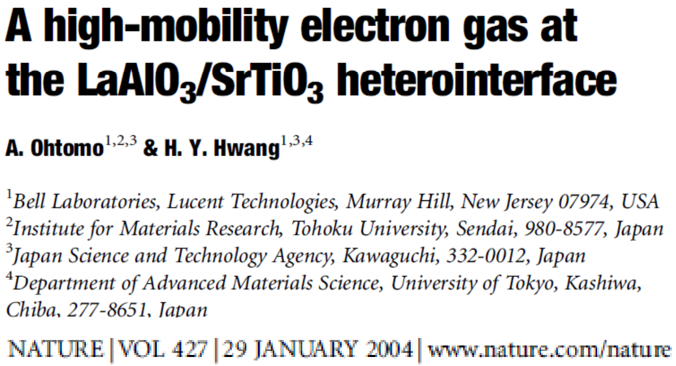
Polar Discontinuity: $LaAlO_3$ / $SrTiO_3$





Nakagawa, Hwang, and Muller, *Nature Materials* **5**, 204 (2006)

High-Mobility 2DEGs at Oxide Interfaces

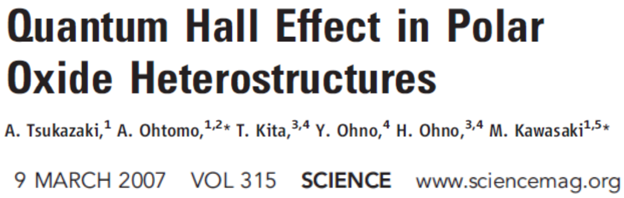


A high-mobility electron gas at the $LaAlO_3/SrTiO_3$ heterointerface

A. Ohtomo[1,2,3] **& H. Y. Hwang**[1,3,4]

[1] *Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA*
[2] *Institute for Materials Research, Tohoku University, Sendai, 980-8577, Japan*
[3] *Japan Science and Technology Agency, Kawaguchi, 332-0012, Japan*
[4] *Department of Advanced Materials Science, University of Tokyo, Kashiwa, Chiba, 277-8651, Japan*

NATURE | VOL 427 | 29 JANUARY 2004 | www.nature.com/nature

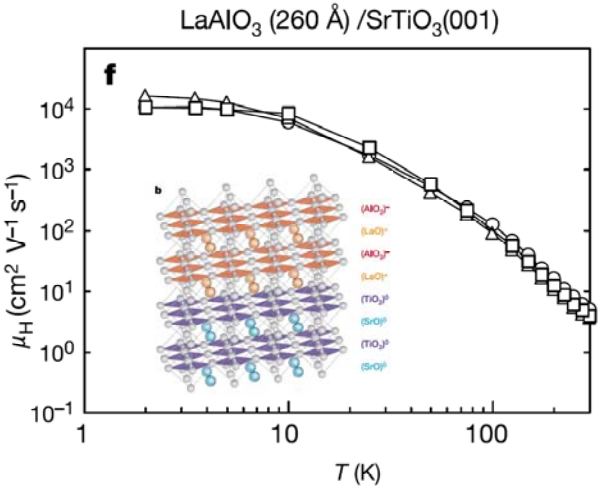


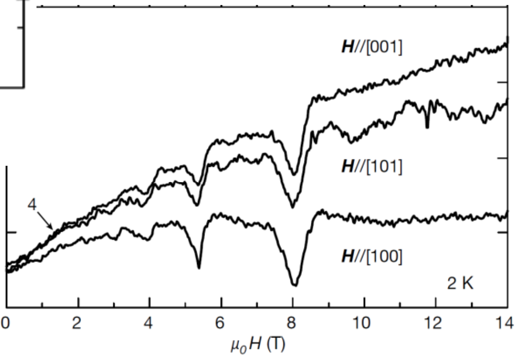
Quantum Hall Effect in Polar Oxide Heterostructures

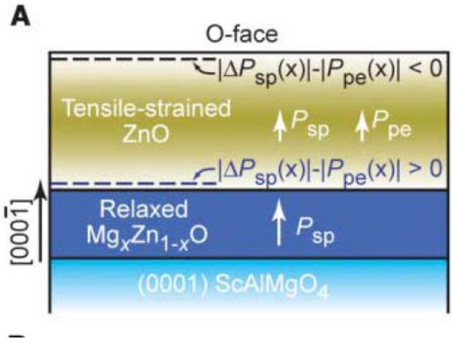
A. Tsukazaki,[1] A. Ohtomo,[1,2]* T. Kita,[3,4] Y. Ohno,[4] H. Ohno,[3,4] M. Kawasaki[1,5]*

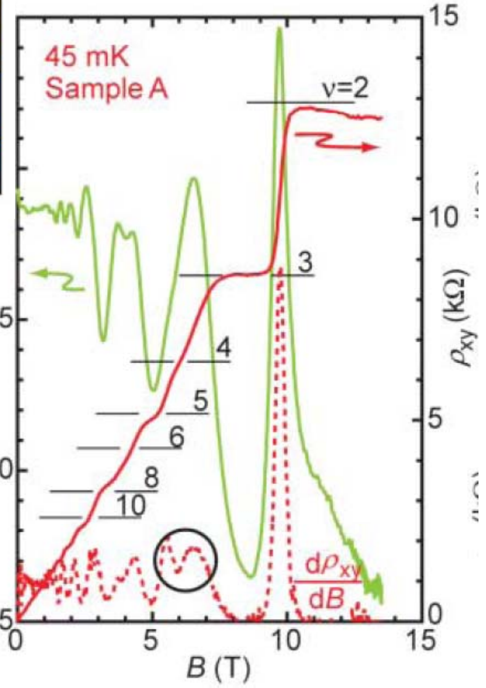
9 MARCH 2007 VOL 315 **SCIENCE** www.sciencemag.org

$\mu_H \sim 5000\ cm^2/Vs$



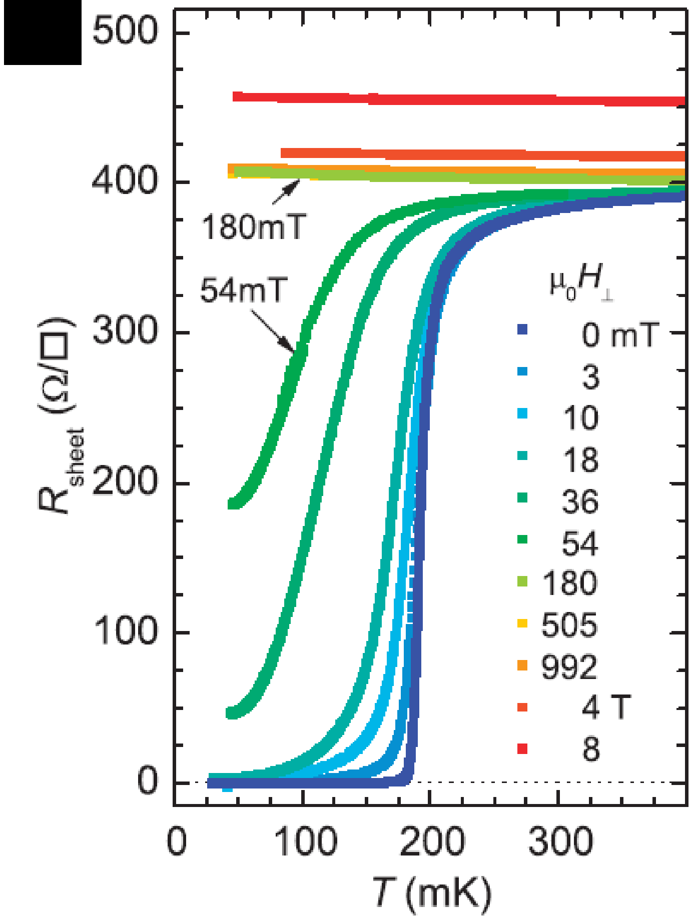




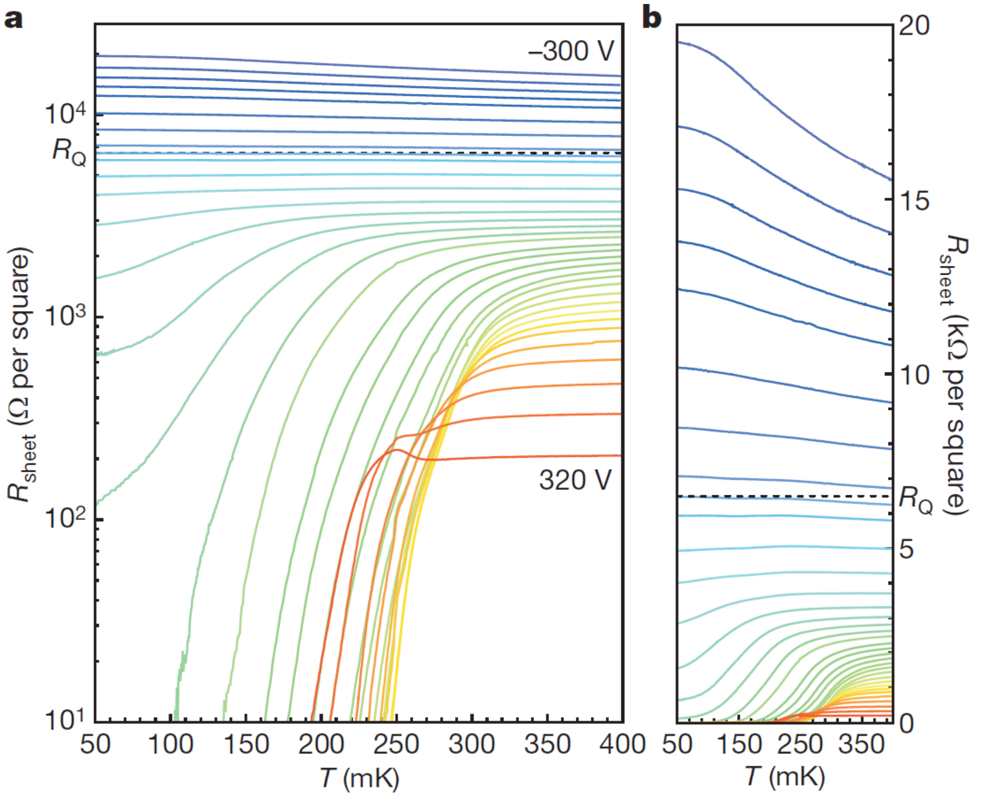


Superconductivity at the $LaAlO_3/SrTiO_3$ Interface

[redacted]



Superconducting Interfaces Between Insulating Oxides
N. Reyren, *et al.*
Science **317**, 1196 (2007);
DOI: 10.1126/science.1146006



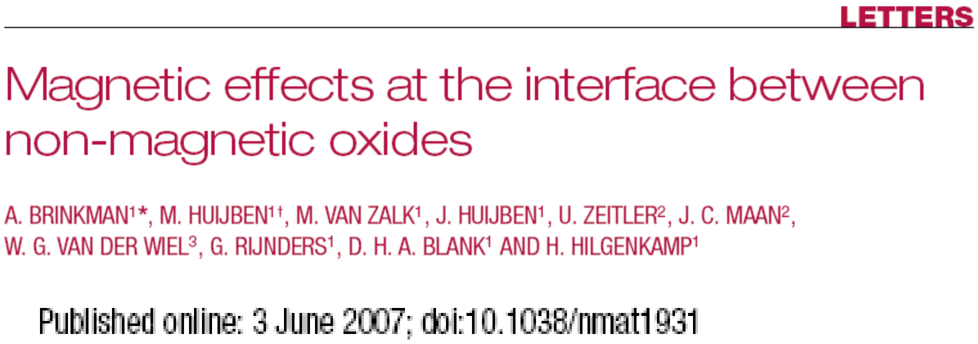
LETTERS

nature Vol 456 | 4 December 2008 | doi:10.1038/nature07576

Electric field control of the $LaAlO_3/SrTiO_3$ interface ground state

A. D. Caviglia[1], S. Gariglio[1], N. Reyren[1], D. Jaccard[1], T. Schneider[2], M. Gabay[3], S. Thiel[4], G. Hammerl[4], J. Mannhart[4] & J.-M. Triscone[1]

Magnetism at the $LaAlO_3/SrTiO_3$ Interface



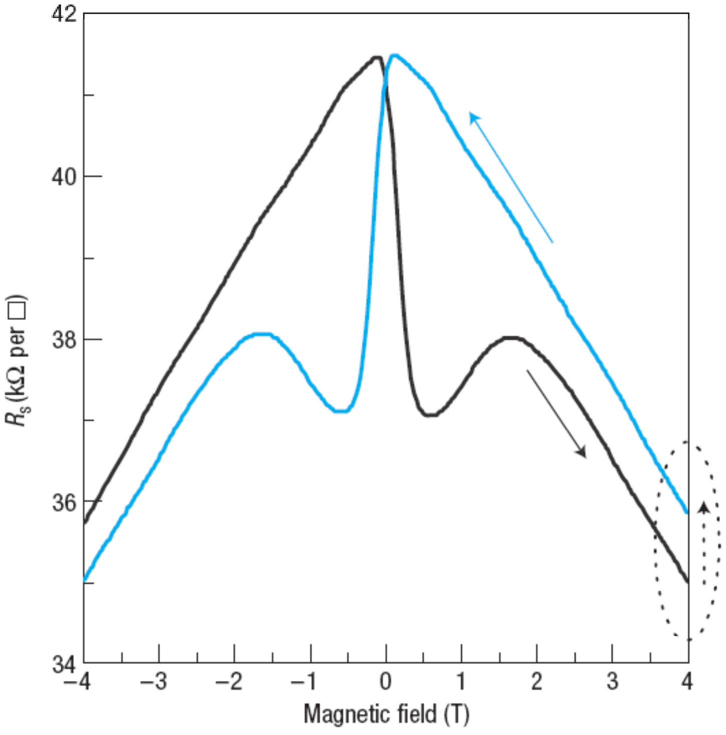
LETTERS

Magnetic effects at the interface between non-magnetic oxides

A. BRINKMAN[1]*, M. HUIJBEN[1†], M. VAN ZALK[1], J. HUIJBEN[1], U. ZEITLER[2], J. C. MAAN[2], W. G. VAN DER WIEL[3], G. RIJNDERS[1], D. H. A. BLANK[1] AND H. HILGENKAMP[1]

Published online: 3 June 2007; doi:10.1038/nmat1931

- Magnetoresistance independent of field direction
- Long time scale (~10 sec)



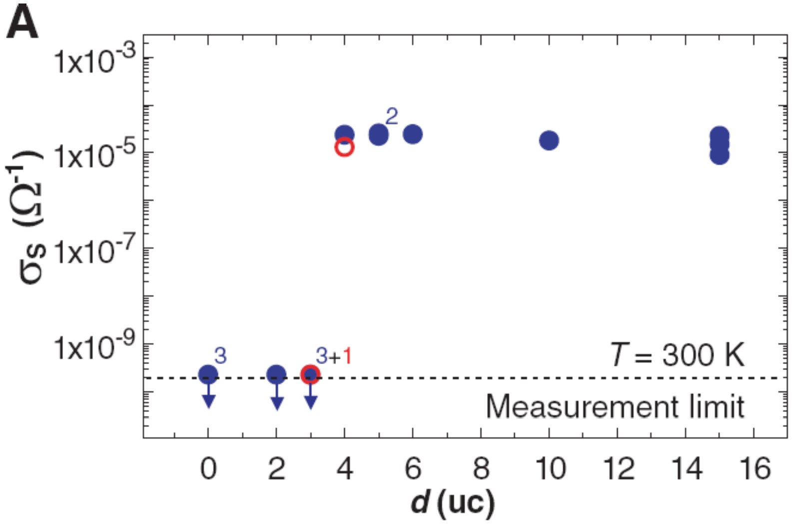
Metal-Insulator Transition

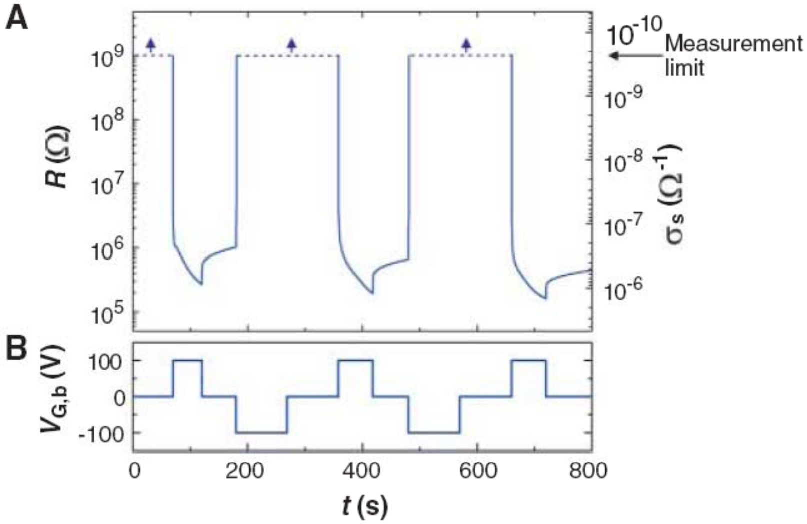
Tunable Quasi–Two-Dimensional Electron Gases in Oxide Heterostructures

S. Thiel,[1] G. Hammerl,[1] A. Schmehl,[2] C. W. Schneider,[1] J. Mannhart[1]*

29 SEPTEMBER 2006 VOL 313 **SCIENCE** www.sciencemag.org

- Electric-field driven phase transition
- Voltage applied across $SrTiO_3$ substrate
- Critical thickness
    - – ~ 3 unit cells $LaAlO_3$



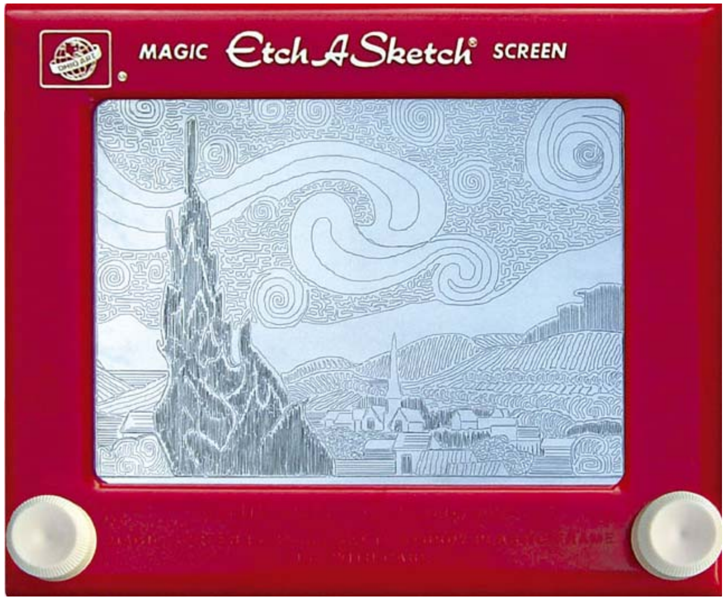


$LaAlO_3/SrTiO_3$

Etch-a-Sketch Nanoelectronics

Toy

(a)

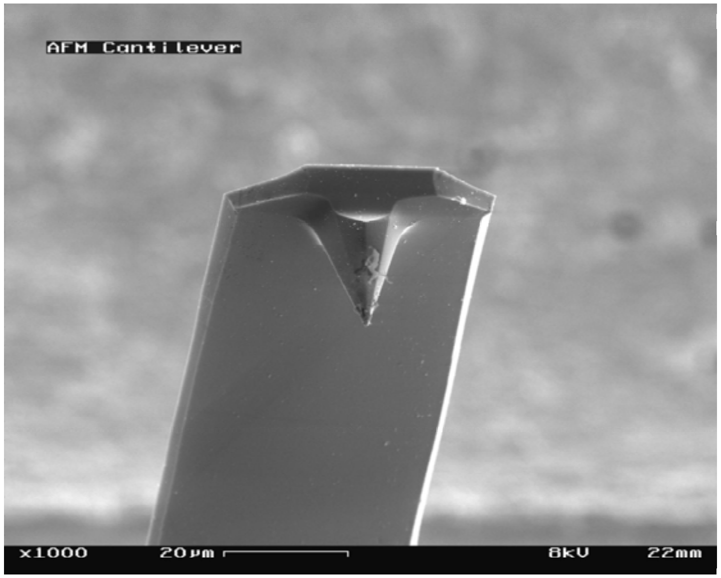


(b)

Tool

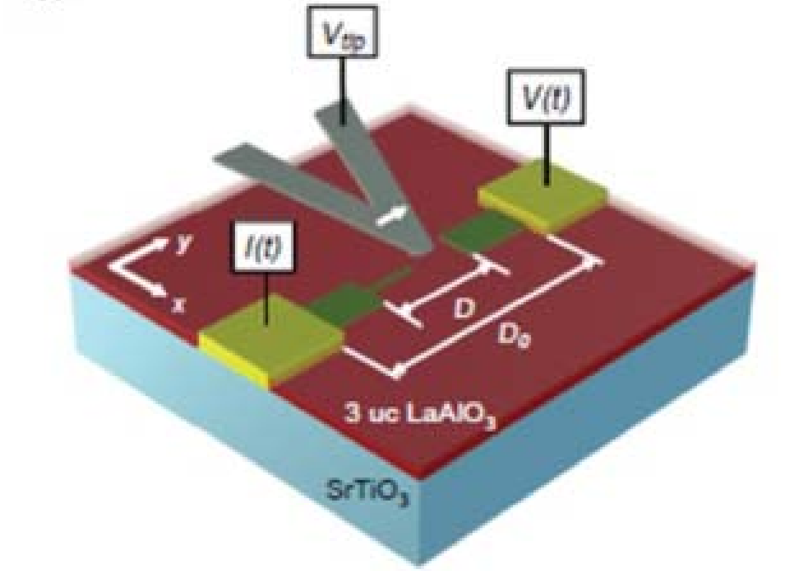
(c)

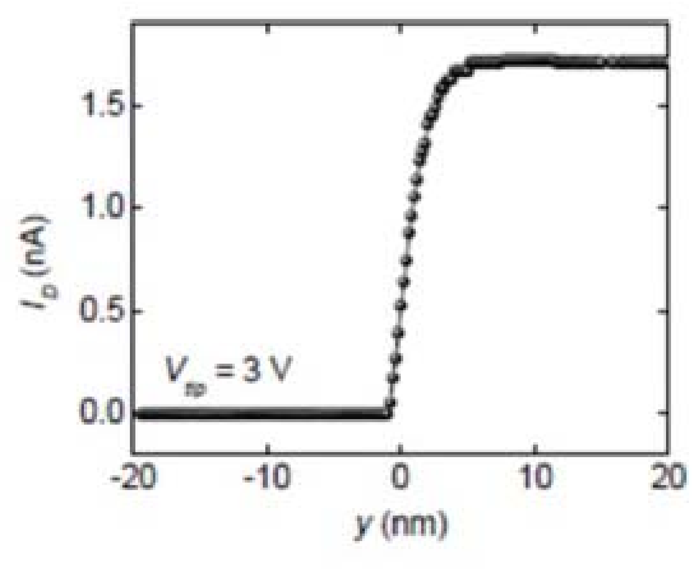
(d)



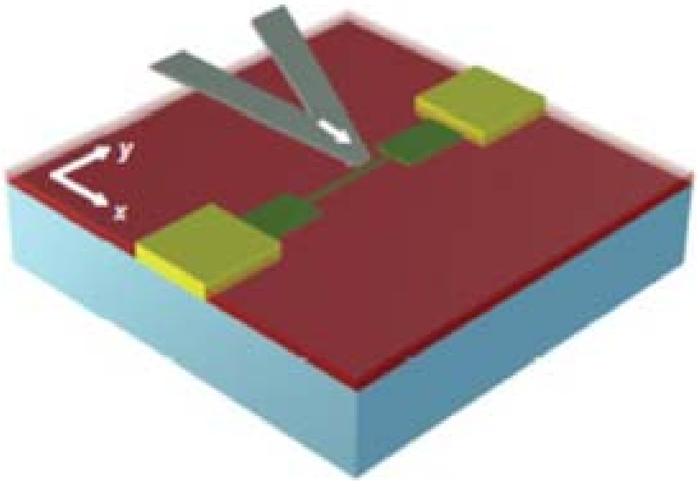
Conducting AFM Lithography of $LaAlO_3/SrTiO_3$

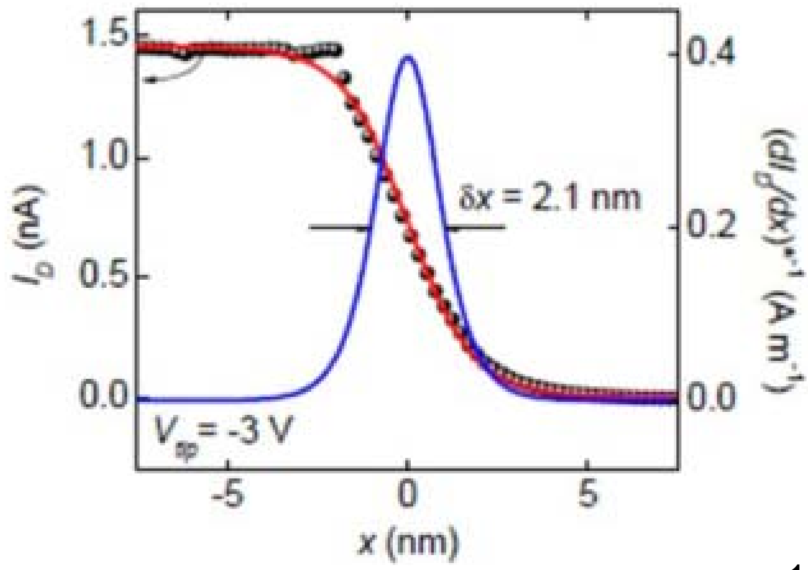
Writing





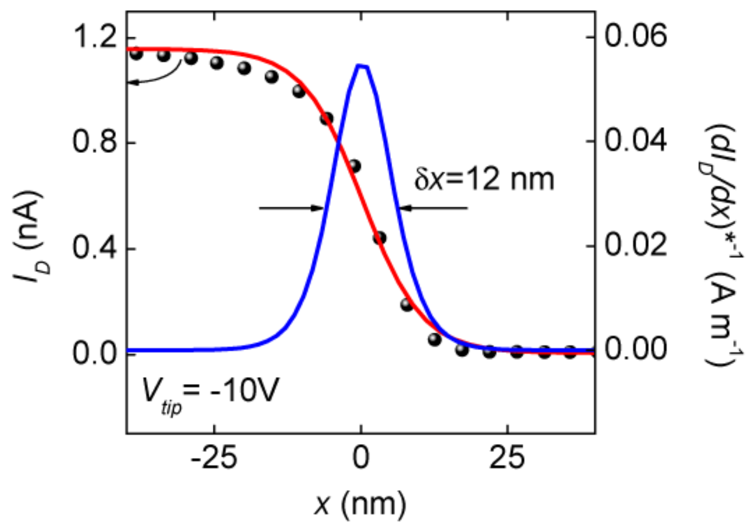
Erasing





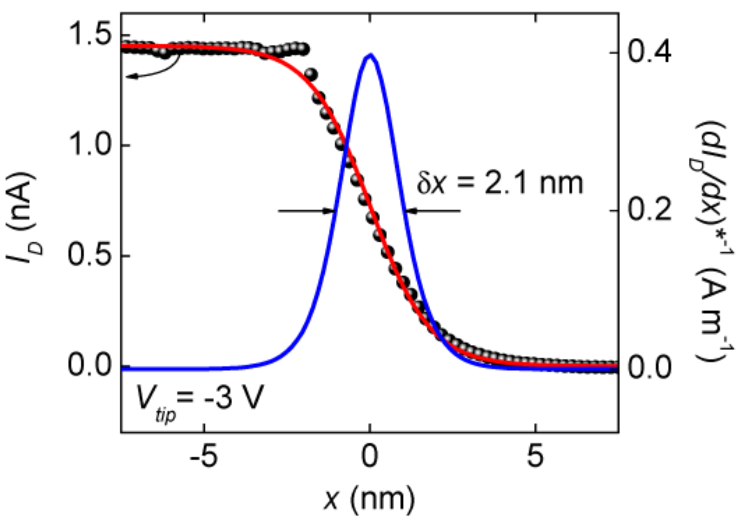
Ultranarrow Wires

V_{tip}=+10 V



12 nm

V_{tip}=+3 V

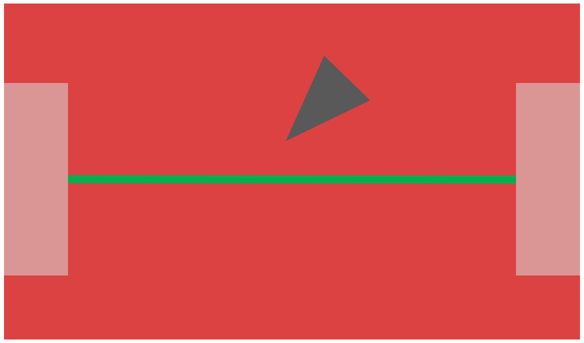


2 nm

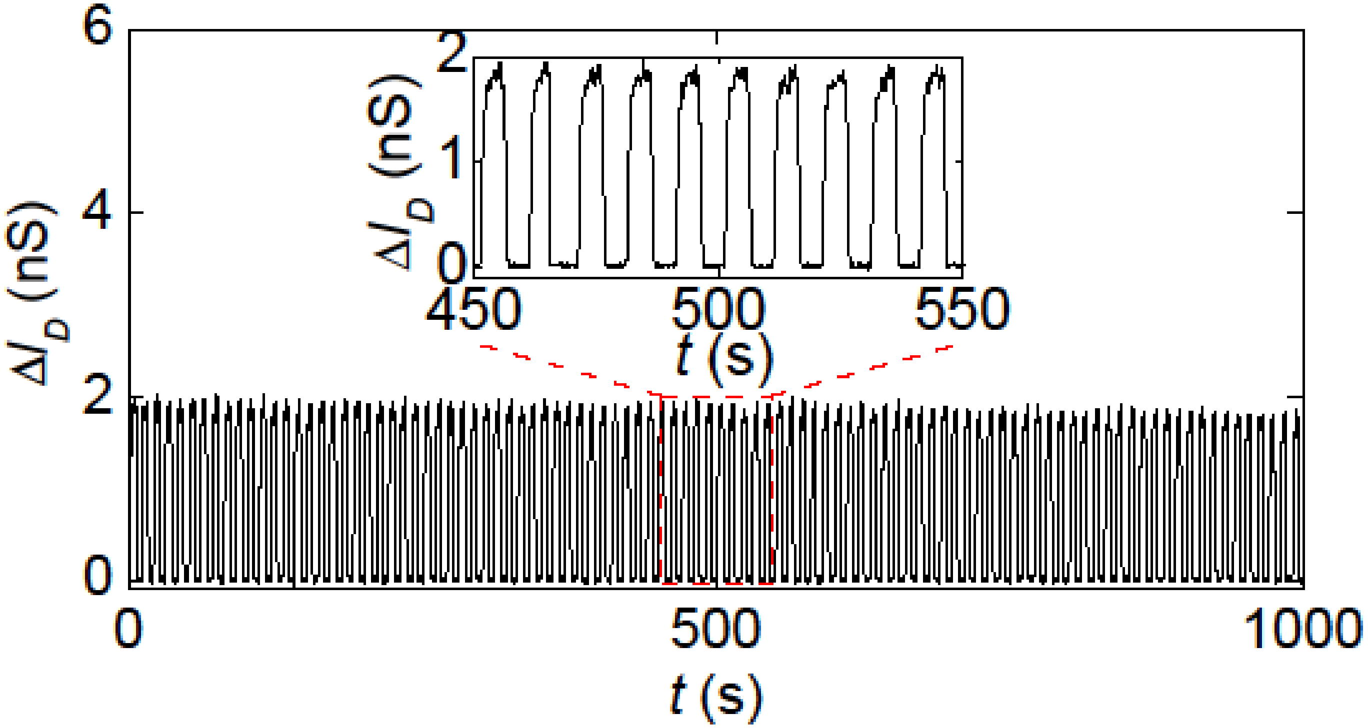
C. Cen, S. Thiel, J. Mannhart, and J. Levy, *Science* ***323****, 1026 (2009).*

Multiple Write/Erase

Write with $V_{tip}>0$



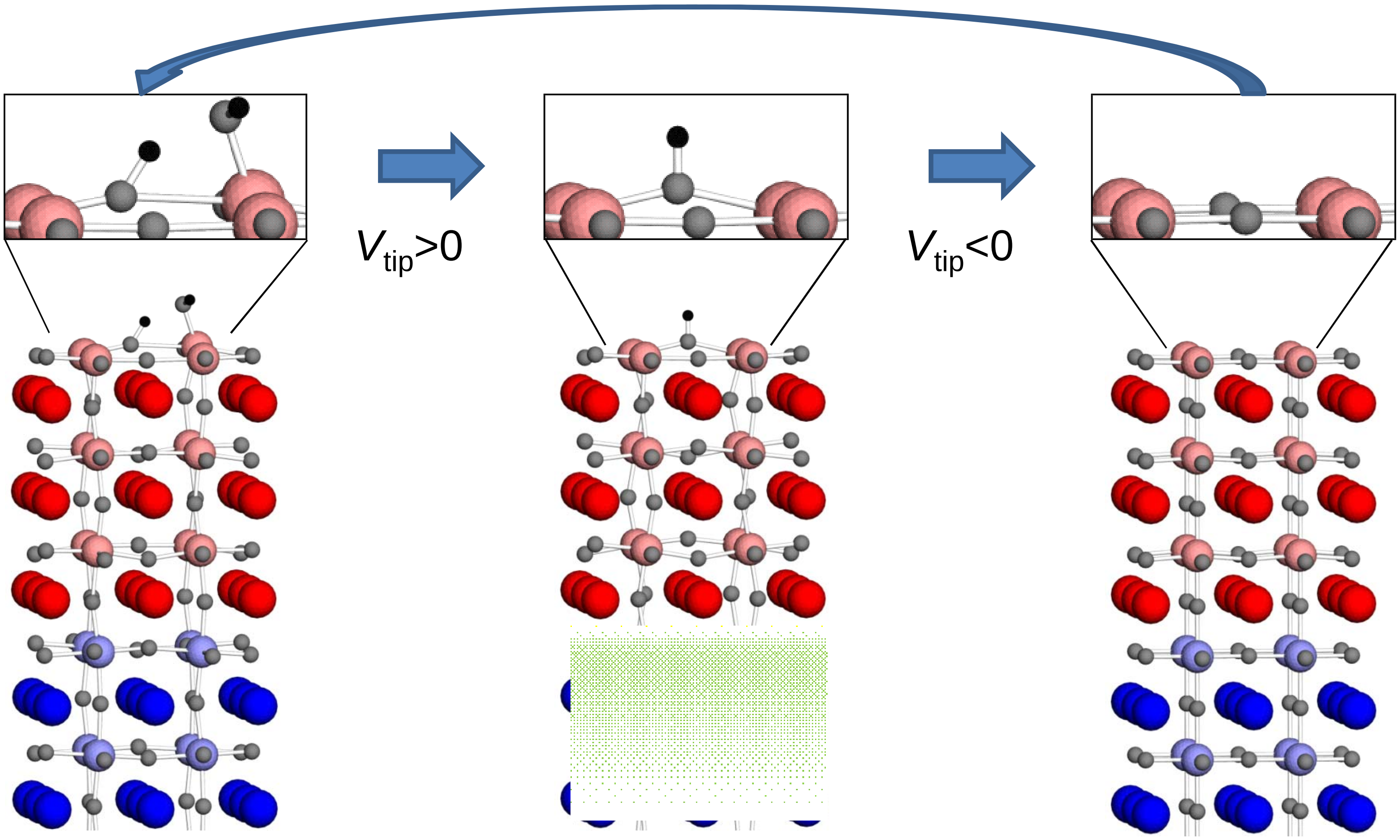
Erase with $V_{tip}<0$



C. Cen, S. Thiel, J. Mannhart, and J. Levy, *Science* ***323****, 1026 (2009).*

Possible Mechanism: “Water Cycle”

(C. S. Hellberg, unpublished)



$V_{tip}>0$

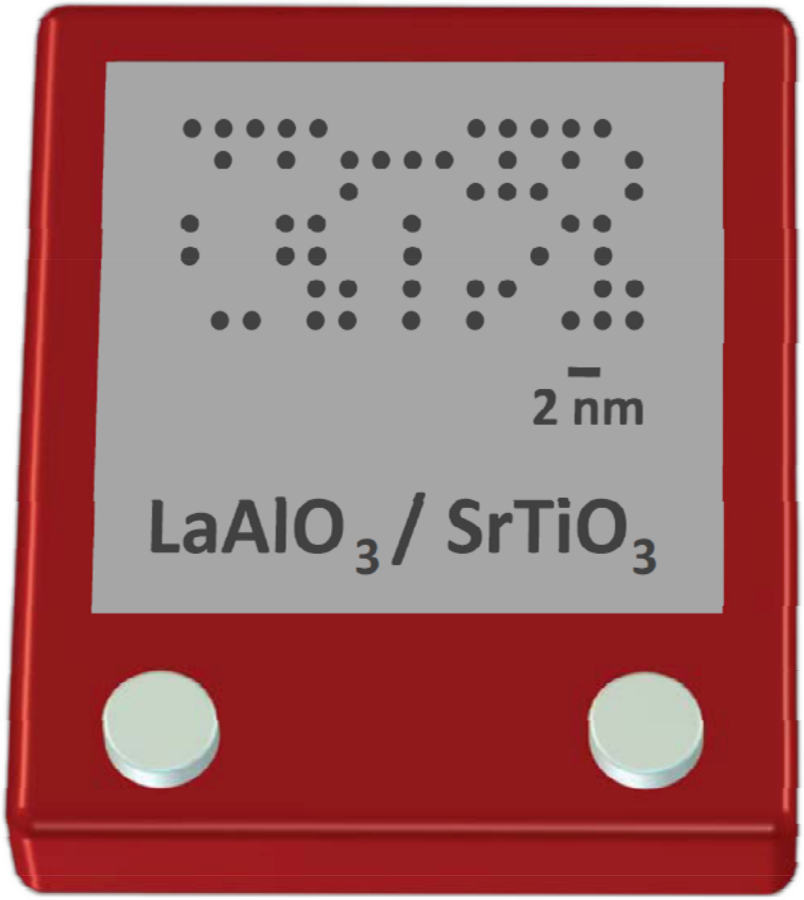
$V_{tip}<0$

H_2O adsorbs, dissociates on $LaAlO_3$ surface

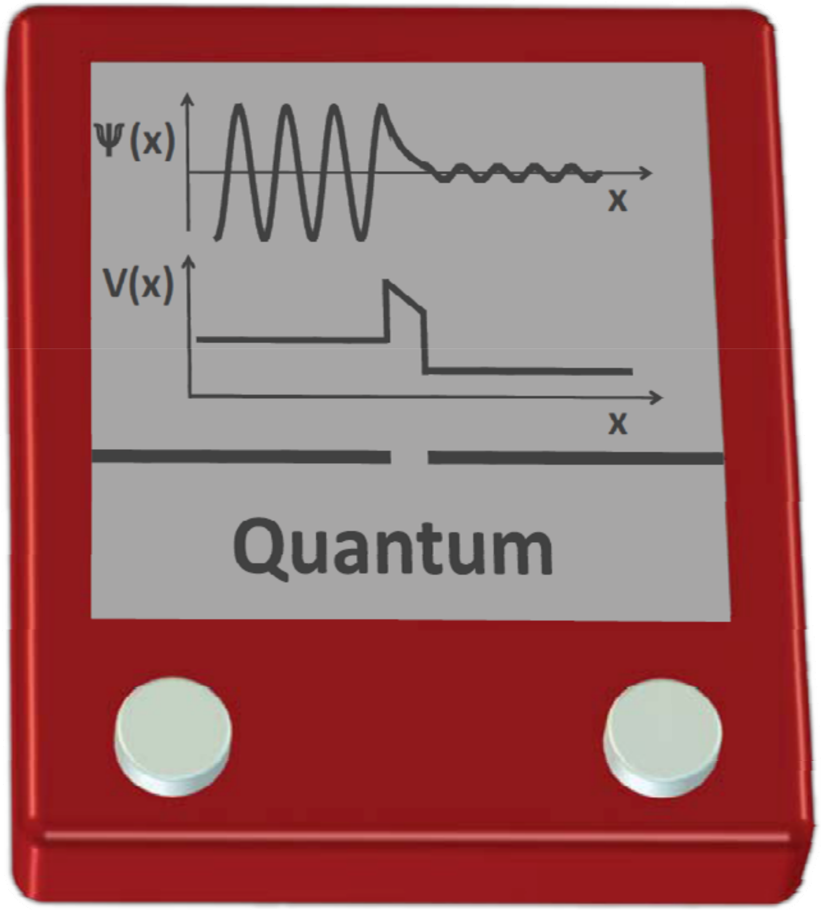
Positive tip removes OH-, leaving H^+ on surface and producing conducting interface

Positive tip removes H^+, restoring insulating state.

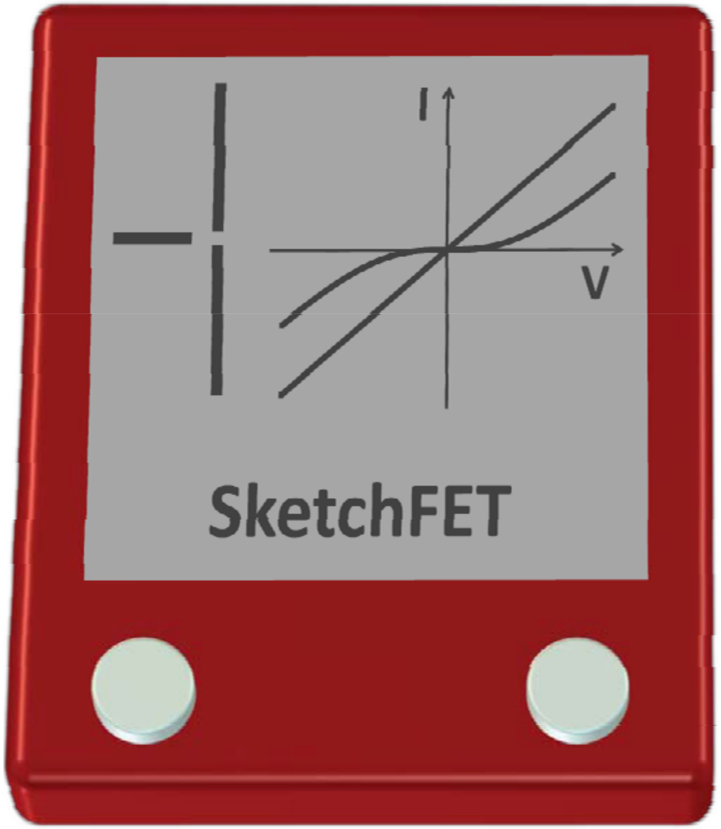
Ultrahigh Density Memory



Quantum Mechanics On-The-Fly



Transistor



Sketch-based Electronic Transport within Complex-oxide Heterostructure Field-Effect Transistor

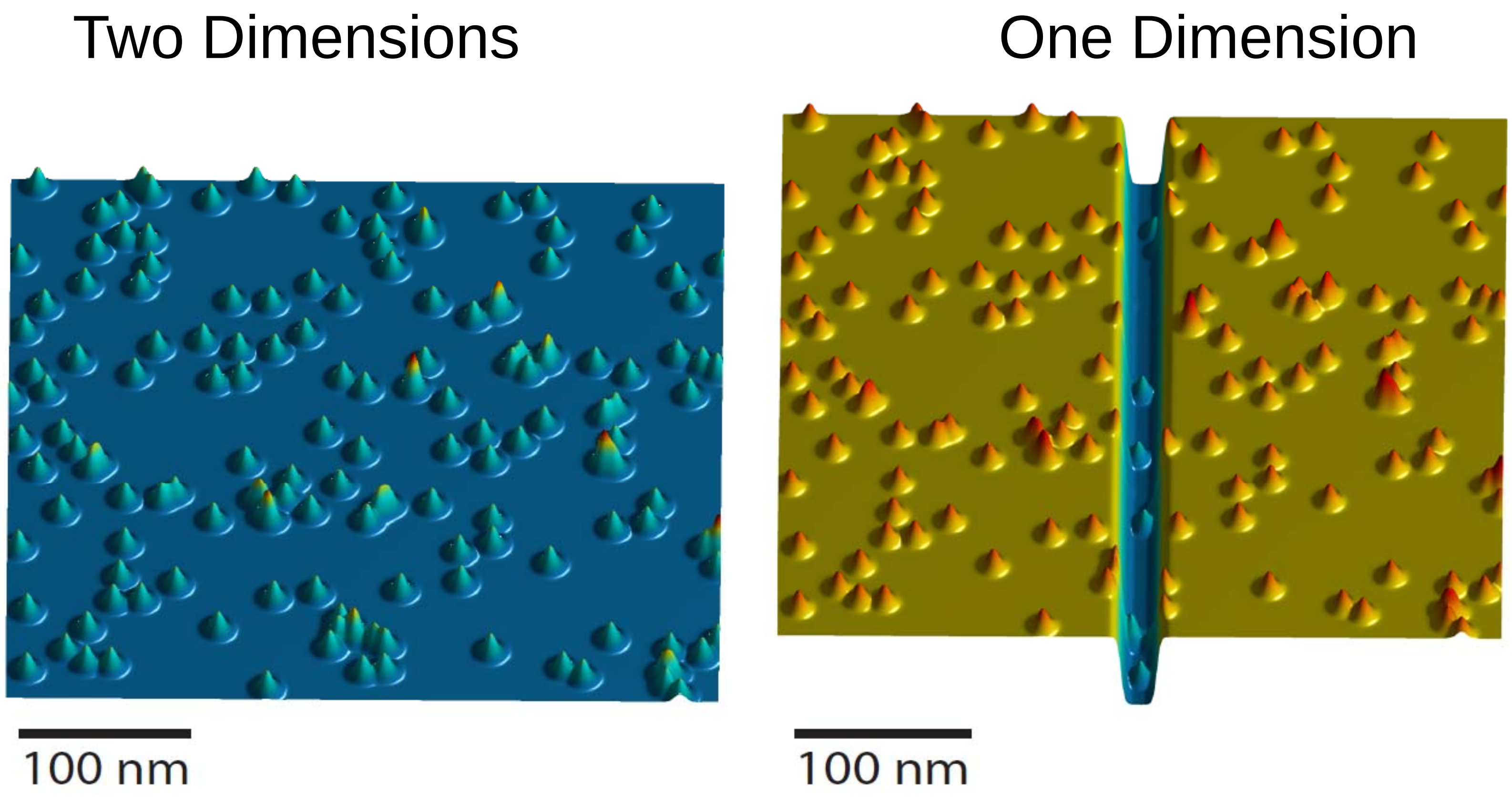
QUANTUM TRANSPORT AT LOW TEMPERATURES

- Spin-Orbit (Rashba) Coupling
- Quantum Coherence
- Quantum Hall states

Experiments performed at:

NATIONAL HIGH MAGNETIC FIELD LABORATORY
FSU • UF • LANL

Effect of Dimensionality on Transport

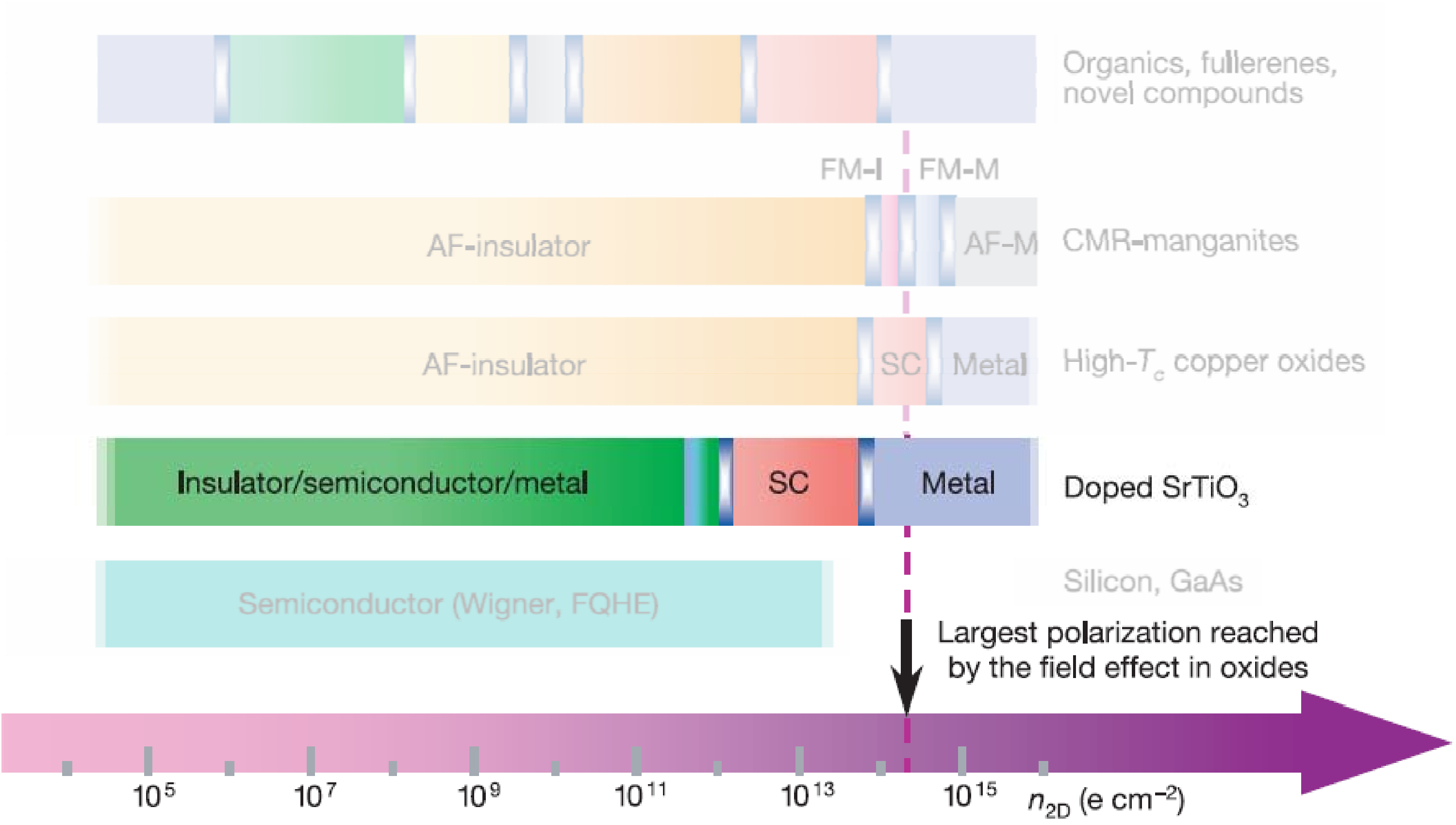

Two Dimensions

One Dimension

Mean free path ~16 nm (mobility~1000 cm^2/Vs at low temp)

Quasi-1D confinement may help to suppress scattering in 1d

Effect of Carrier Density on Transport



C. H. Ahn, J. M. Triscone, J. Mannhart, Nature **424**, 1023 (2003)

Transport Parameters

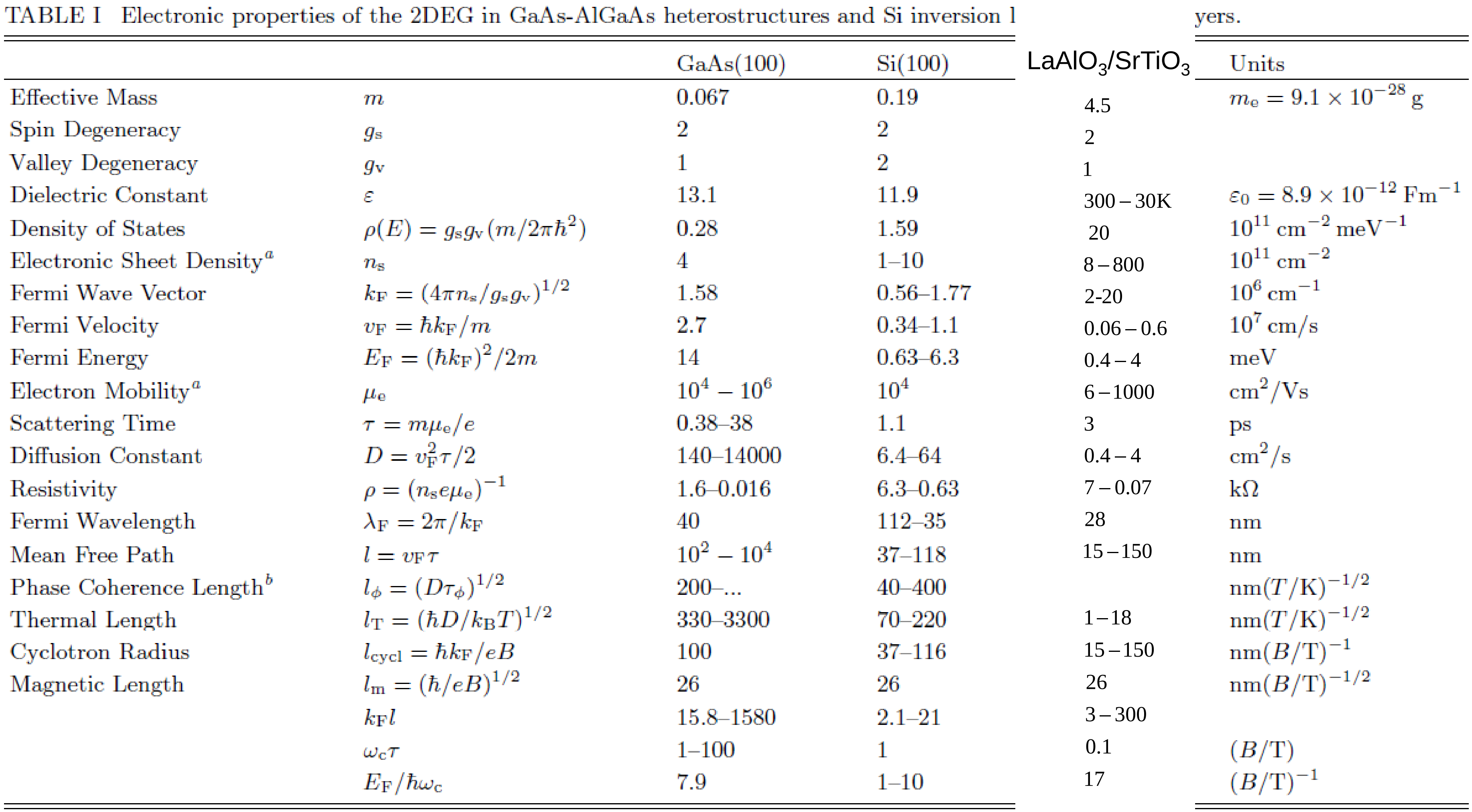
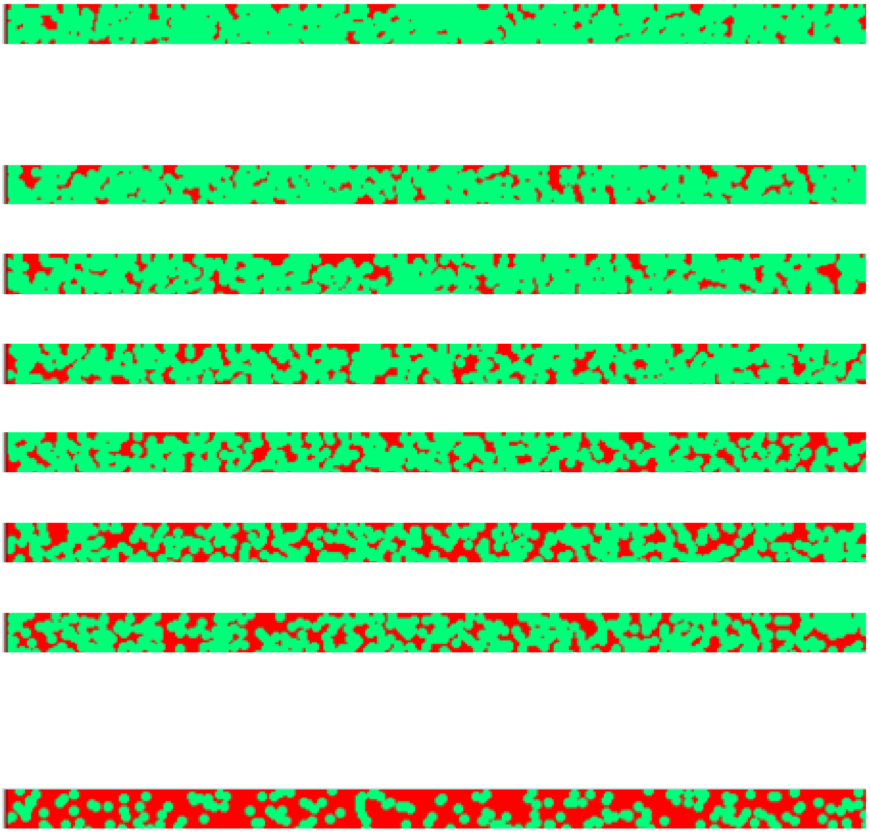


TABLE I Electronic properties of the 2DEG in GaAs-AlGaAs heterostructures and Si inversion l yers.

		GaAs(100)	Si(100)	$LaAlO_3/SrTiO_3$	Units
Effective Mass	m	0.067	0.19	4.5	$m_e = 9.1 \times 10^{-28}$ g
Spin Degeneracy	g_s	2	2	2	
Valley Degeneracy	g_v	1	2	1	
Dielectric Constant	ε	13.1	11.9	300 – 30K	$\varepsilon_0 = 8.9 \times 10^{-12}\ \mathrm{Fm}^{-1}$
Density of States	$\rho(E) = g_s g_v (m/2\pi\hbar^2)$	0.28	1.59	20	$10^{11}\ \mathrm{cm}^{-2}\ \mathrm{meV}^{-1}$
Electronic Sheet Density[a]	n_s	4	1–10	8 – 800	$10^{11}\ \mathrm{cm}^{-2}$
Fermi Wave Vector	$k_F = (4\pi n_s/g_s g_v)^{1/2}$	1.58	0.56–1.77	2-20	$10^6\ \mathrm{cm}^{-1}$
Fermi Velocity	$v_F = \hbar k_F/m$	2.7	0.34–1.1	0.06 – 0.6	10^7 cm/s
Fermi Energy	$E_F = (\hbar k_F)^2/2m$	14	0.63–6.3	0.4 – 4	meV
Electron Mobility[a]	μ_e	$10^4 - 10^6$	10^4	6 – 1000	$\mathrm{cm}^2/\mathrm{Vs}$
Scattering Time	$\tau = m\mu_e/e$	0.38–38	1.1	3	ps
Diffusion Constant	$D = v_F^2\tau/2$	140–14000	6.4–64	0.4 – 4	cm^2/s
Resistivity	$\rho = (n_s e \mu_e)^{-1}$	1.6–0.016	6.3–0.63	7 – 0.07	kΩ
Fermi Wavelength	$\lambda_F = 2\pi/k_F$	40	112–35	28	nm
Mean Free Path	$l = v_F\tau$	$10^2 - 10^4$	37–118	15 – 150	nm
Phase Coherence Length[b]	$l_\phi = (D\tau_\phi)^{1/2}$	200–...	40–400		$\mathrm{nm}(T/\mathrm{K})^{-1/2}$
Thermal Length	$l_T = (\hbar D/k_B T)^{1/2}$	330–3300	70–220	1 – 18	$\mathrm{nm}(T/\mathrm{K})^{-1/2}$
Cyclotron Radius	$l_{\mathrm{cycl}} = \hbar k_F/eB$	100	37–116	15 – 150	$\mathrm{nm}(B/\mathrm{T})^{-1}$
Magnetic Length	$l_m = (\hbar/eB)^{1/2}$	26	26	26	$\mathrm{nm}(B/\mathrm{T})^{-1/2}$
	$k_F l$	15.8–1580	2.1–21	3 – 300	
	$\omega_c\tau$	1–100	1	0.1	(B/T)
	$E_F/\hbar\omega_c$	7.9	1–10	17	$(B/\mathrm{T})^{-1}$

Metal-Insulator Transition in SrTiO$_3$ Nanowires

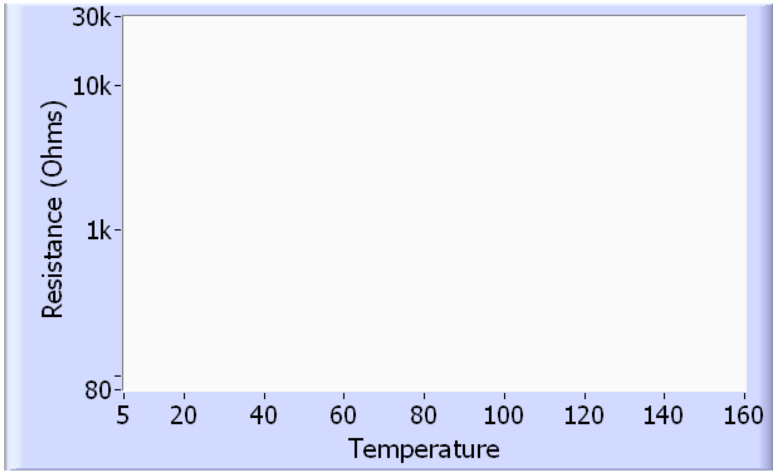
Metal



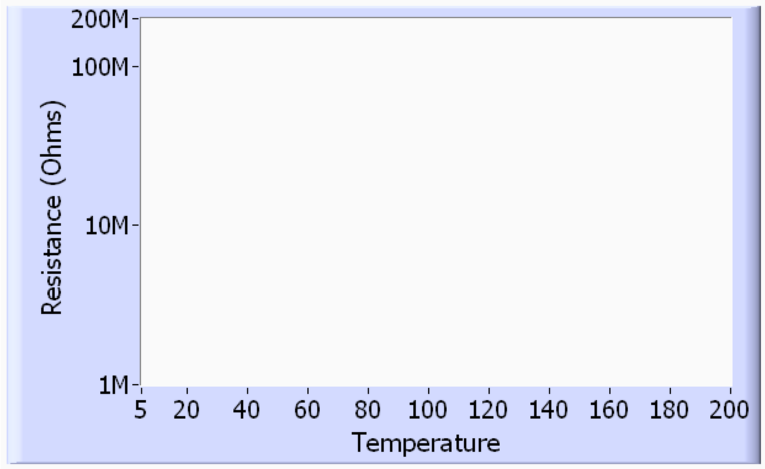
Insulator

Fluctuations enhanced in 1d

n=8x10^{13} cm^{-2}



n=8x10^{11} cm^{-2}



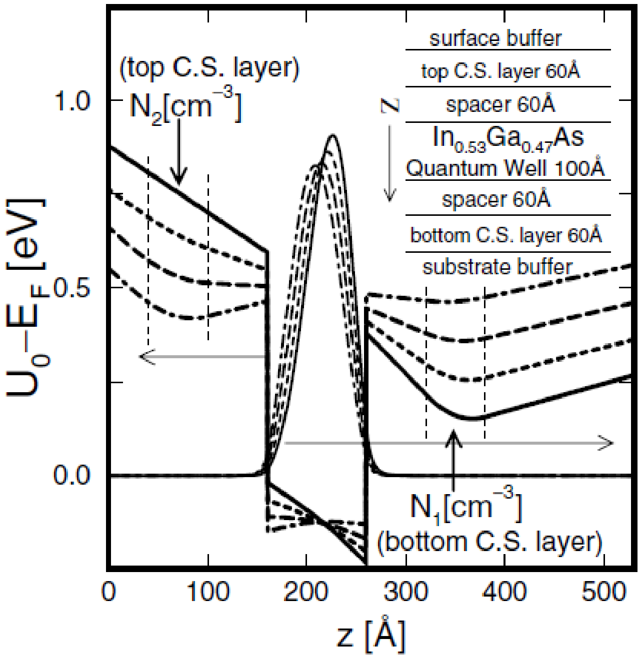
Weak Antilocalization

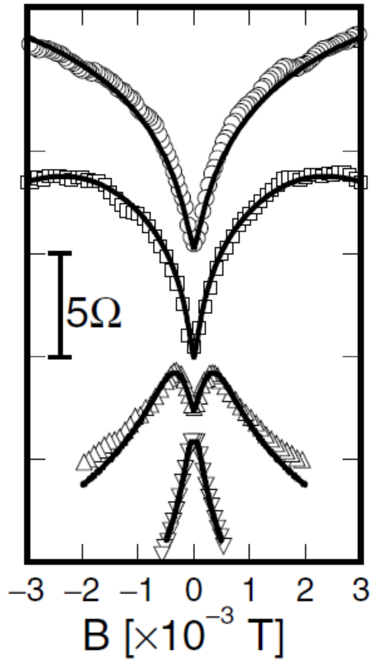
SPIN-ORBIT COUPLING

VOLUME 89, NUMBER 4 PHYSICAL REVIEW LETTERS 22 JULY 2002

Rashba Spin-Orbit Coupling Probed by the Weak Antilocalization Analysis in InAlAs/InGaAs/InAlAs Quantum Wells as a Function of Quantum Well Asymmetry

Takaaki Koga,* Junsaku Nitta, Tatsushi Akazaki, and Hideaki Takayanagi
NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation, 3-1 Morinosato-Wakamiya,
Atsugi, Kanagawa 243-0198, Japan
(Received 3 October 2001; published 2 July 2002)





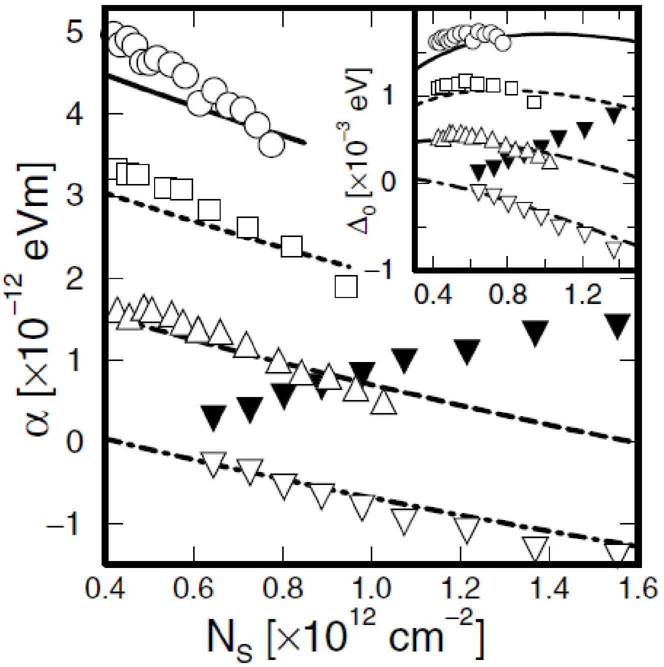
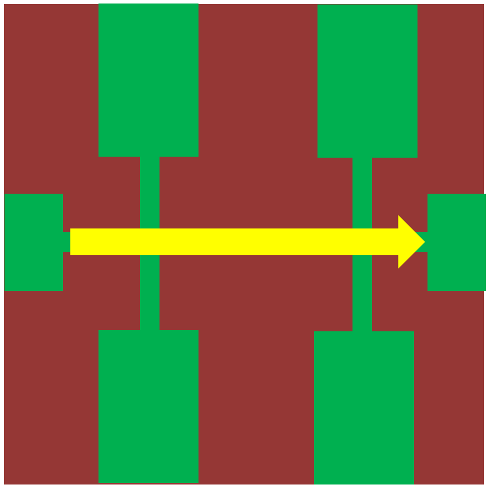


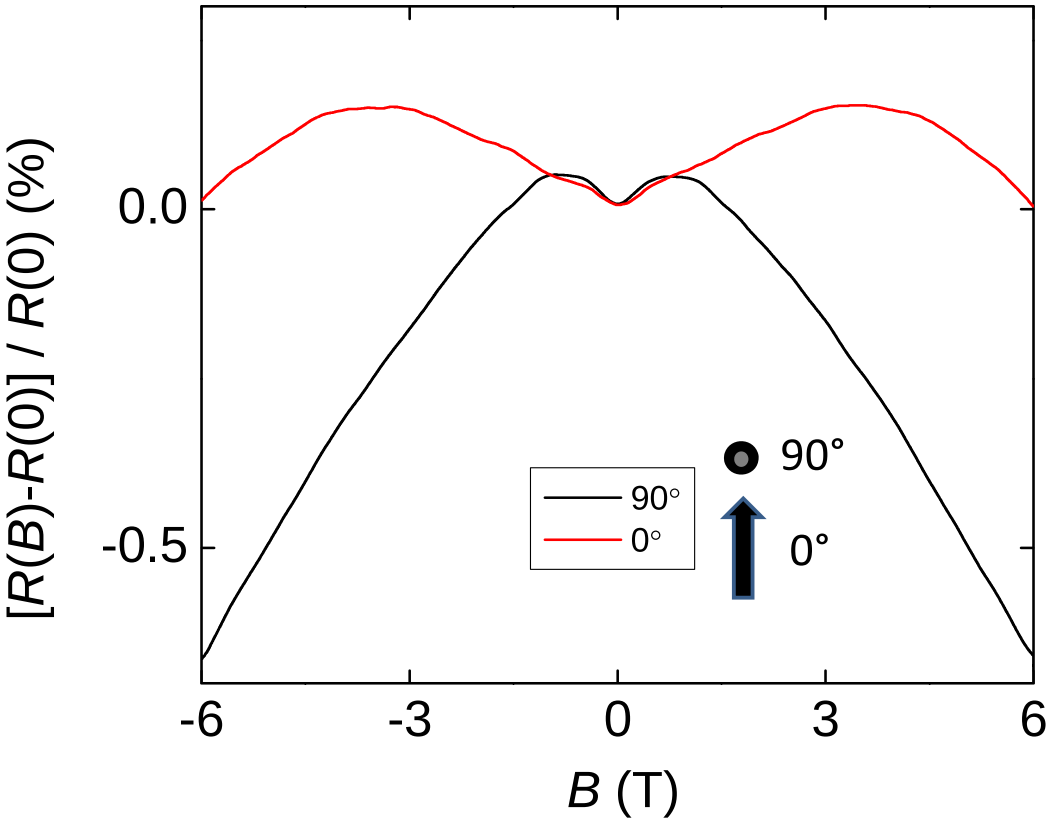
TABLE I. Impurity concentrations used in the present samples.

	Sample 1	Sample 2	Sample 3	Sample 4
N_1 [cm^{-3}]	4×10^{18}	3×10^{18}	2×10^{18}	1×10^{18}
N_2 [cm^{-3}]	0×10^{18}	1×10^{18}	2×10^{18}	3×10^{18}

Weak Antilocalization

T=250 mK

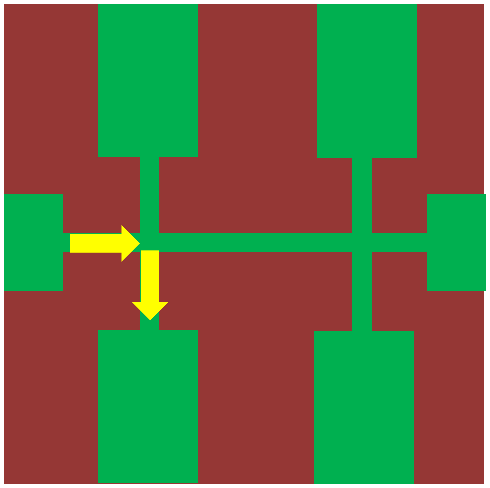


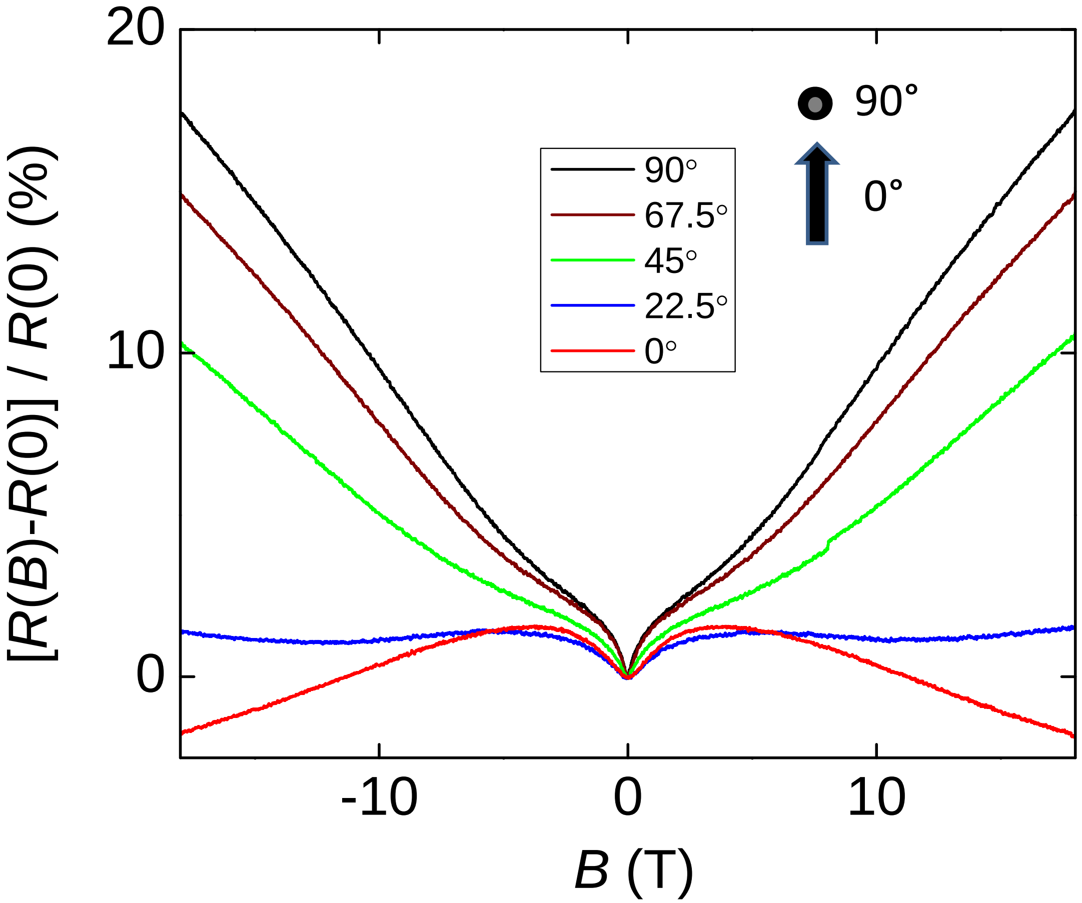


Evidence for spin-orbit coupling (Rashba)

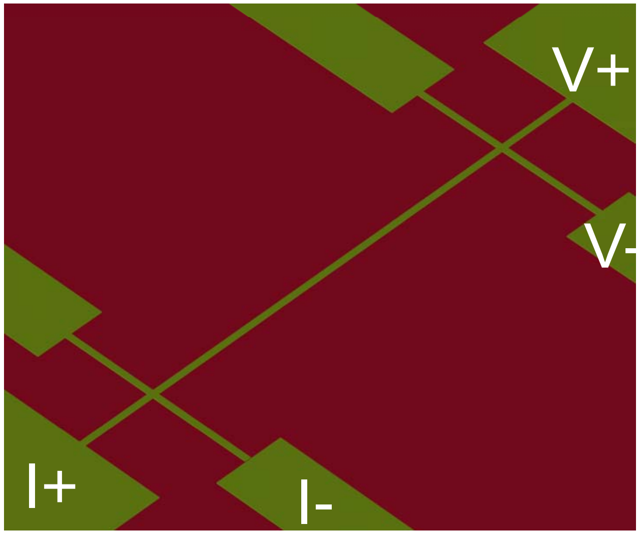
Weak Antilocalization (I)

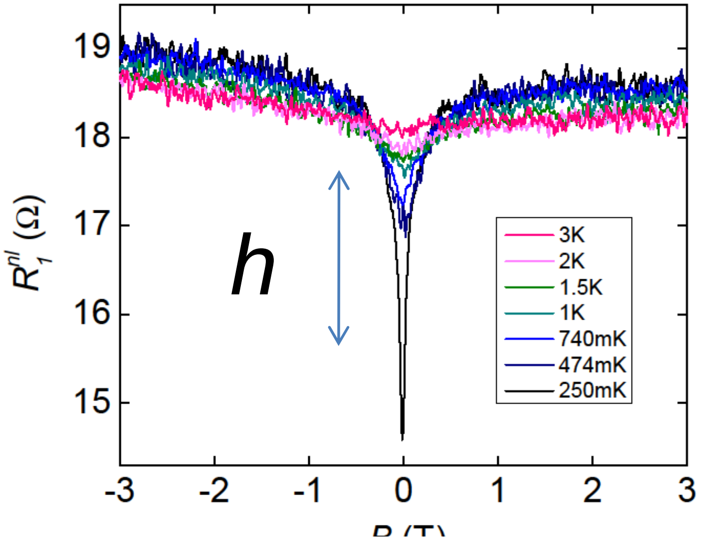
T=250 mK

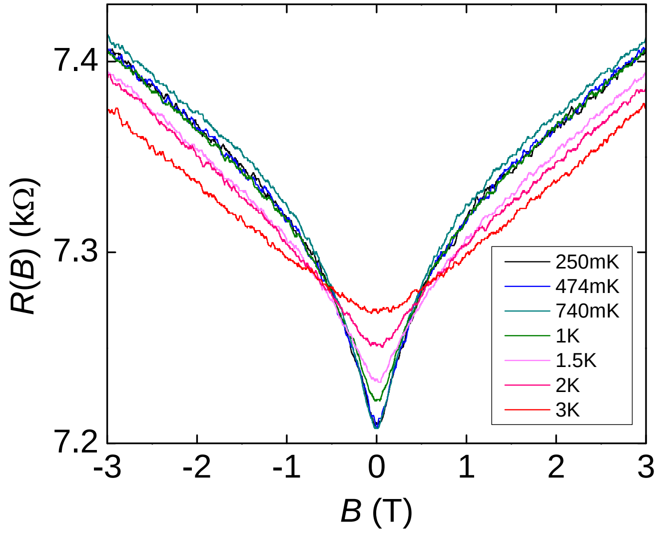


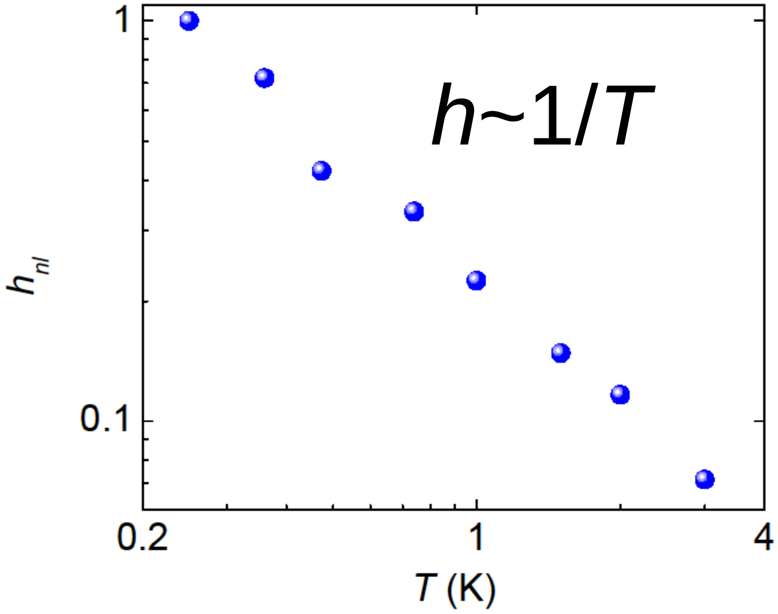


Non-Local Magnetoresistance

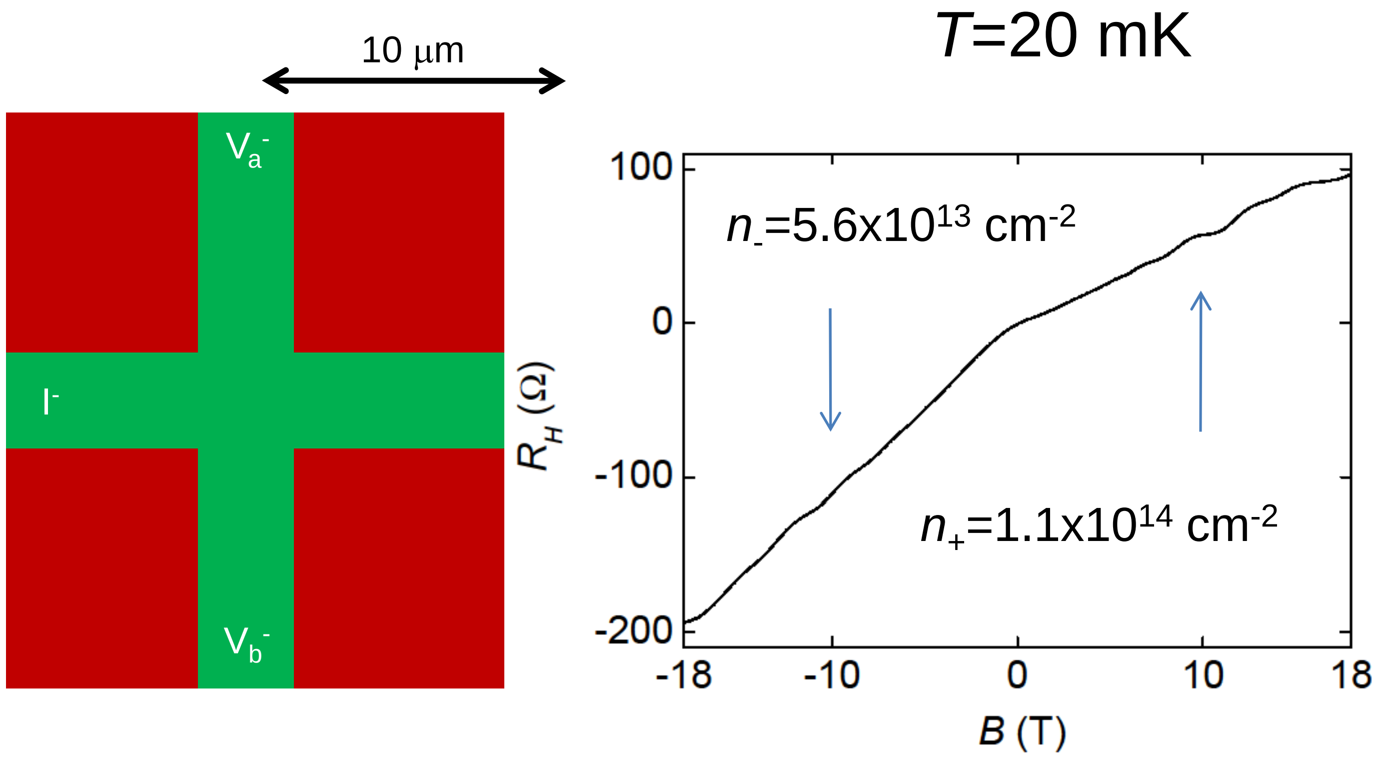




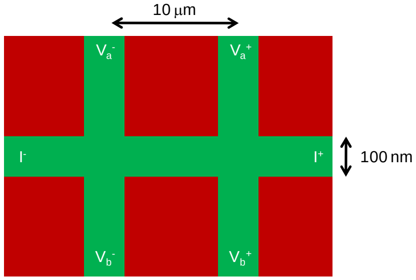




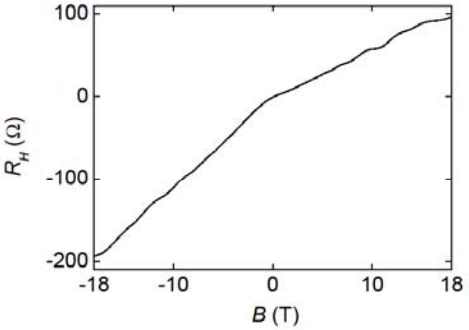
Hall Effect



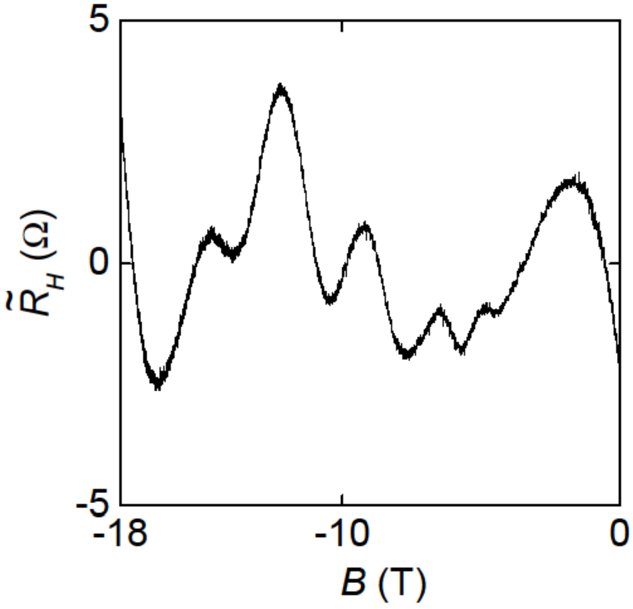
Symmetric component between B>0 and B<0

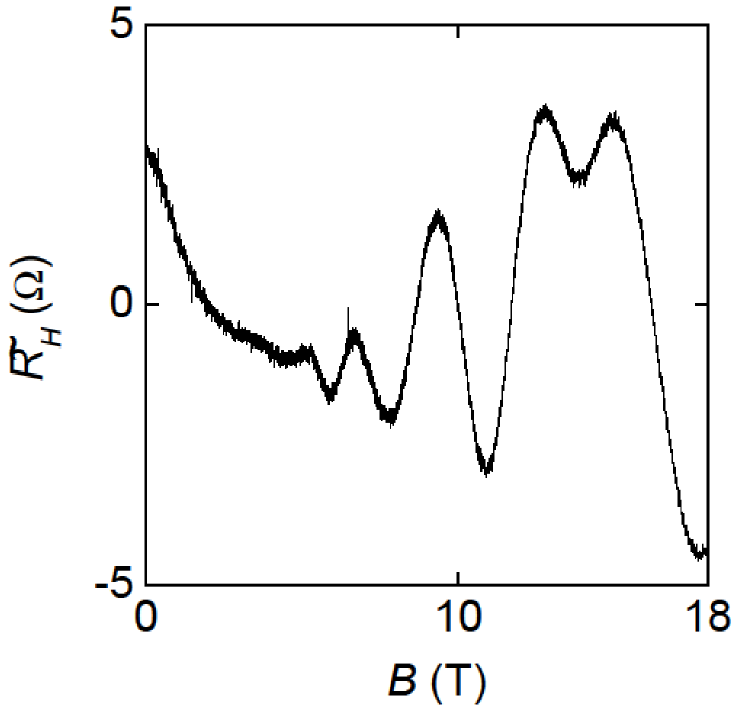


Hall Effect: Closeup

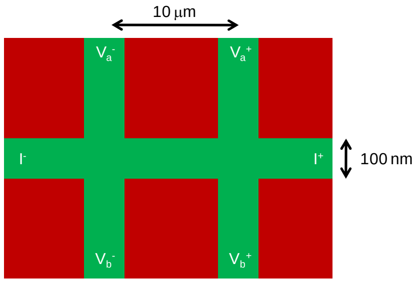


Subtract linear term

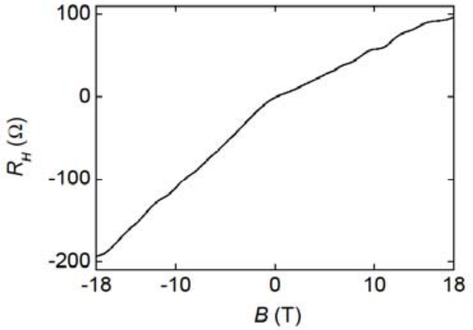




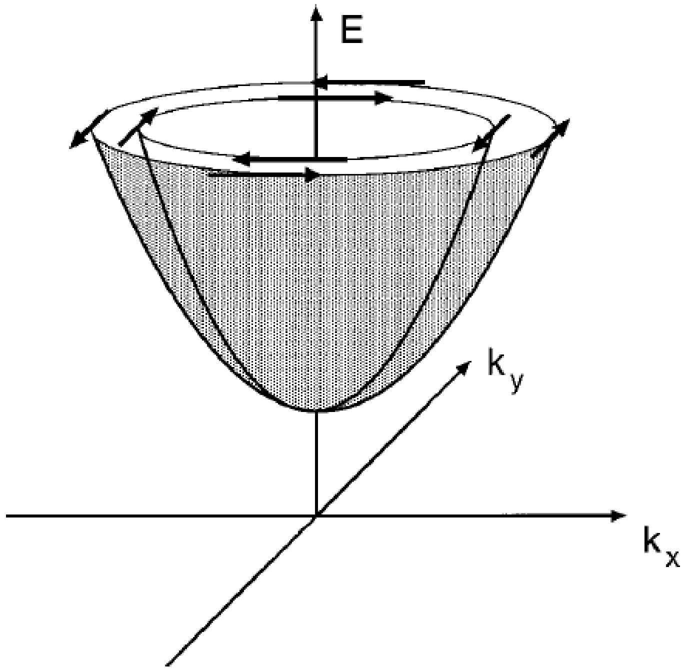
Shubnikov-de Haas oscillations (high ν)



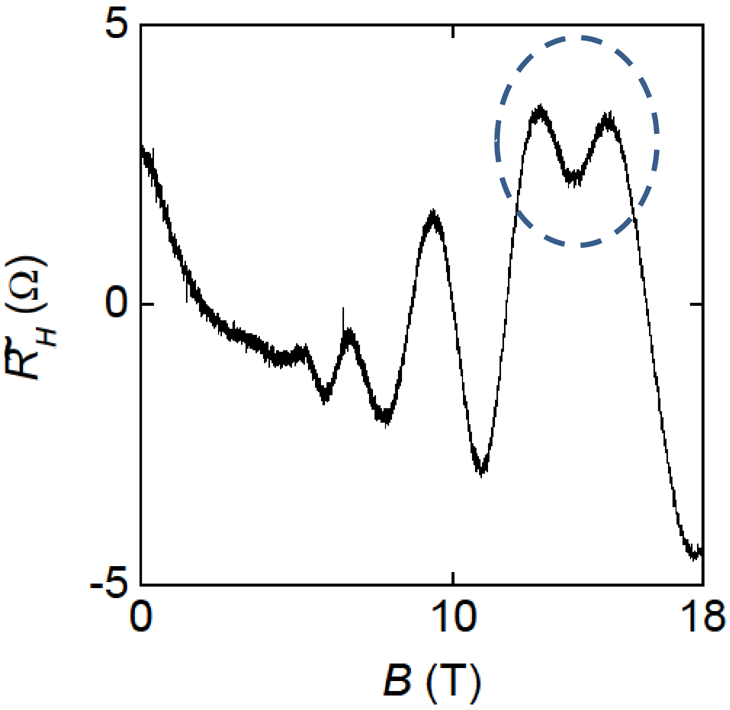
Hall Effect: Closeup



SdH beats-> Spin-Orbit coupling



J. Appl. Phys., Vol. 83, No. 8, 15 April 1998



PHYSICAL REVIEW B VOLUME 39, NUMBER 2 15 JANUARY 1989-I

Evidence for spin splitting in $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ heterostructures as $B \rightarrow 0$

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R. Reifenberger
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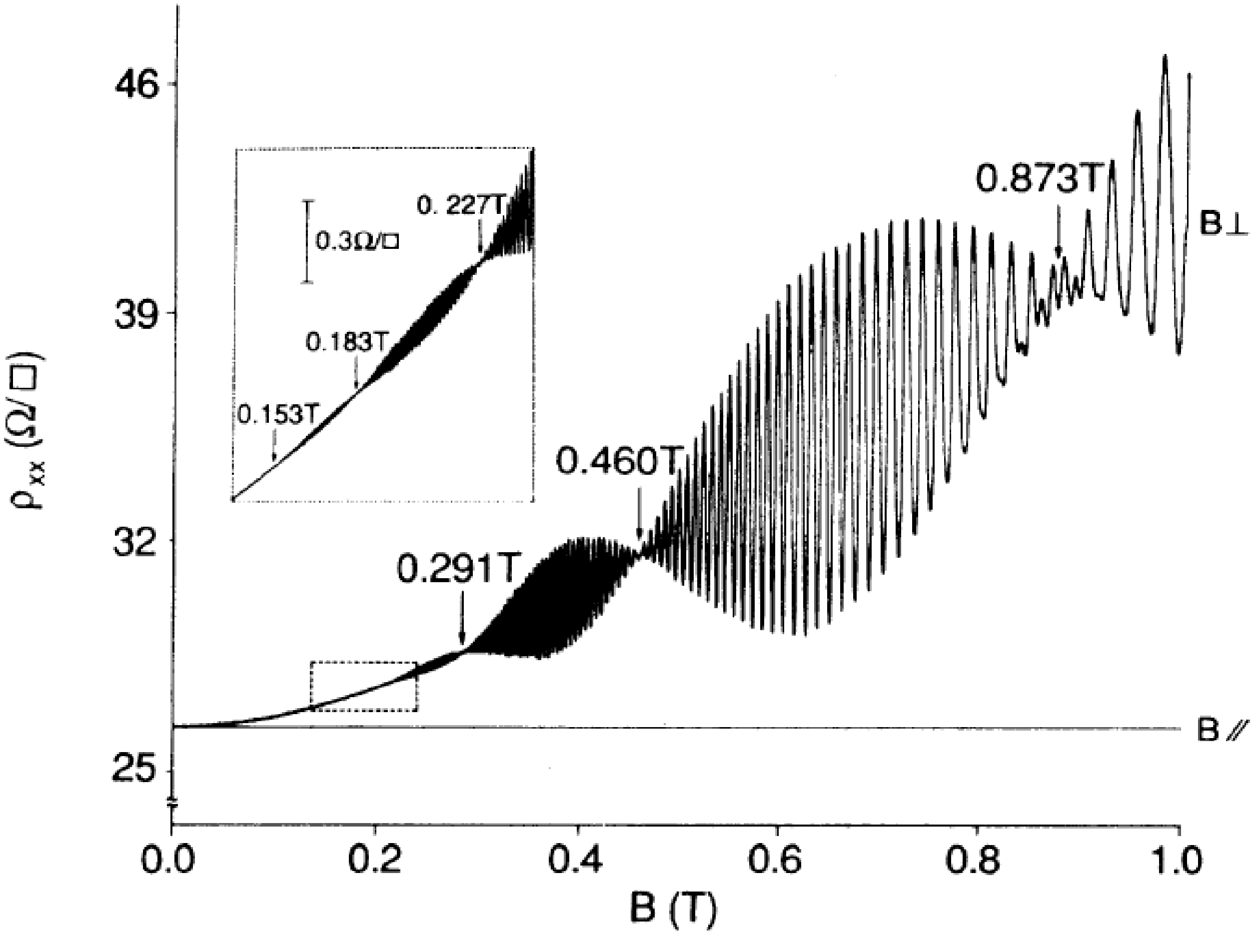
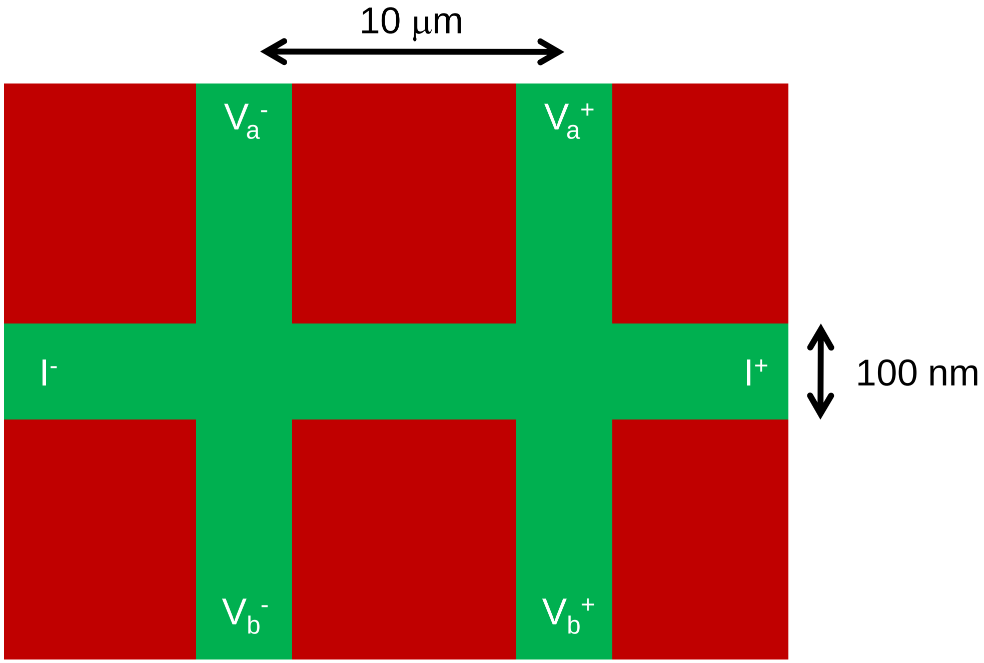
W. P. Hong, P. K. Bhattacharya, J. Singh, and M. Jaffe
Department of Electrical Engineering and Computer Science, The University of Michigan,
Ann Arbor, Michigan 48109

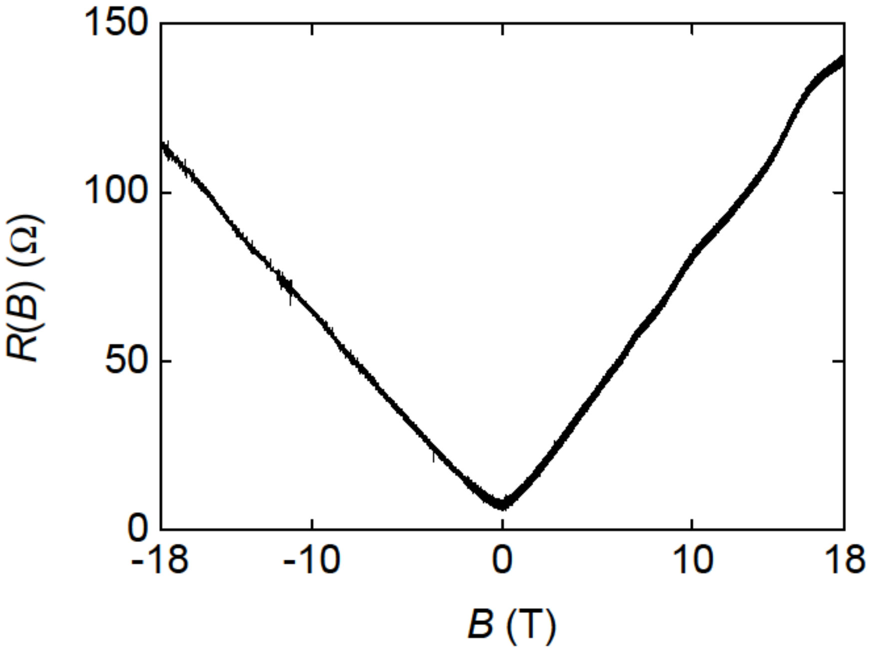
(Received 19 April 1988; revised manuscript received 30 September 1988)



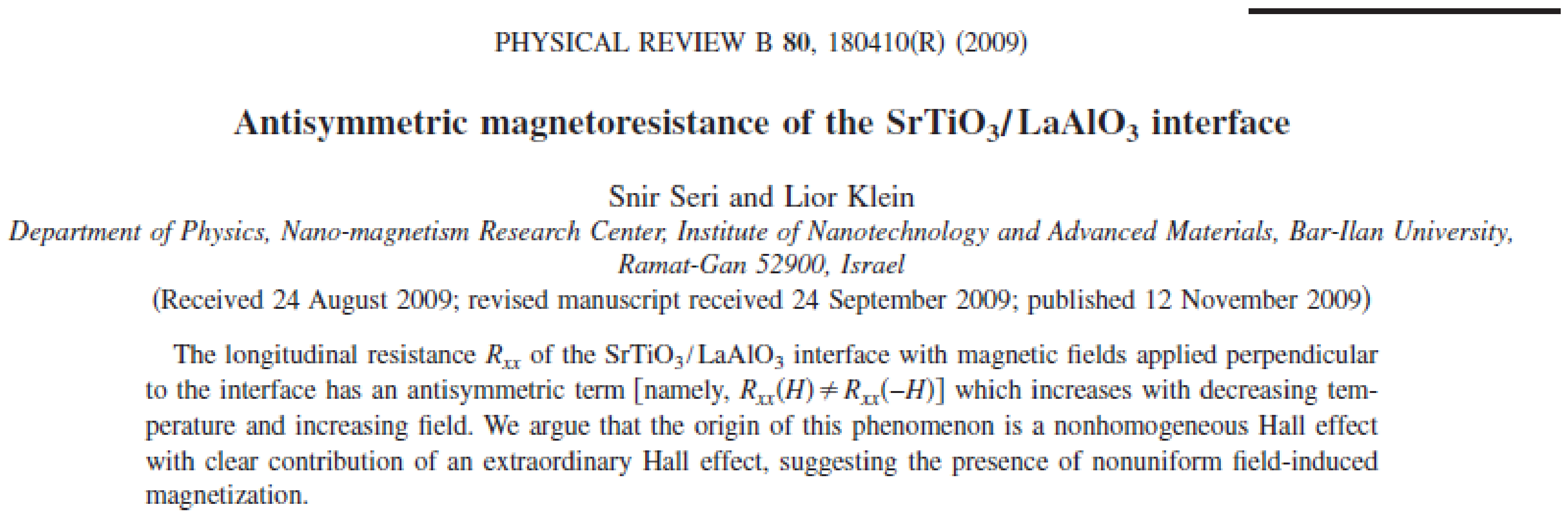
Magnetoresistance



T=20 mK



Large linear magnetoresistance for |B|>2 T
→ Asymmetry, possibly due to Hall coupling



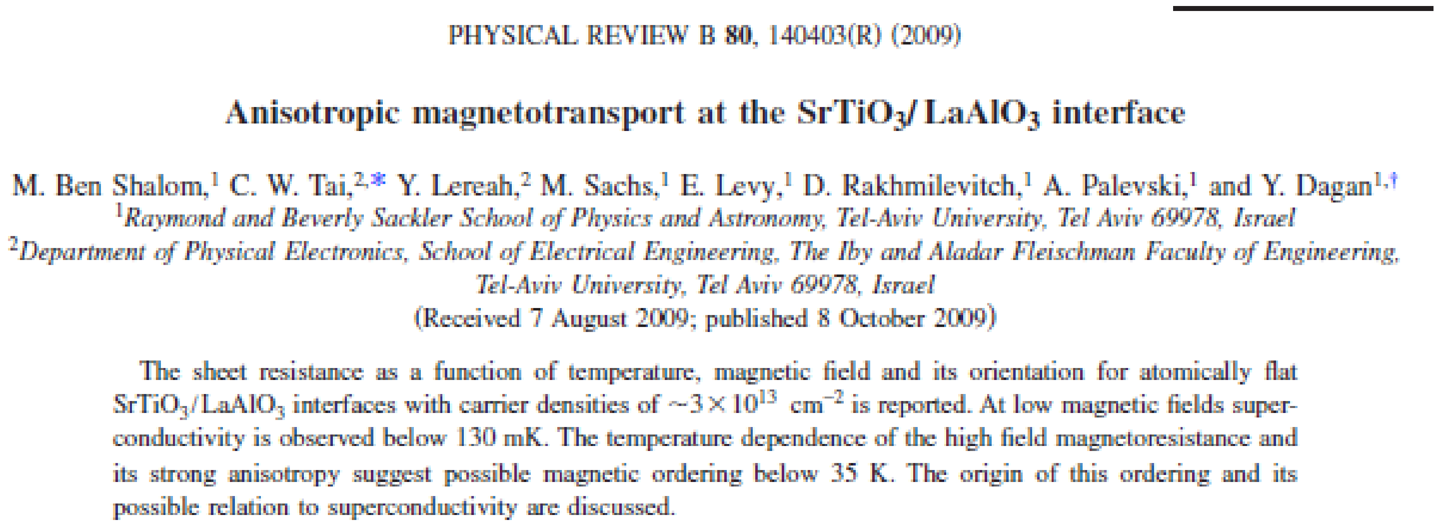
PHYSICAL REVIEW B **80**, 180410(R) (2009)

Antisymmetric magnetoresistance of the $SrTiO_3/LaAlO_3$ interface

Snir Seri and Lior Klein
Department of Physics, Nano-magnetism Research Center, Institute of Nanotechnology and Advanced Materials, Bar-Ilan University,
Ramat-Gan 52900, Israel

(Received 24 August 2009; revised manuscript received 24 September 2009; published 12 November 2009)

The longitudinal resistance R_{xx} of the $SrTiO_3/LaAlO_3$ interface with magnetic fields applied perpendicular to the interface has an antisymmetric term [namely, $R_{xx}(H) \neq R_{xx}(-H)$] which increases with decreasing temperature and increasing field. We argue that the origin of this phenomenon is a nonhomogeneous Hall effect with clear contribution of an extraordinary Hall effect, suggesting the presence of nonuniform field-induced magnetization.



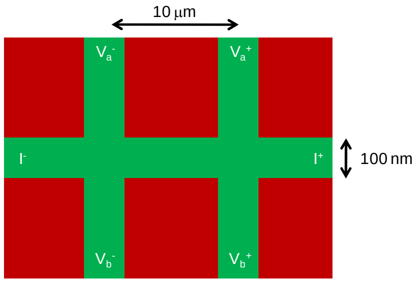
PHYSICAL REVIEW B **80**, 140403(R) (2009)

Anisotropic magnetotransport at the $SrTiO_3/LaAlO_3$ interface

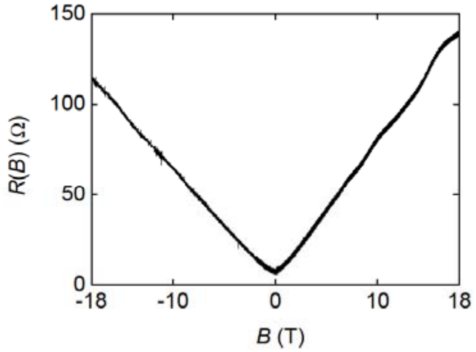
M. Ben Shalom,[1] C. W. Tai,[2,*] Y. Lereah,[2] M. Sachs,[1] E. Levy,[1] D. Rakhmilevitch,[1] A. Palevski,[1] and Y. Dagan[1,†]
[1]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel Aviv 69978, Israel*
[2]*Department of Physical Electronics, School of Electrical Engineering, The Iby and Aladar Fleischman Faculty of Engineering,*
Tel-Aviv University, Tel Aviv 69978, Israel

(Received 7 August 2009; published 8 October 2009)

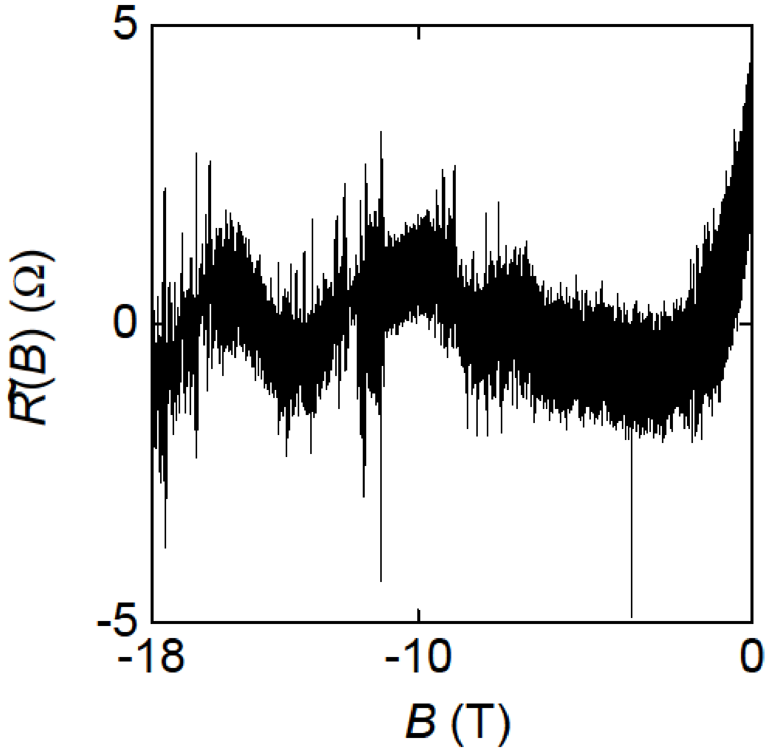
The sheet resistance as a function of temperature, magnetic field and its orientation for atomically flat $SrTiO_3/LaAlO_3$ interfaces with carrier densities of $\sim 3 \times 10^{13}$ cm^{-2} is reported. At low magnetic fields superconductivity is observed below 130 mK. The temperature dependence of the high field magnetoresistance and its strong anisotropy suggest possible magnetic ordering below 35 K. The origin of this ordering and its possible relation to superconductivity are discussed.

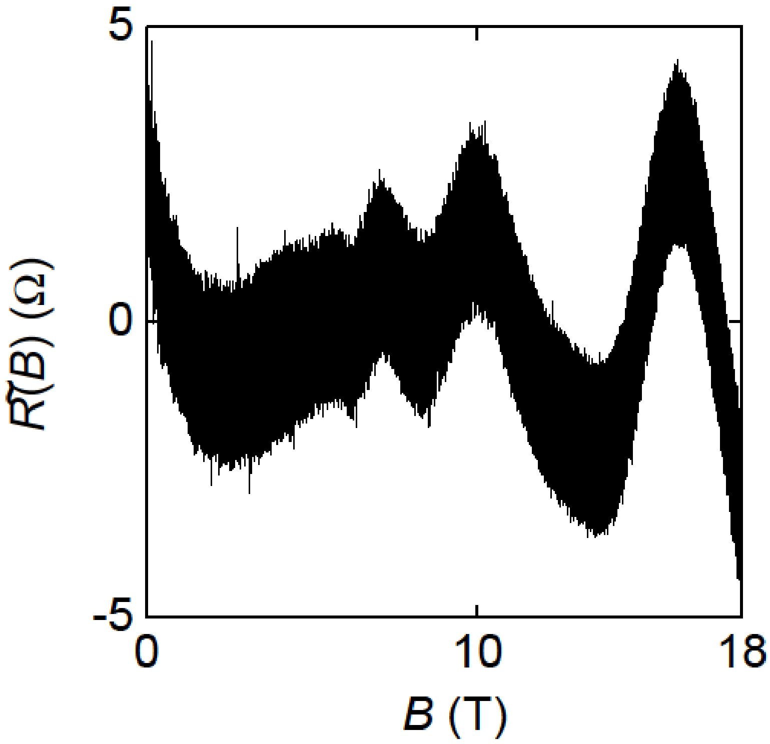


Magnetoresistance: close-up



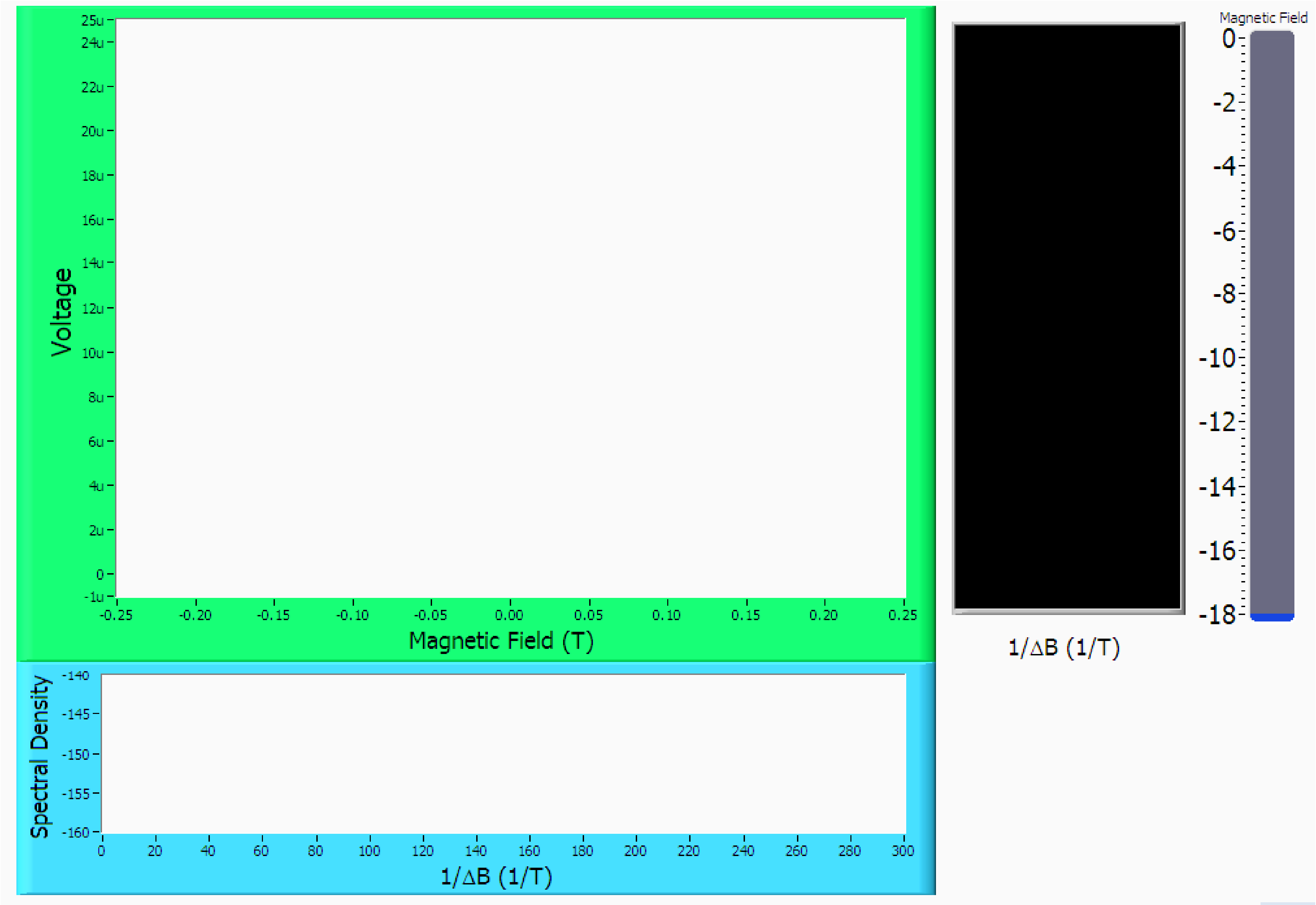
Subtract linear term



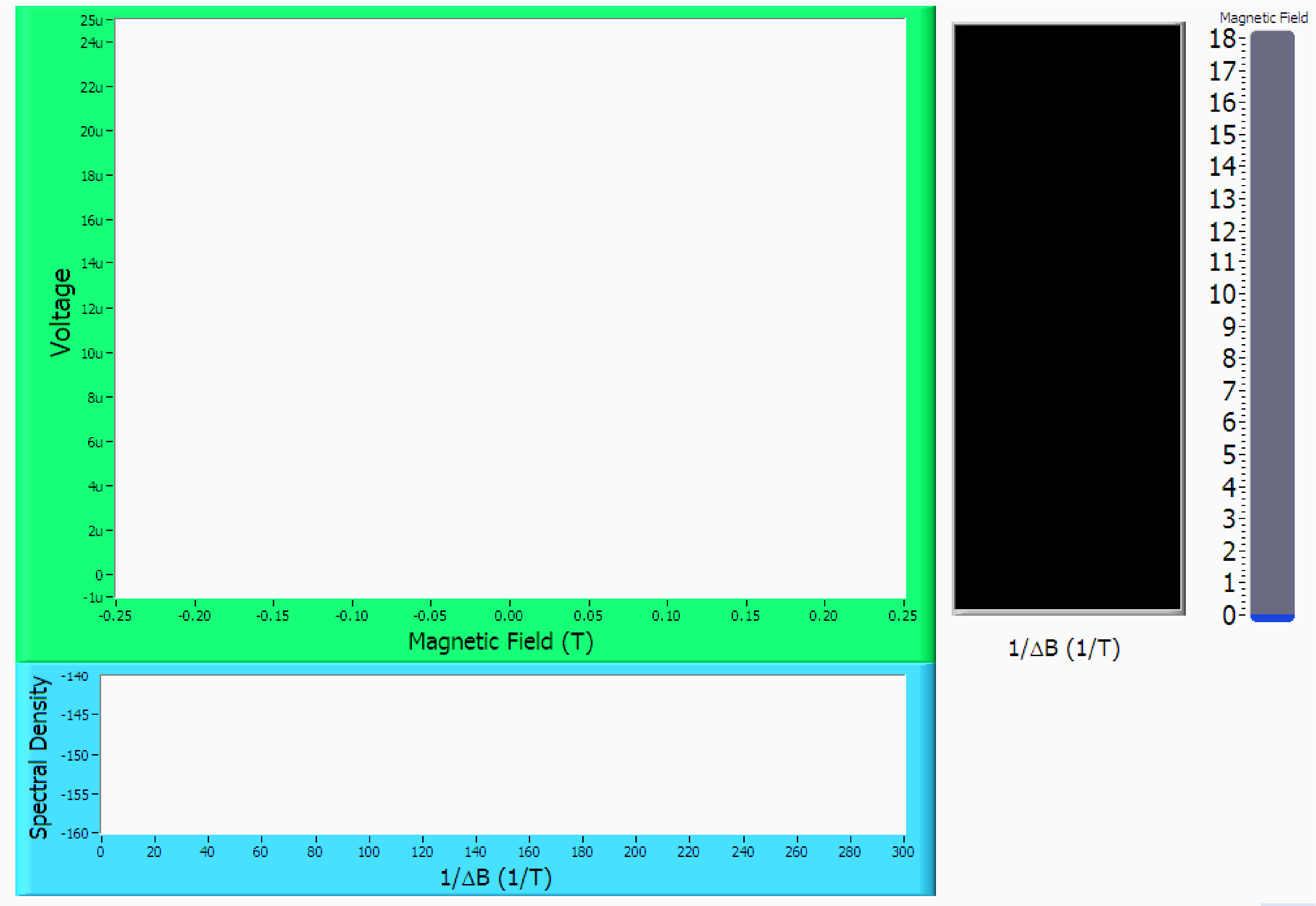


Shubnikov de Haas oscillations

→ Noisy!



Voltage
25u
24u
22u
20u
18u
16u
14u
12u
10u
8u
6u
4u
2u
0
-1u
-0.25
-0.20
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
Magnetic Field (T)
Spectral Density
-140
-145
-150
-155
-160
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
1/ΔB (1/T)
1/ΔB (1/T)
Magnetic Field
0
-2
-4
-6
-8
-10
-12
-14
-16
-18


Voltage
25u
24u
22u
20u
18u
16u
14u
12u
10u
8u
6u
4u
2u
0
-1u
-0.25
-0.20
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
0.20
0.25
Magnetic Field (T)
Spectral Density
-140
-145
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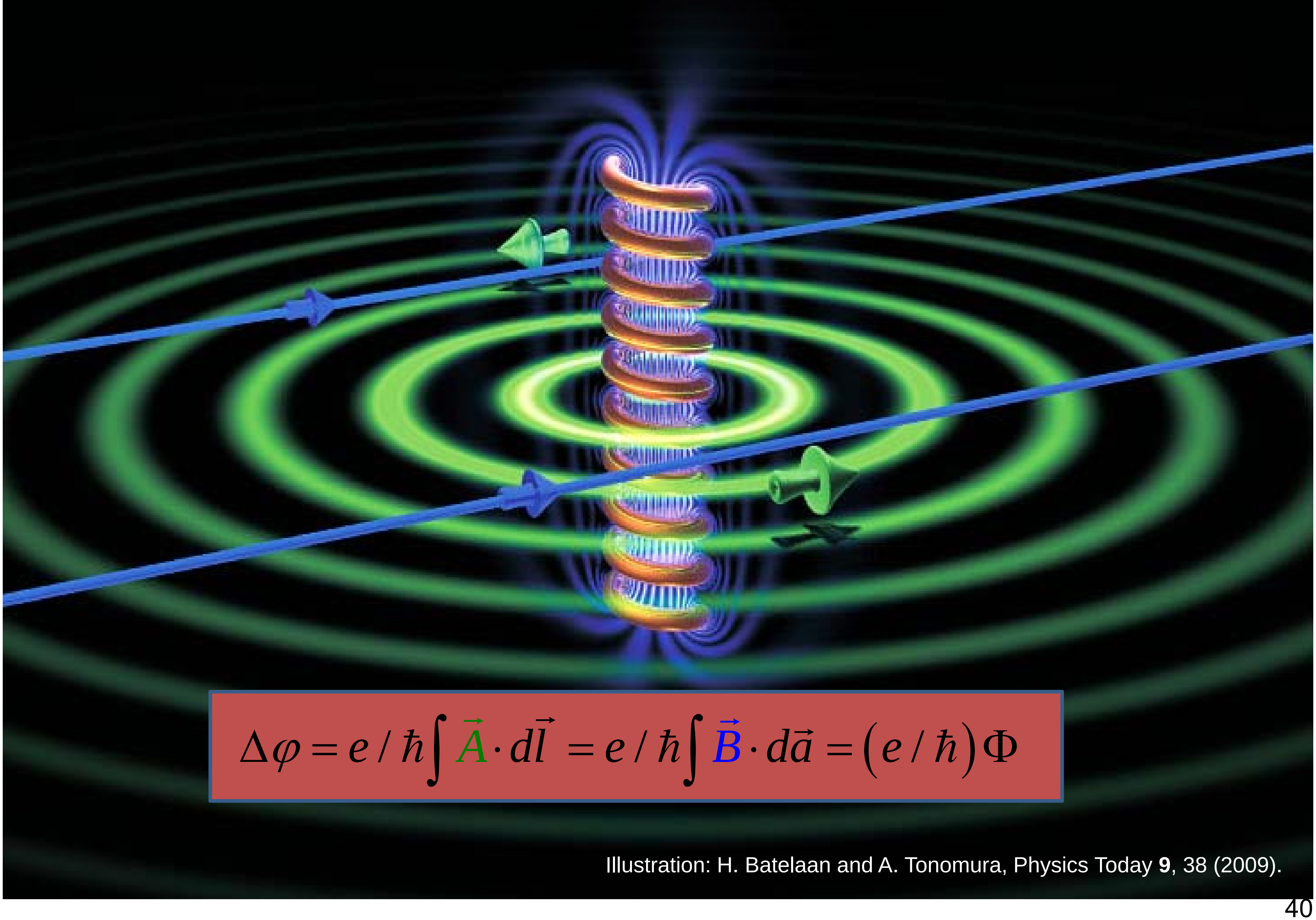
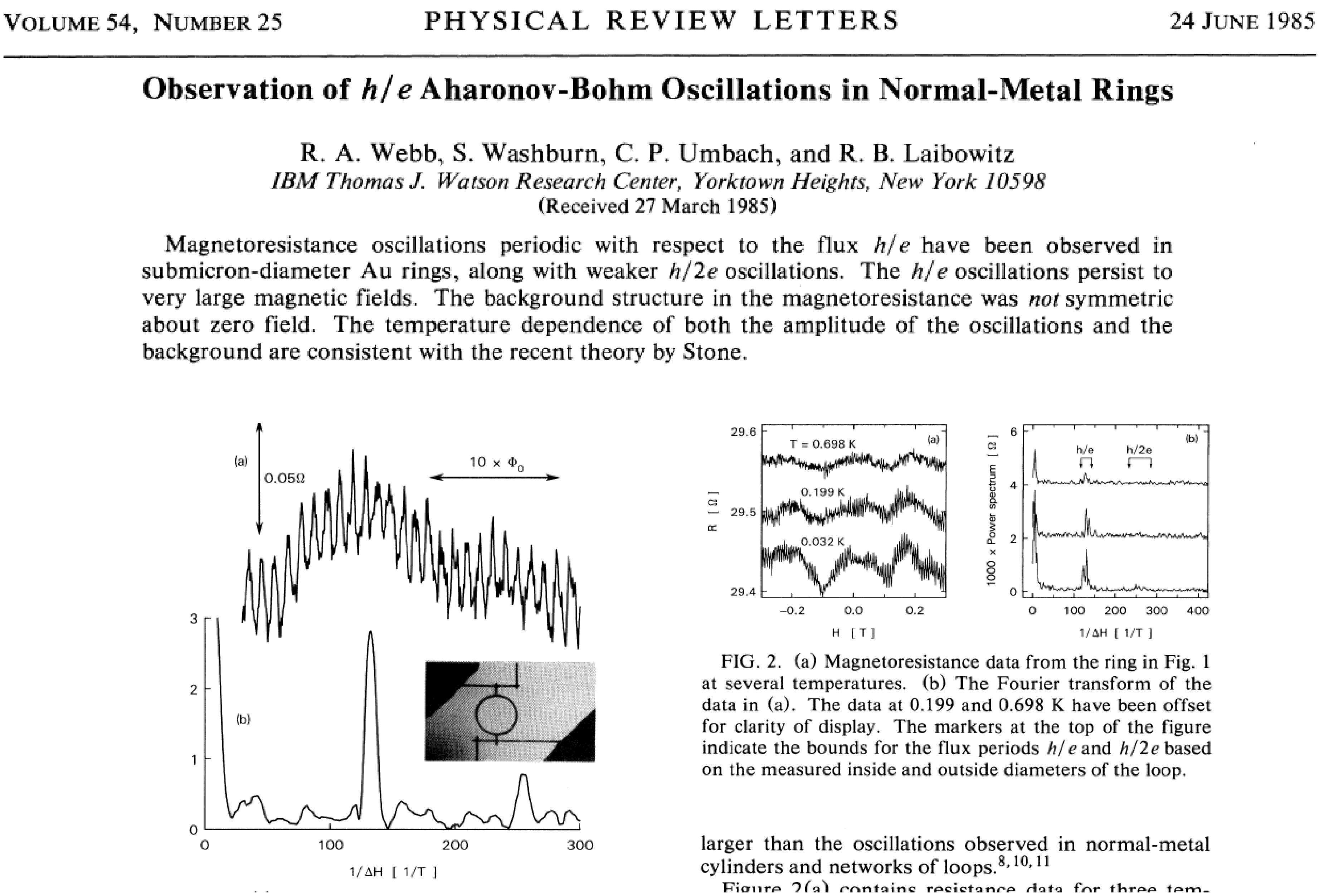
-155
-160
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
1/ΔB (1/T)
1/ΔB (1/T)
Magnetic Field
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0

Aharonov-Bohm Effect



$$\Delta\varphi = e/\hbar\int \vec{A}\cdot d\vec{l} = e/\hbar\int \vec{B}\cdot d\vec{a} = \left(e/\hbar\right)\Phi$$

Illustration: H. Batelaan and A. Tonomura, Physics Today **9**, 38 (2009).



VOLUME 54, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 1985

Observation of h/e Aharonov-Bohm Oscillations in Normal-Metal Rings

R. A. Webb, S. Washburn, C. P. Umbach, and R. B. Laibowitz
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 27 March 1985)

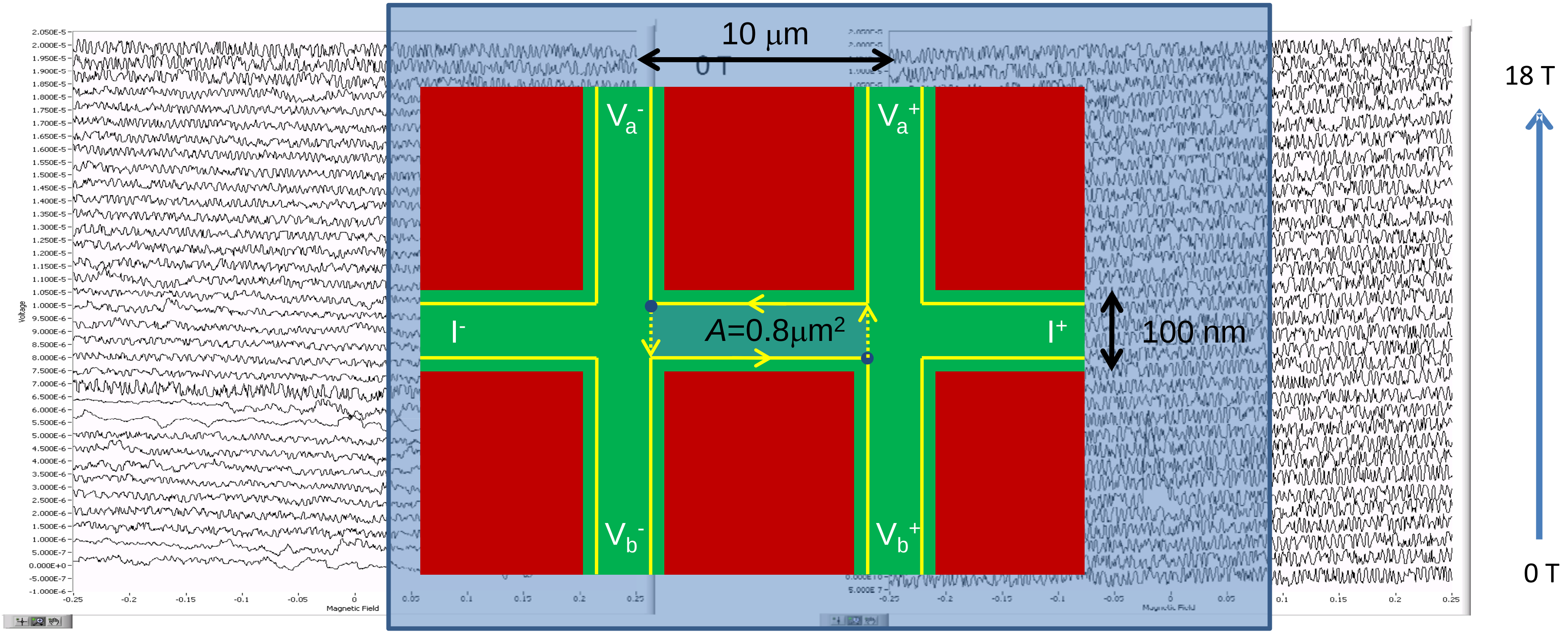
Magnetoresistance oscillations periodic with respect to the flux h/e have been observed in submicron-diameter Au rings, along with weaker $h/2e$ oscillations. The h/e oscillations persist to very large magnetic fields. The background structure in the magnetoresistance was *not* symmetric about zero field. The temperature dependence of both the amplitude of the oscillations and the background are consistent with the recent theory by Stone.

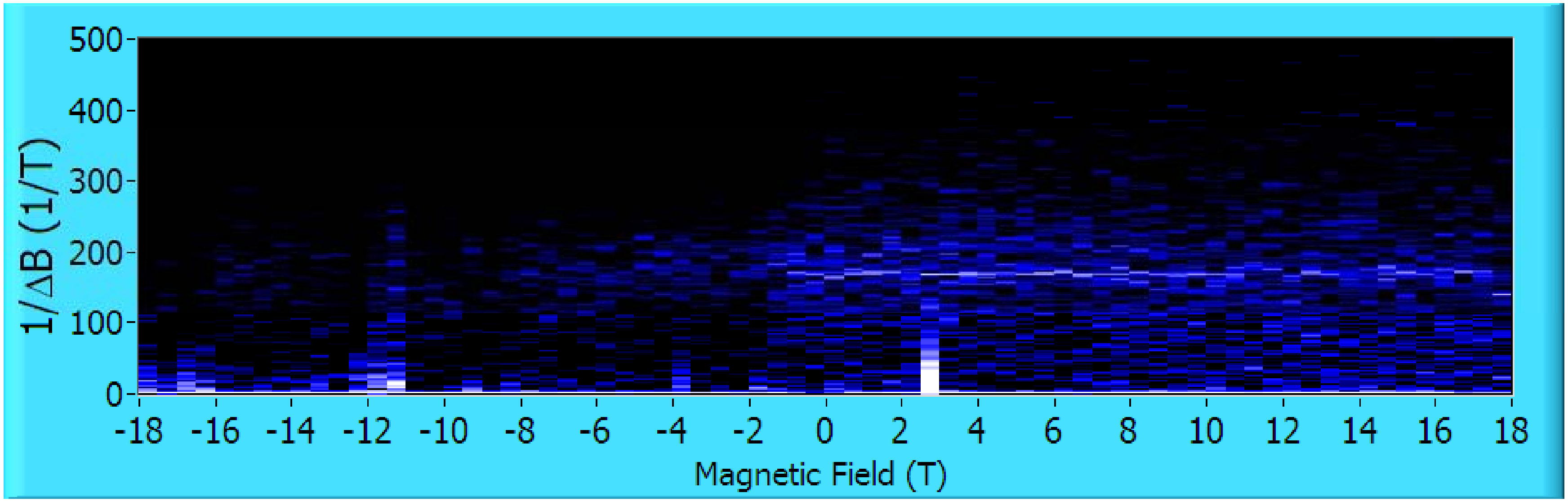
FIG. 2. (a) Magnetoresistance data from the ring in Fig. 1 at several temperatures. (b) The Fourier transform of the data in (a). The data at 0.199 and 0.698 K have been offset for clarity of display. The markers at the top of the figure indicate the bounds for the flux periods h/e and $h/2e$ based on the measured inside and outside diameters of the loop.

larger than the oscillations observed in normal-metal cylinders and networks of loops.[8,10,11]

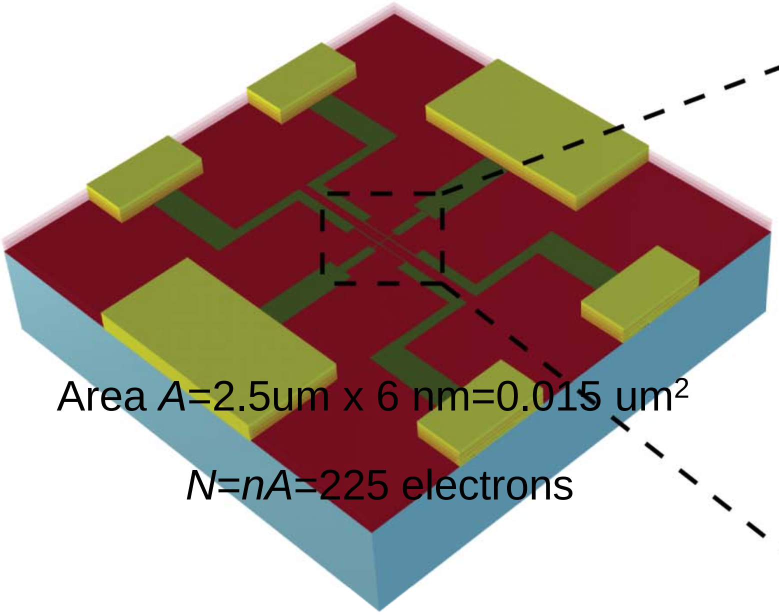
Figure 2(a) contains resistance data for three tem-

Aharanov-Bohm Oscillations



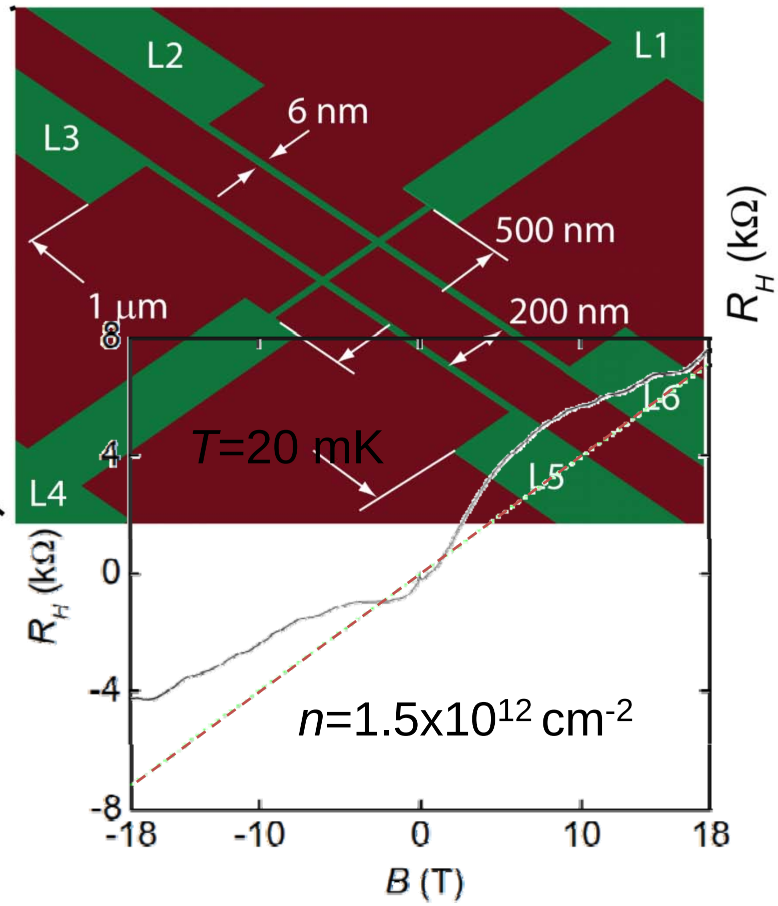


60 Å Hall cross



Area A=2.5um x 6 nm=0.015 um^2

N=nA=225 electrons

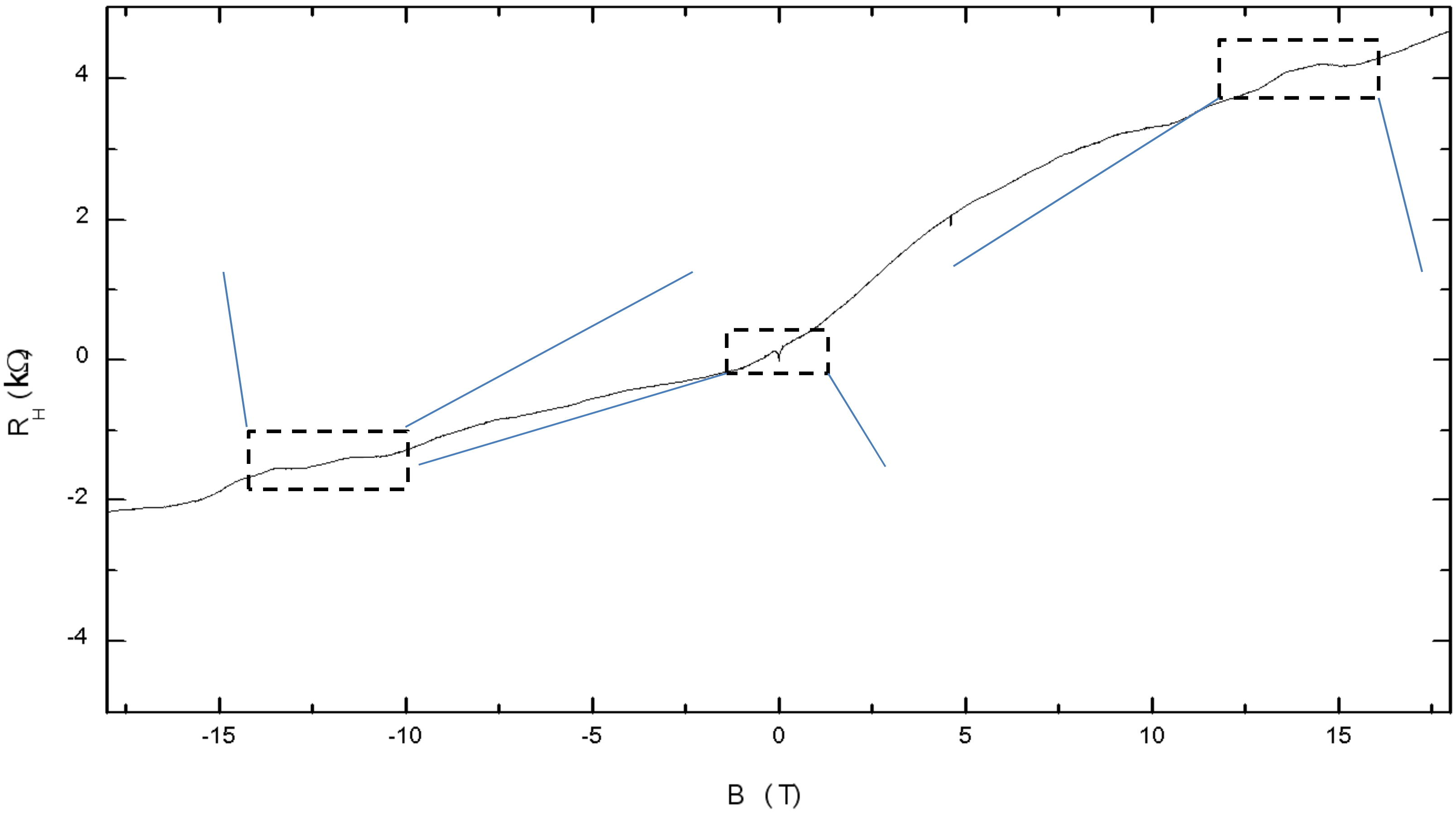


T=20 mK

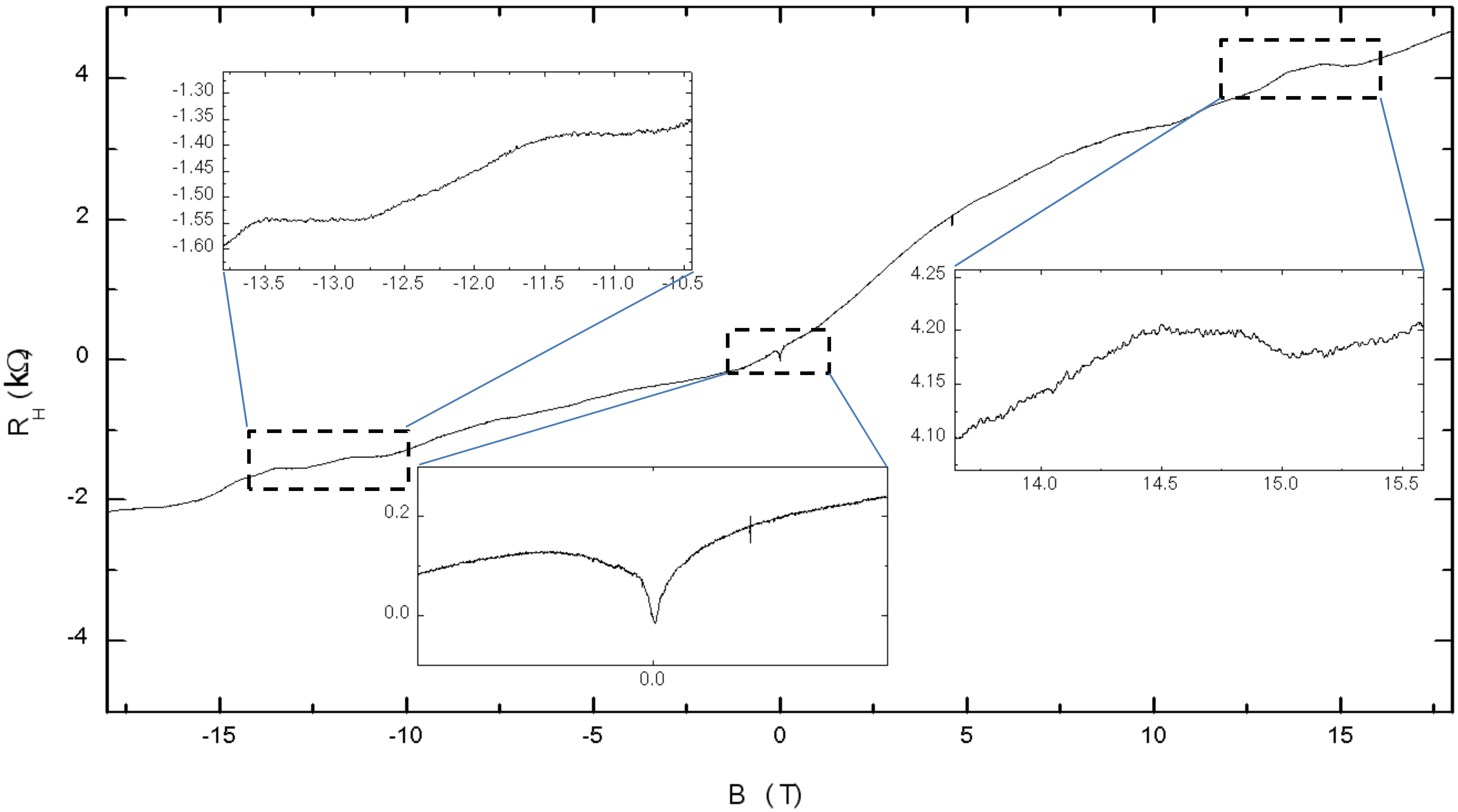
n=1.5x10^{12} cm^{-2}

- Anomalous Hall response for |B|<2 T
- Plateaus for |B|>10 T

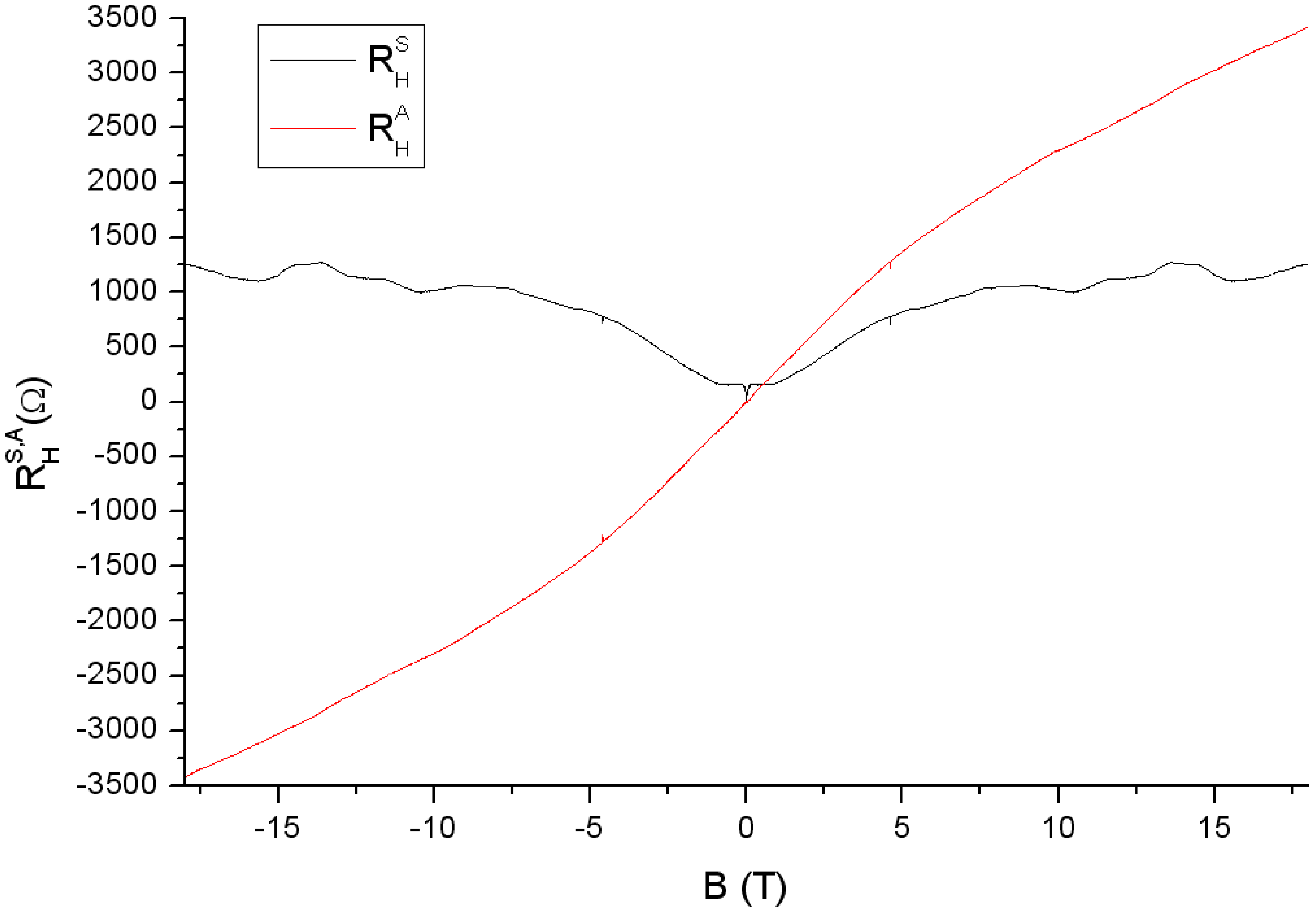
Hall Resistance



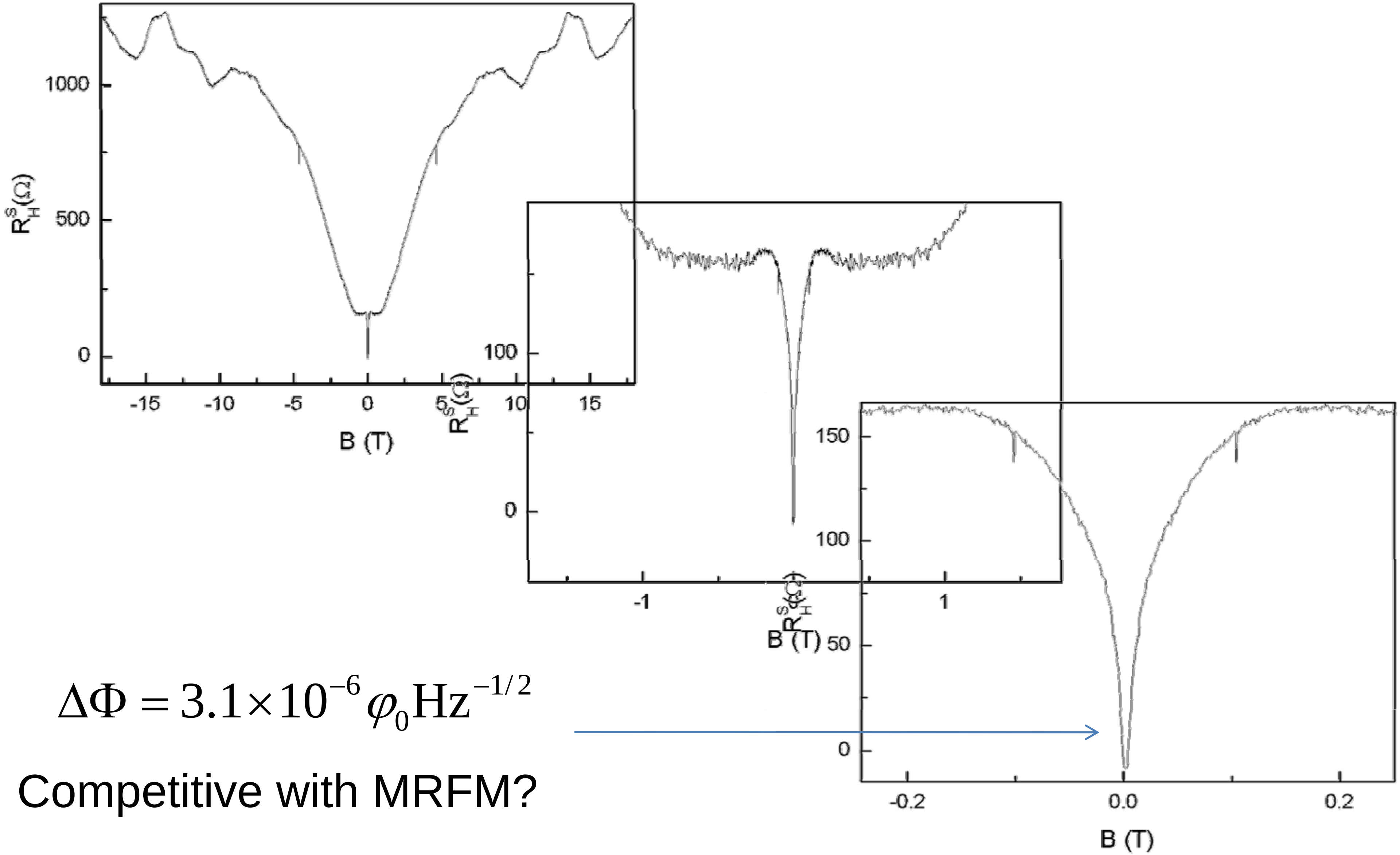
Hall Resistance



Symmetric and Antisymmetric Components



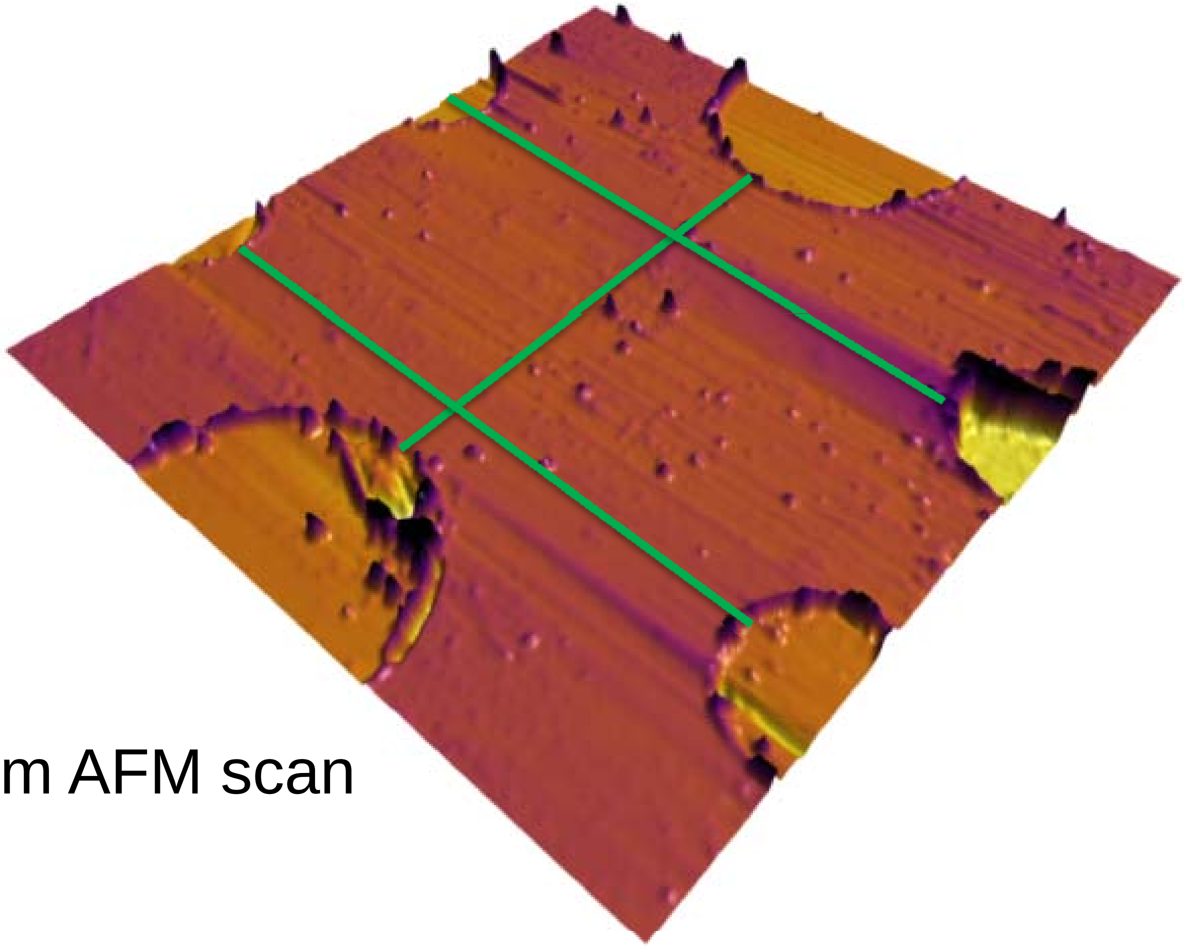
Ultrasensitive (spin?) Hall Nanosensor



$$\Delta\Phi = 3.1\times10^{-6}\varphi_0\mathrm{Hz}^{-1/2}$$

Competitive with MRFM?

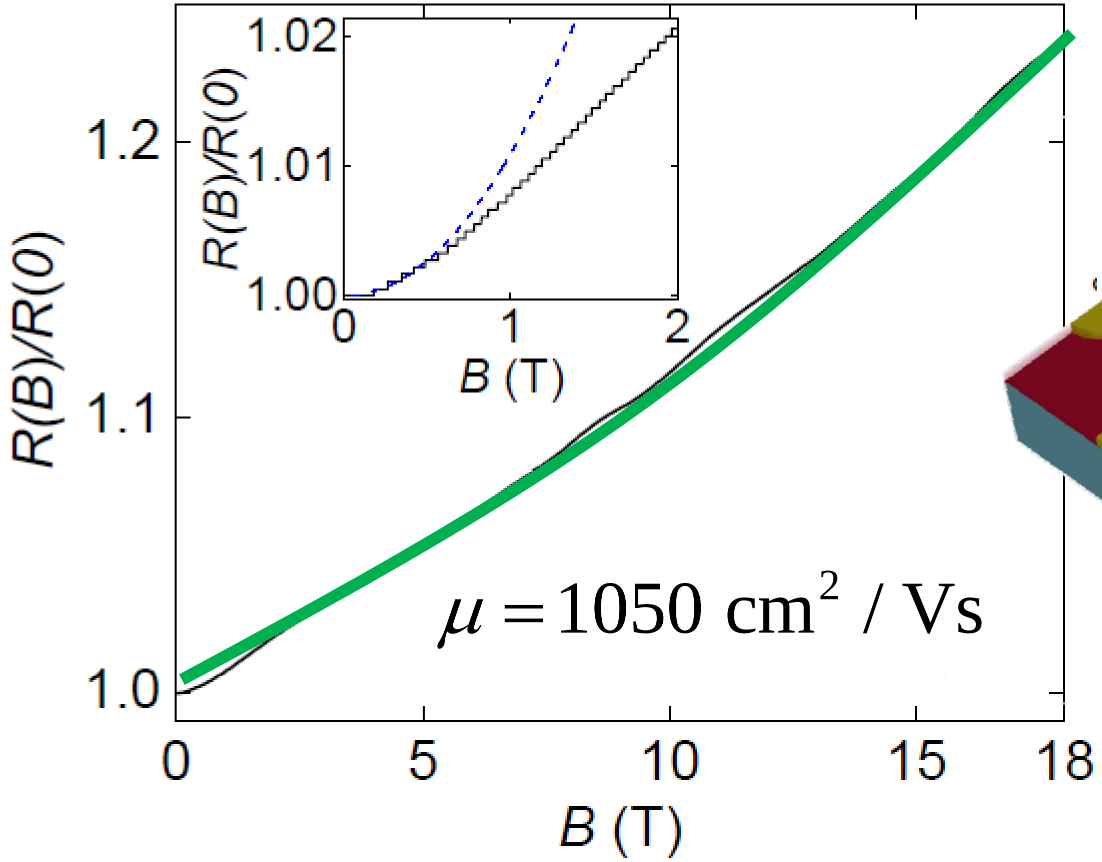
Low-Density Nanostructure



50µm x 50µm AFM scan

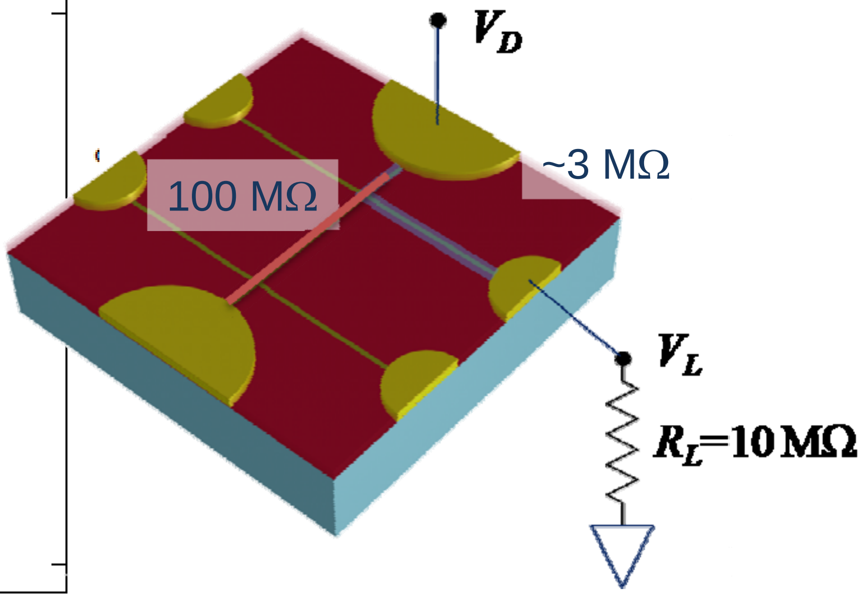
Magnetoresistance @ 250 mK

$$R(B) \approx R(0)\left(1 + (\mu_0 B)^2\right)$$



$$\mu = 1050\ \mathrm{cm}^2/\mathrm{Vs}$$

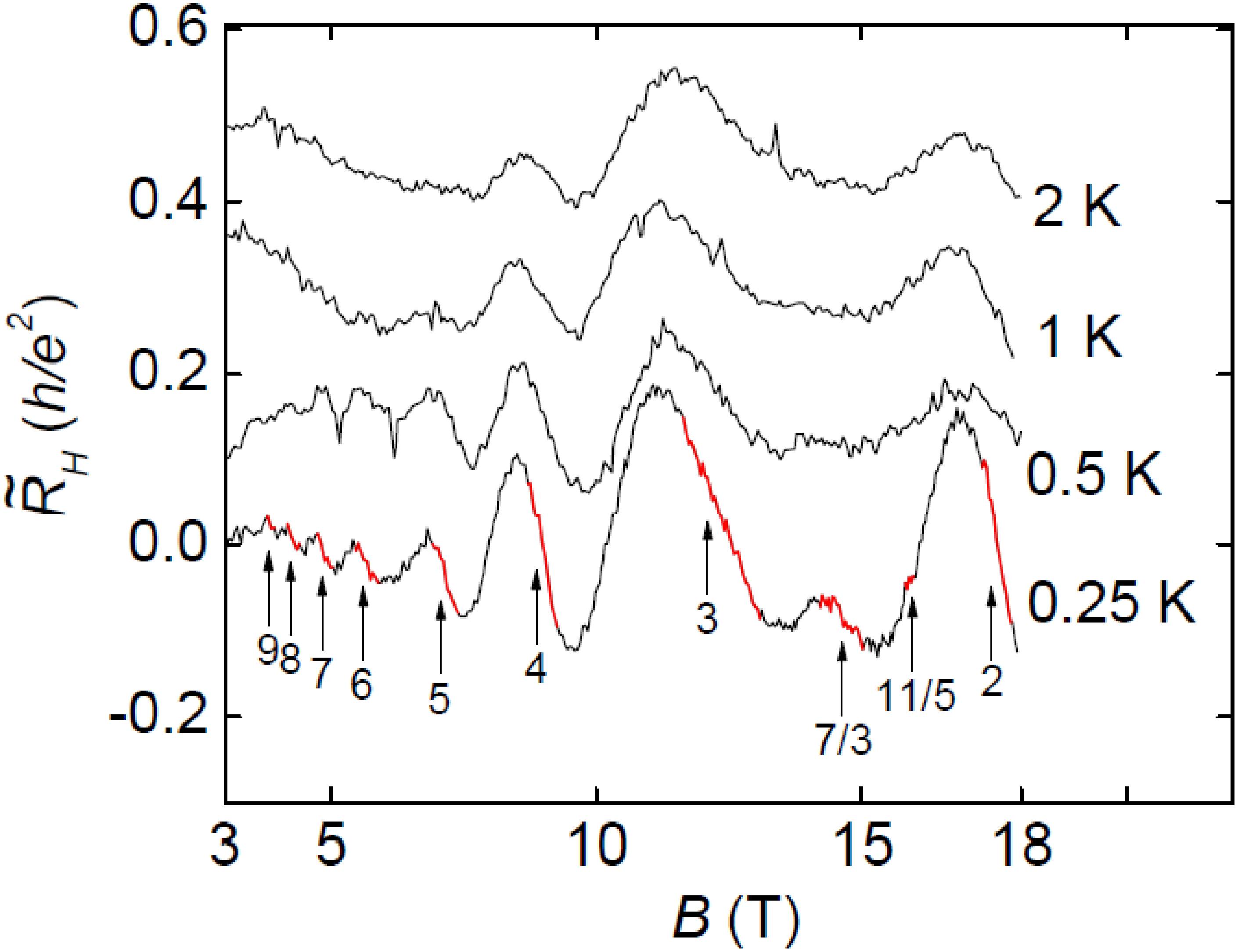
Hall leads -> insulating



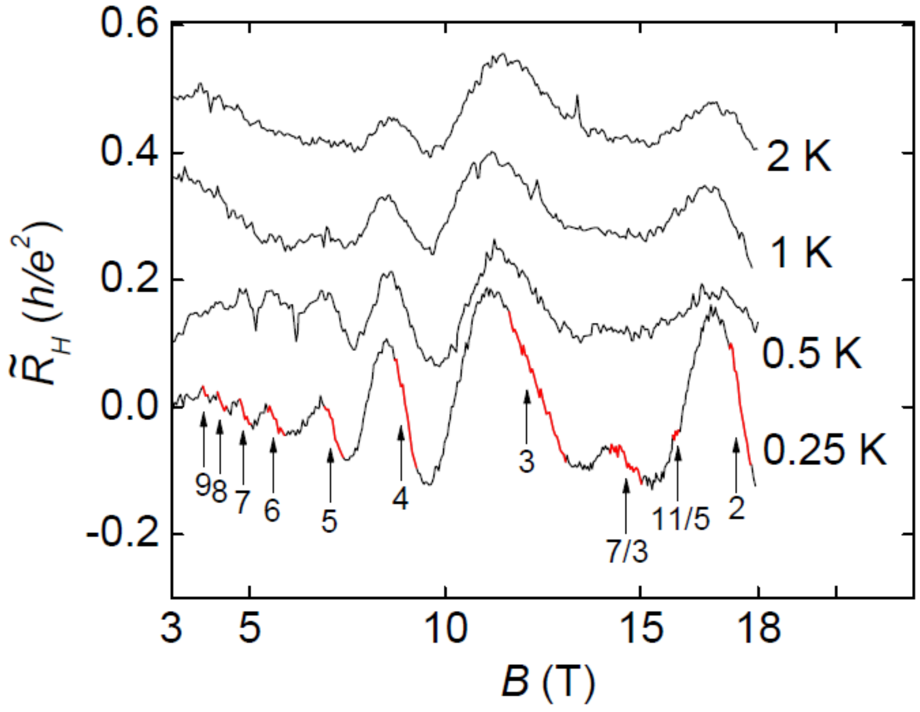
Subtract linear (+ weak parabolic) background…

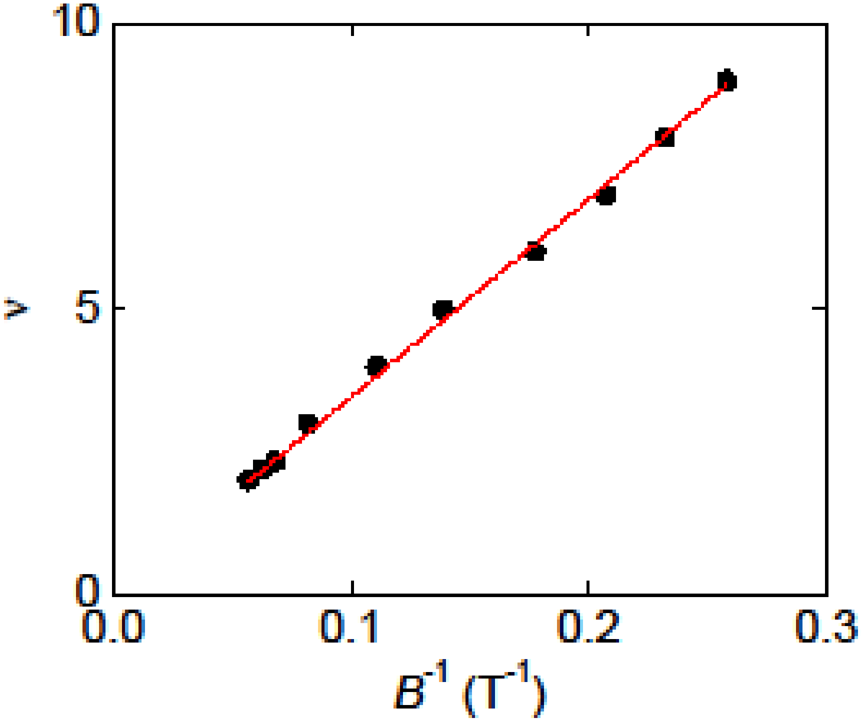
$$R_C(B) = R(0)\left(1 + C_1 B + C_2 B^2\right)$$

Magnetoresistance Plateaus



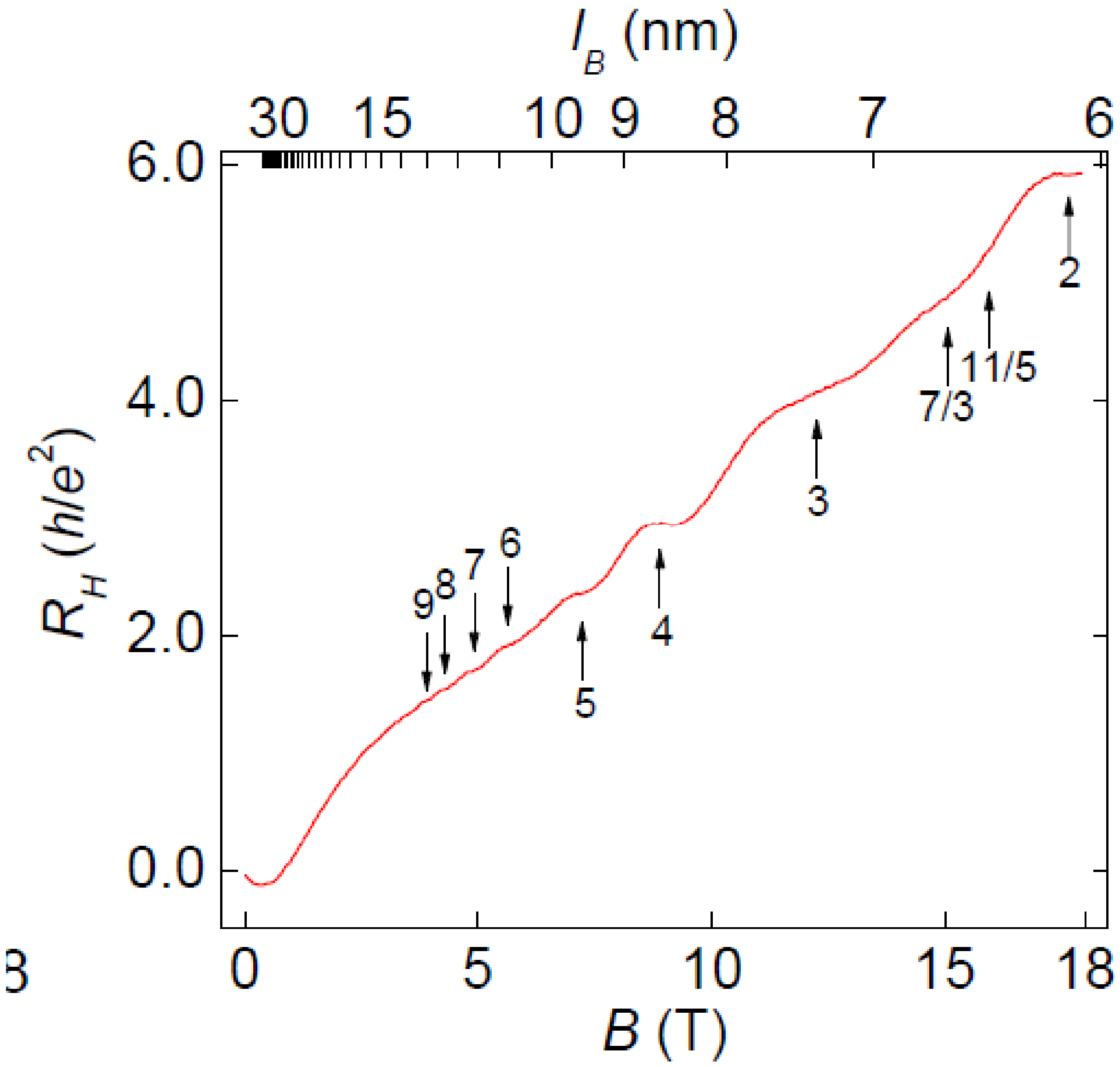
Landau Levels (integer and fractional)





$$n = 8 \times 10^{11} \mathrm{cm}^{-2}$$

Magnetoresistance Plateaus



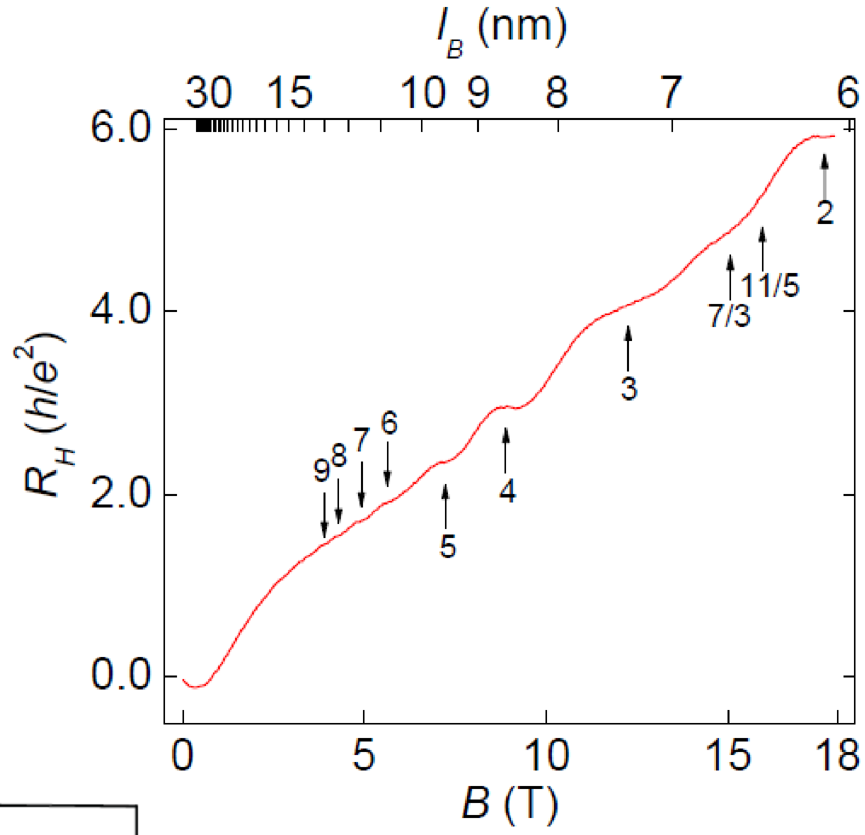
Edge State Picture

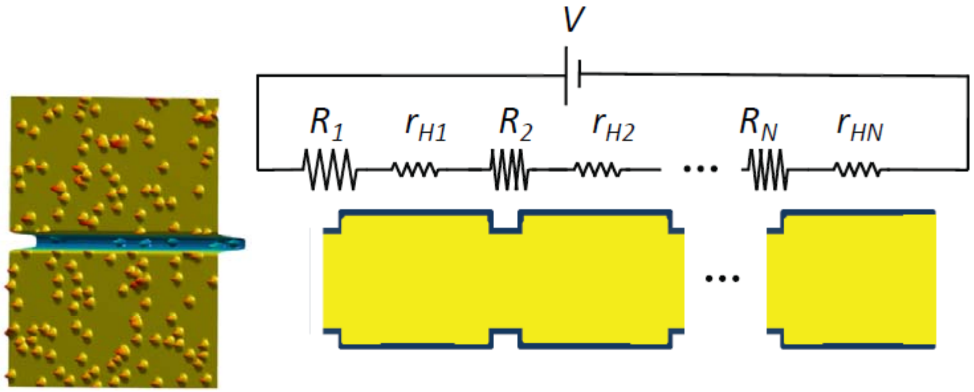
Density is below metal-insulator transition

Two-terminal Landauer-Buttiker formalism: absence of back-scattering from edge states in QH regime

$$R = R_H + R_C$$

$$R_H = \sum_{k=1}^{N} r_{Hk} = \frac{Nh}{\nu e^2}$$



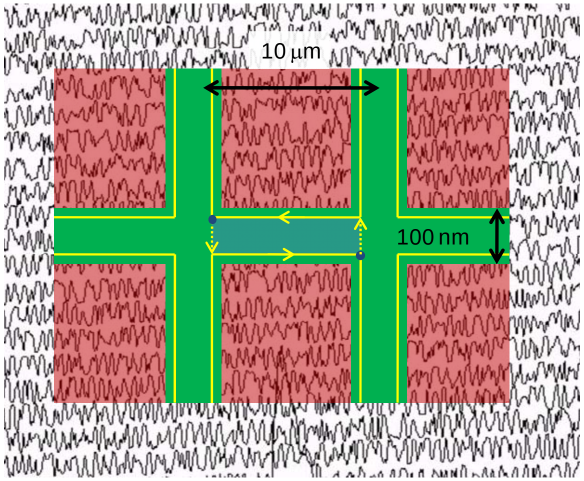


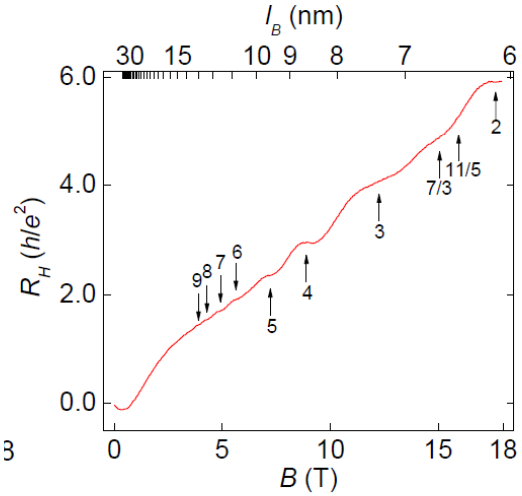
$$N = 12 \pm 2$$

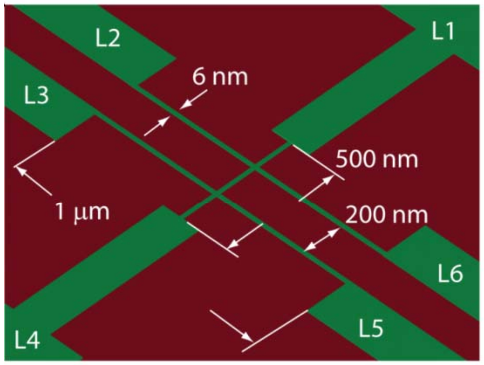
FUTURE DIRECTIONS

Summary and Future Directions

- Oxides replay “Physics Hits of the ’80s”
  - Aharanov-Bohm oscillations
  - Integer and fractional quantum Hall
  - Reduced dimensionality/edge states (1d) plays critical role





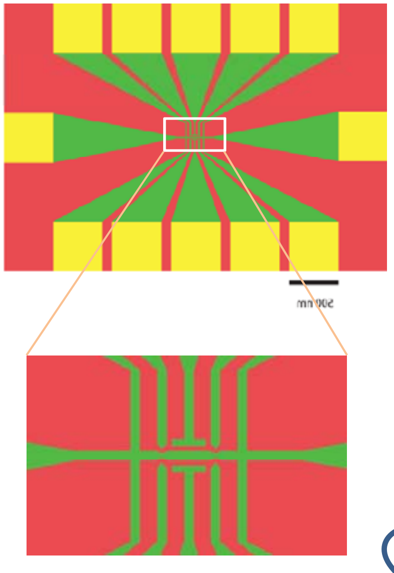


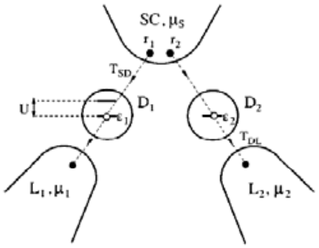
Summary and Future Directions

- Oxides replay “Physics Hits of the ’80s”
  - Aharanov-Bohm oscillations
  - Integer and fractional quantum Hall
  - Reduced dimensionality/edge states (1d) plays critical role

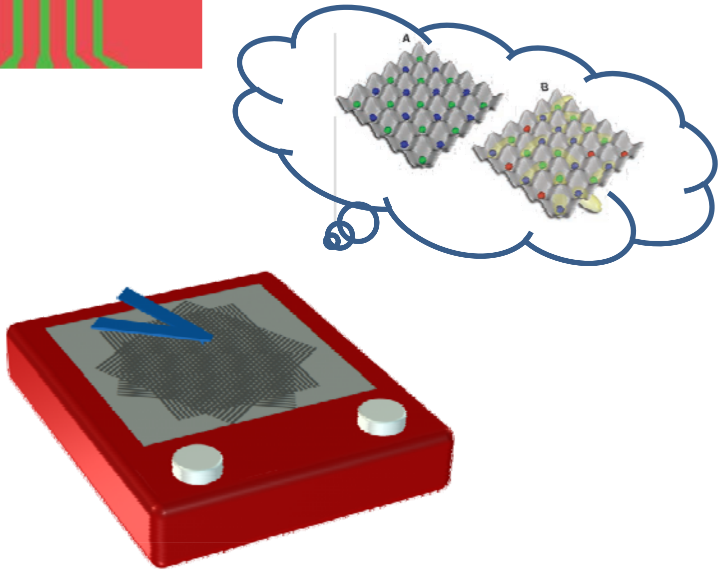
- Future directions
  - Superconducting nanostructures
  - Topological quantum computation
  - Hubbard simulators
  - …

Topological quantum bit





Andreev Entangler
(Recher and Loss, 2001)



Oxide Nanoelectronic
Hubbard Simulator