Quantum Transport in InAs/GaSb

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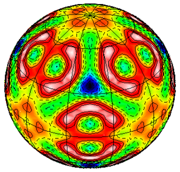

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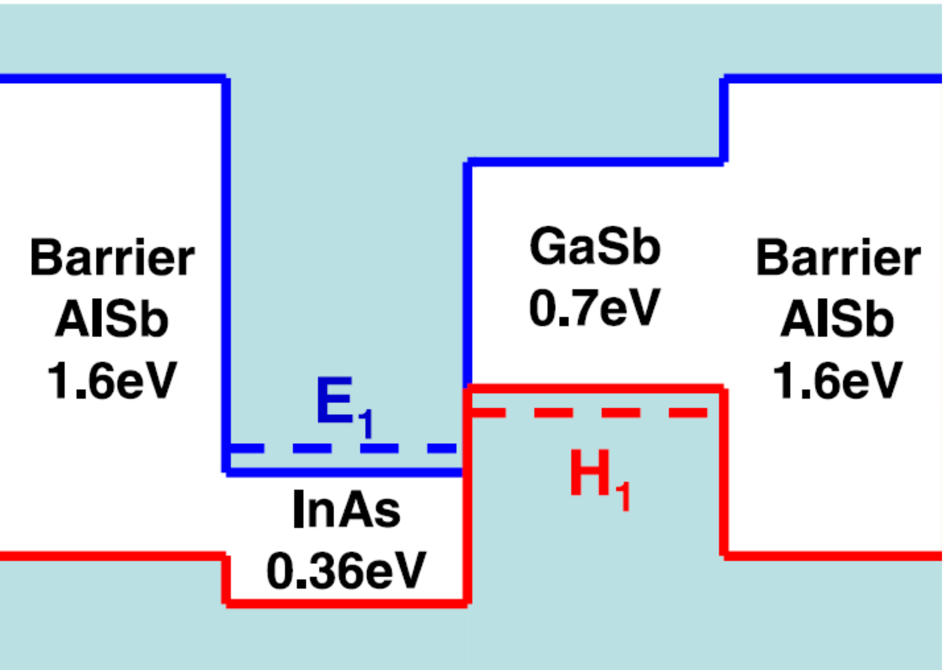
Outline

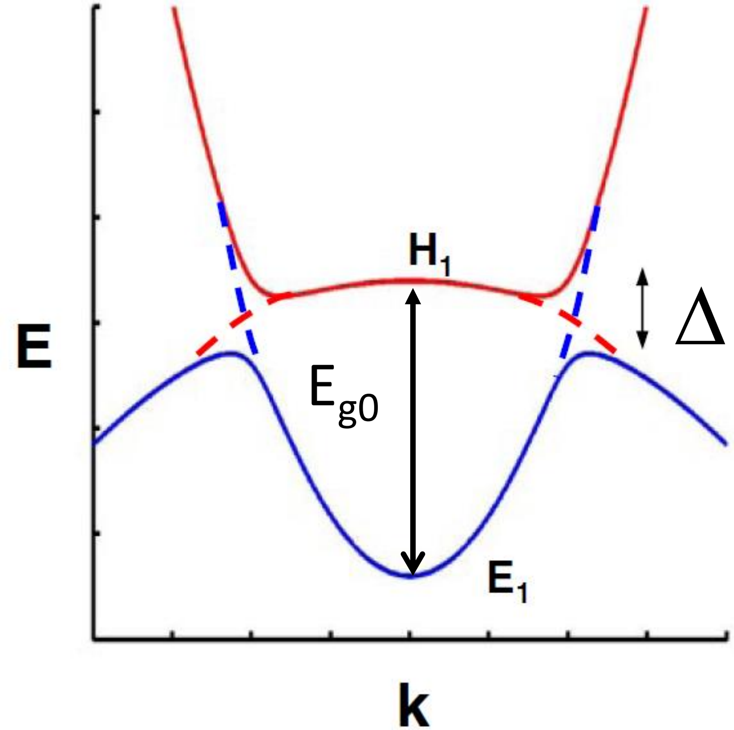
- InAs/GaSb heterostructure

- The experiments and results
  - Circular conductivity law in the charge neutrality regime in an InAs/GaSb field-effect-transistor
  - McMillan-Rowell like oscillations in a Ta-InAs/GaSb-Ta junction
  - Giant supercurrent in a Ta-InAs/GaSb-Ta junction

- Summary

InAs/GaSb heterostructure:





Quantum spin Hall effect

C.X. Liu, T.L. Hughes, X.L. Qi, K. Wang, and S.C. Zhang, Phys. Rev. Lett. **100**, 236601 (2008).

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Growth structure:

air

InAs 20A (or GaSb 20A)

AlSb 500A

GaSb QW 50A

InAs QW 150A

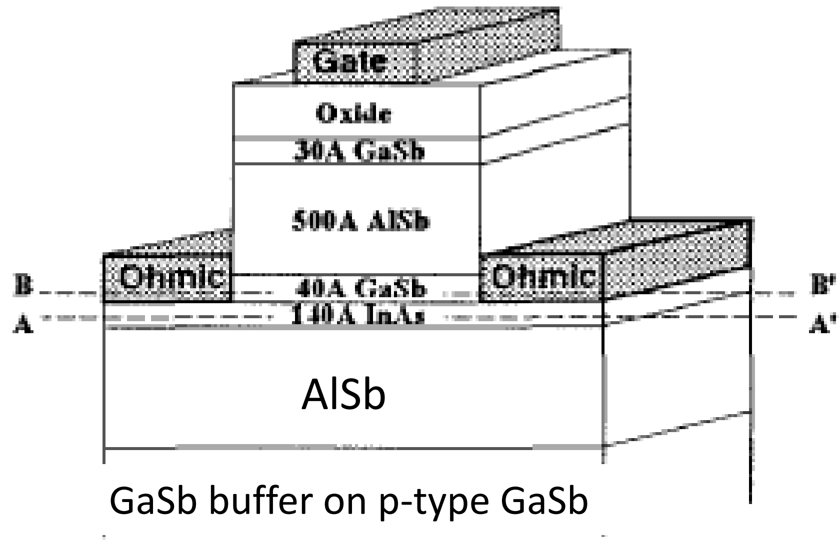
AlSb 1um

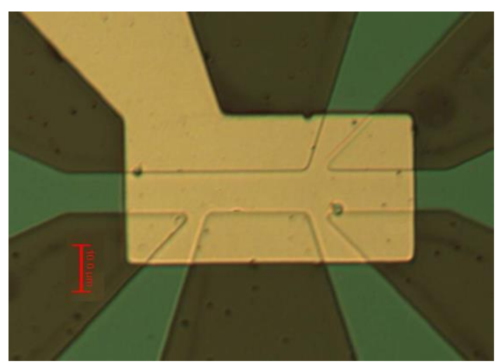
GaSb 1um

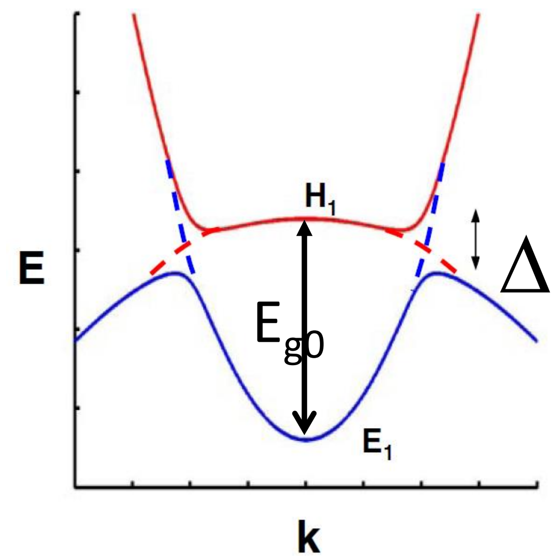
GaSb substrate (p-doped)

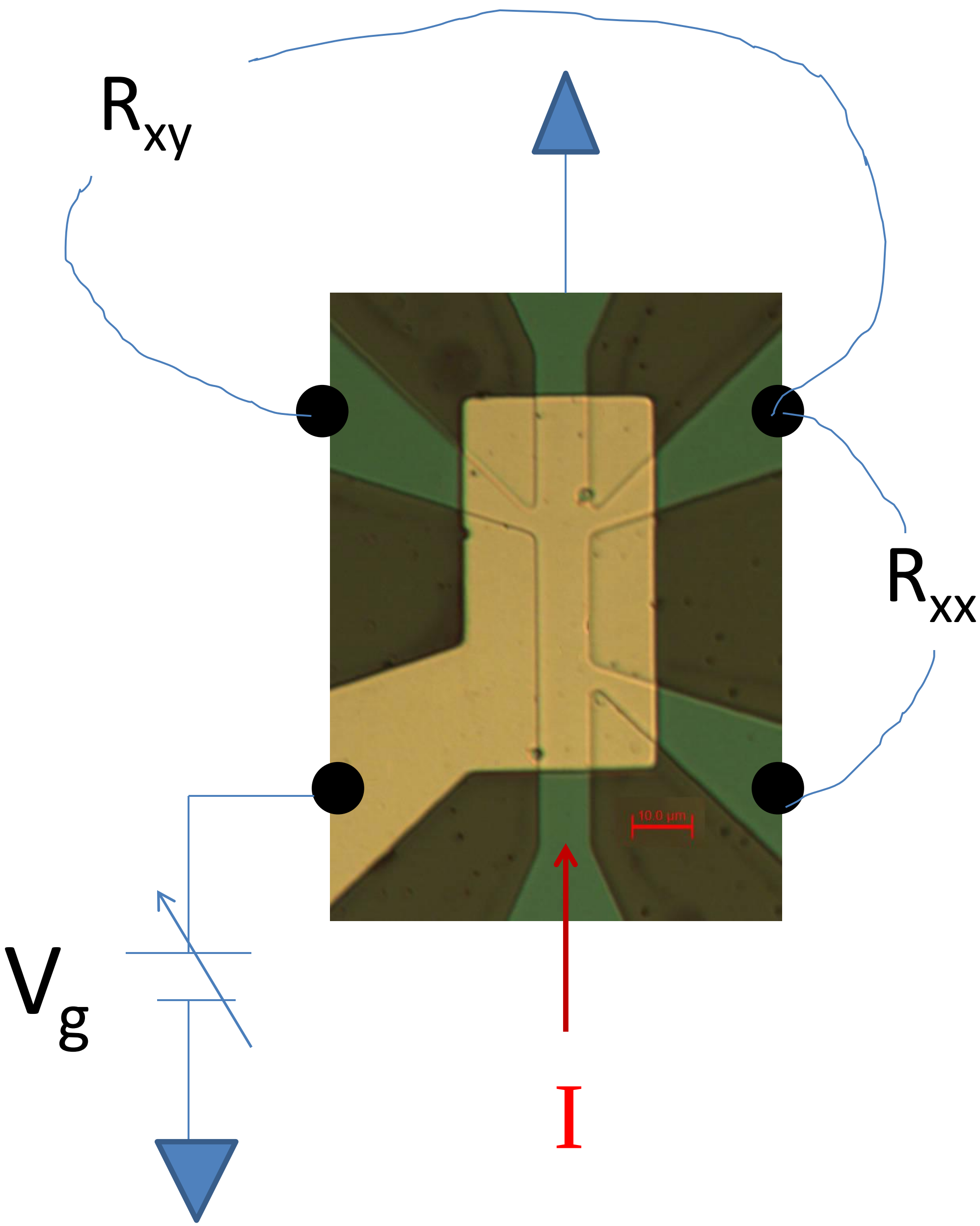
Field-effect transistor:

Yang et al, Appl. Phys. Lett. **69**, 85 (1996).



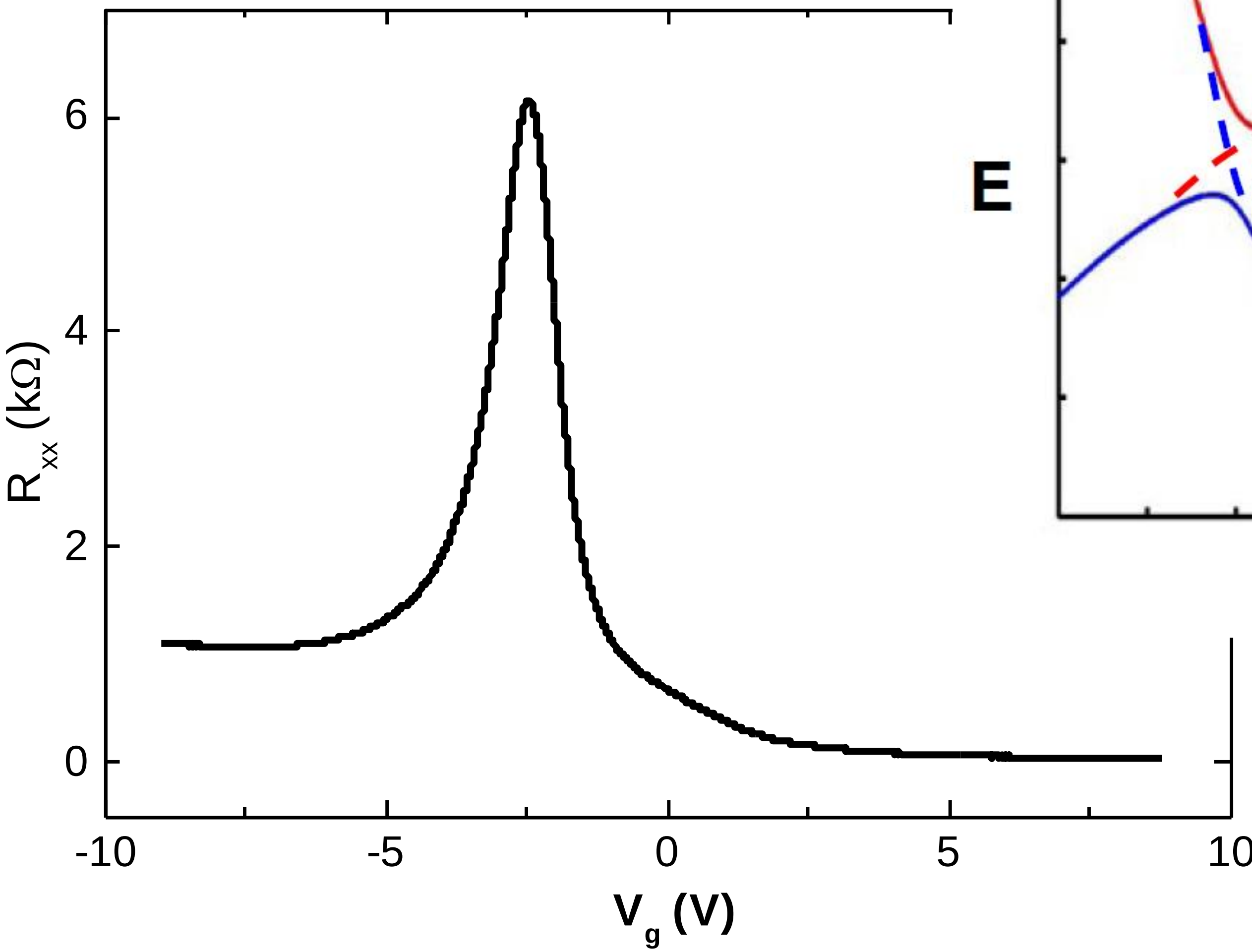


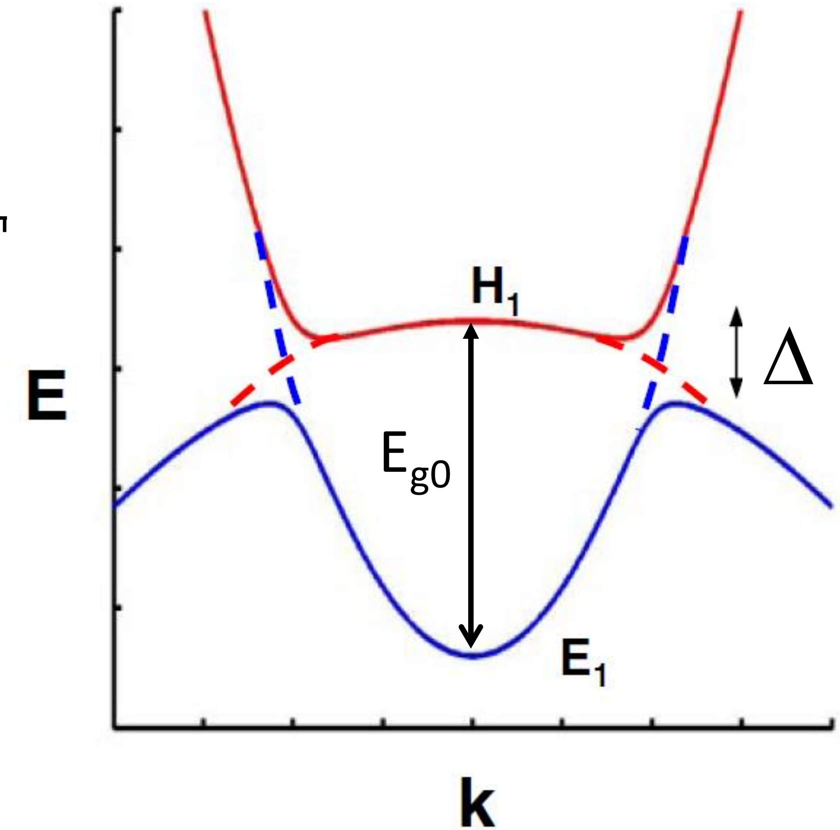


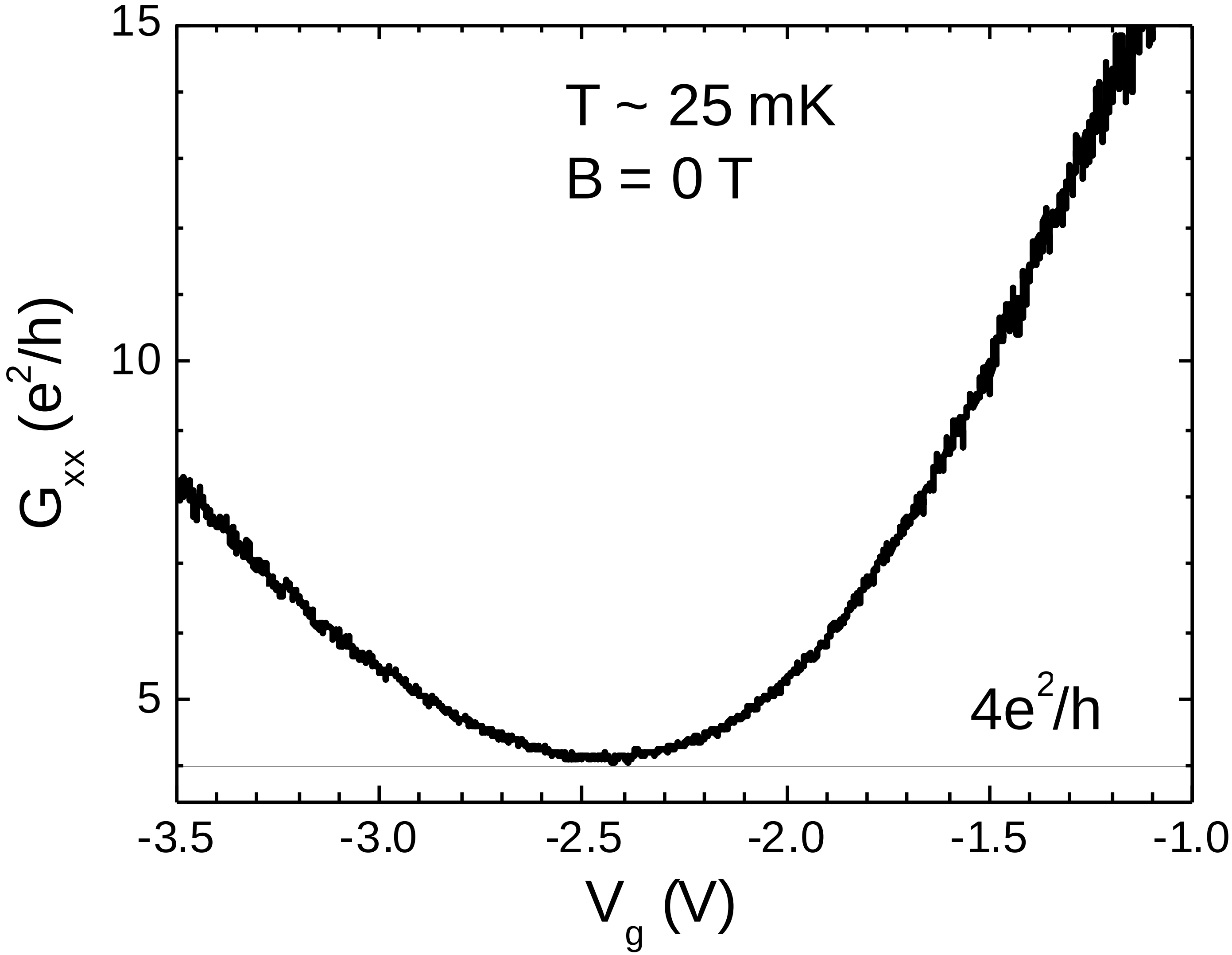


R_xy
R_xx
V_g
I
10.0 µm

Electron transport at zero magnetic field:



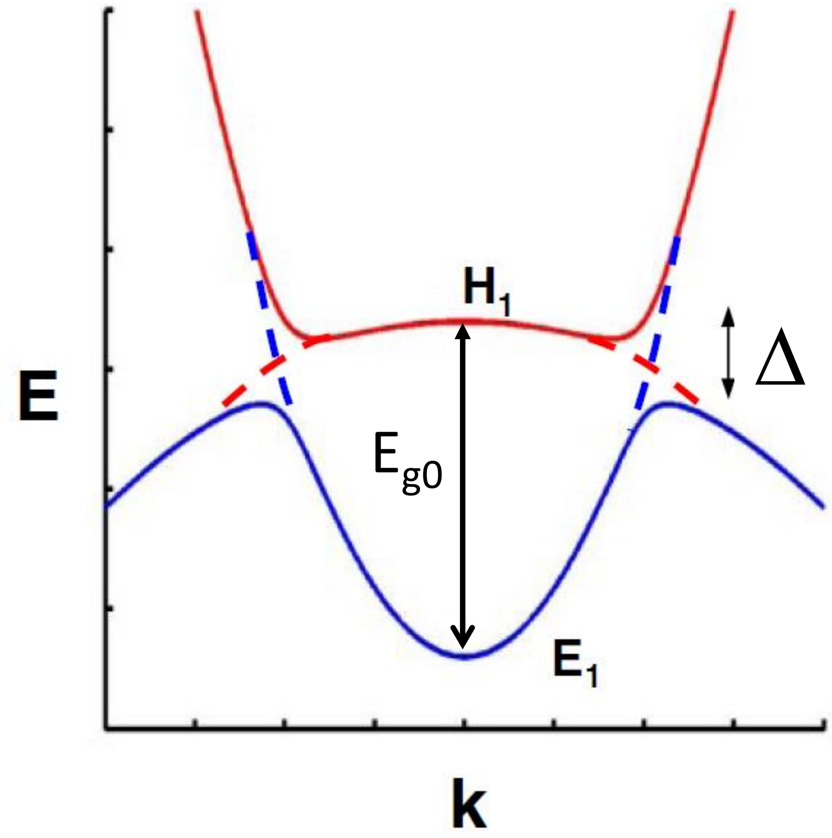




T ~ 25 mK
B = 0 T
4e²/h
15
10
5
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
G_{xx} (e^2/h)
V_g (V)

$$\sigma^{th}_{xx} \approx e^2/h \times E_{g0}/\Delta$$

Y. Naveh and B. Laikhtman, Europhys. Lett. **55**, 545 (2001).

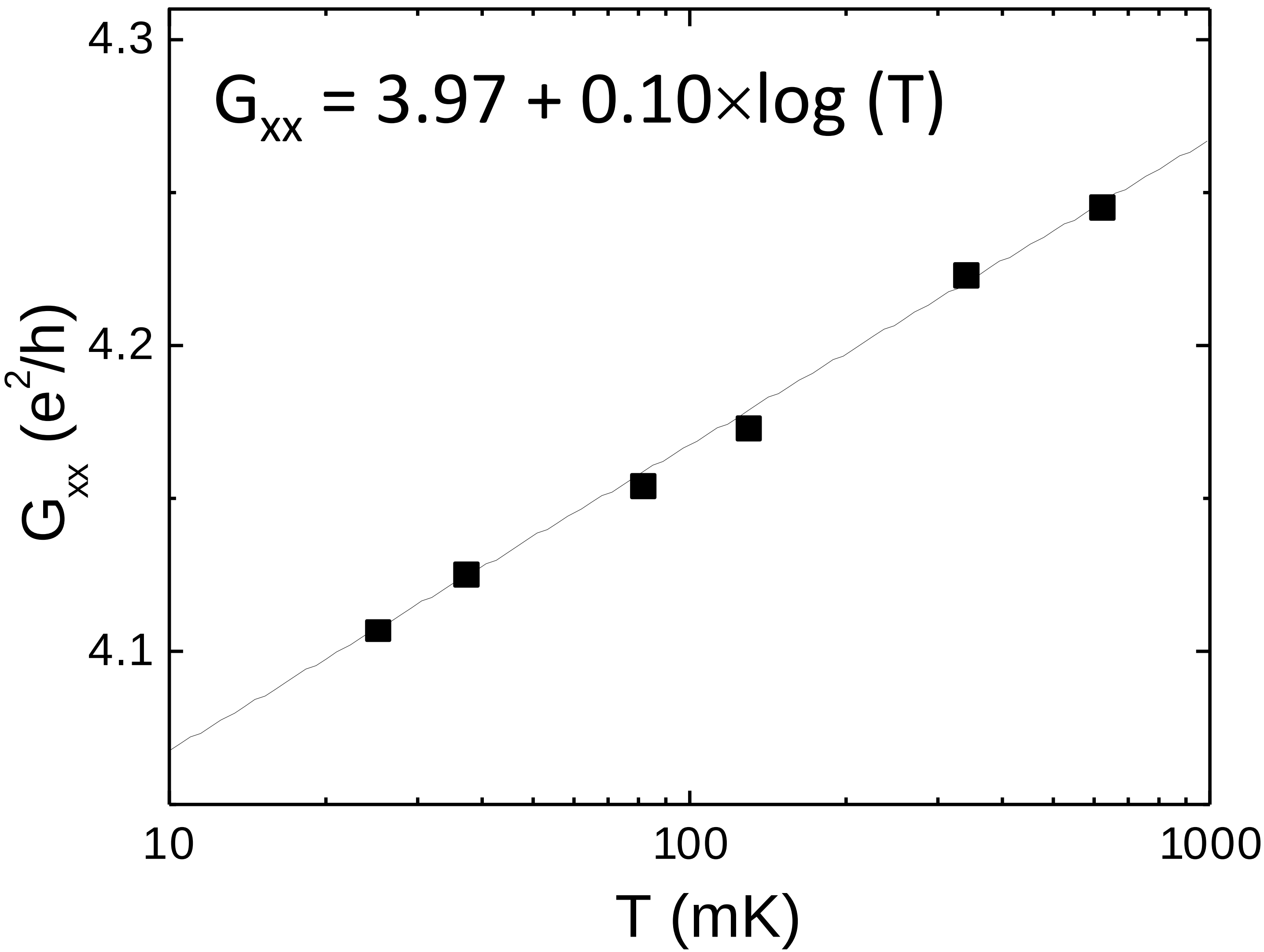


$E_{g0} \sim 15$ meV

$\Delta \sim 1$ meV

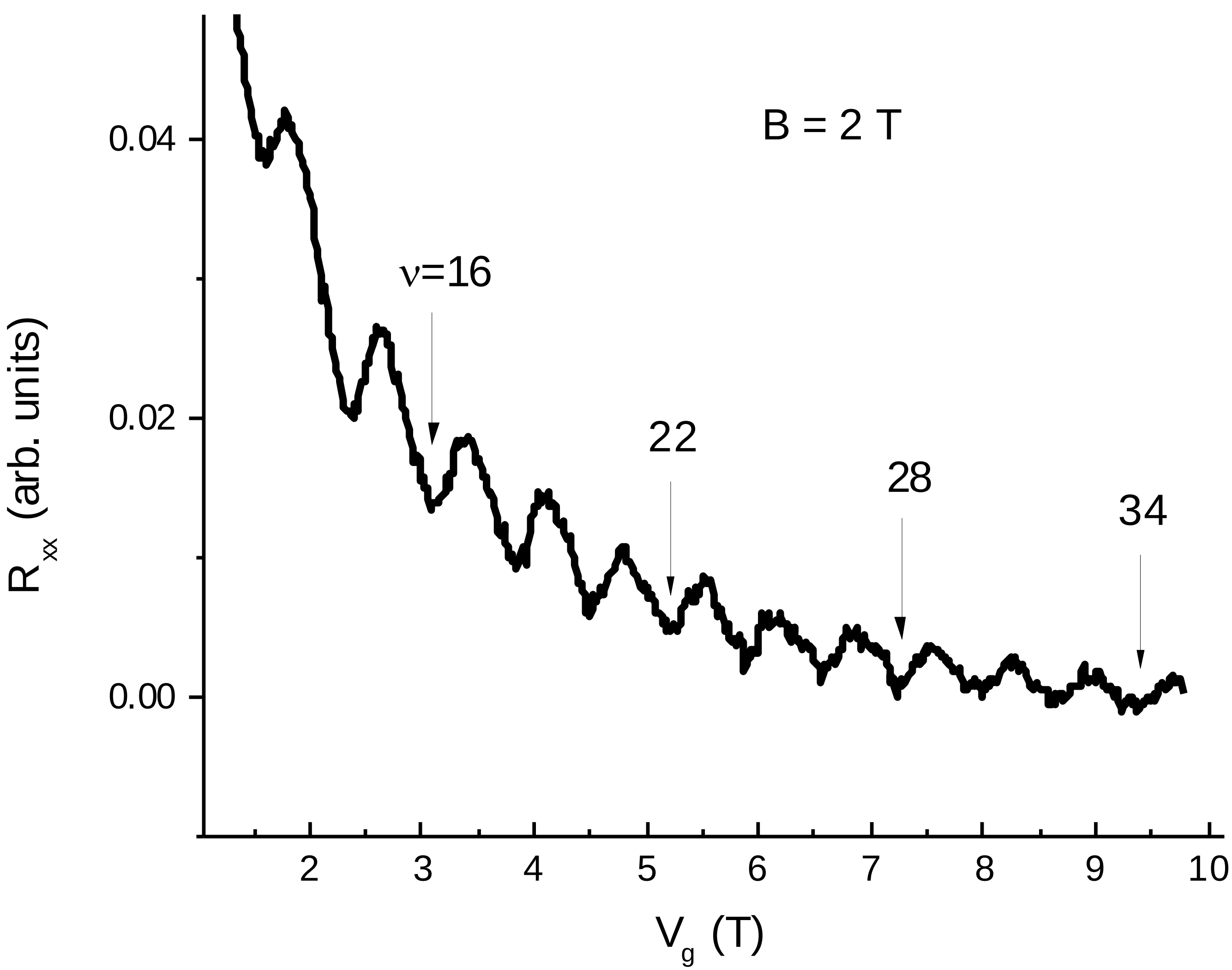
$\sigma^{th}_{xx} \approx 15\ e^2/h$

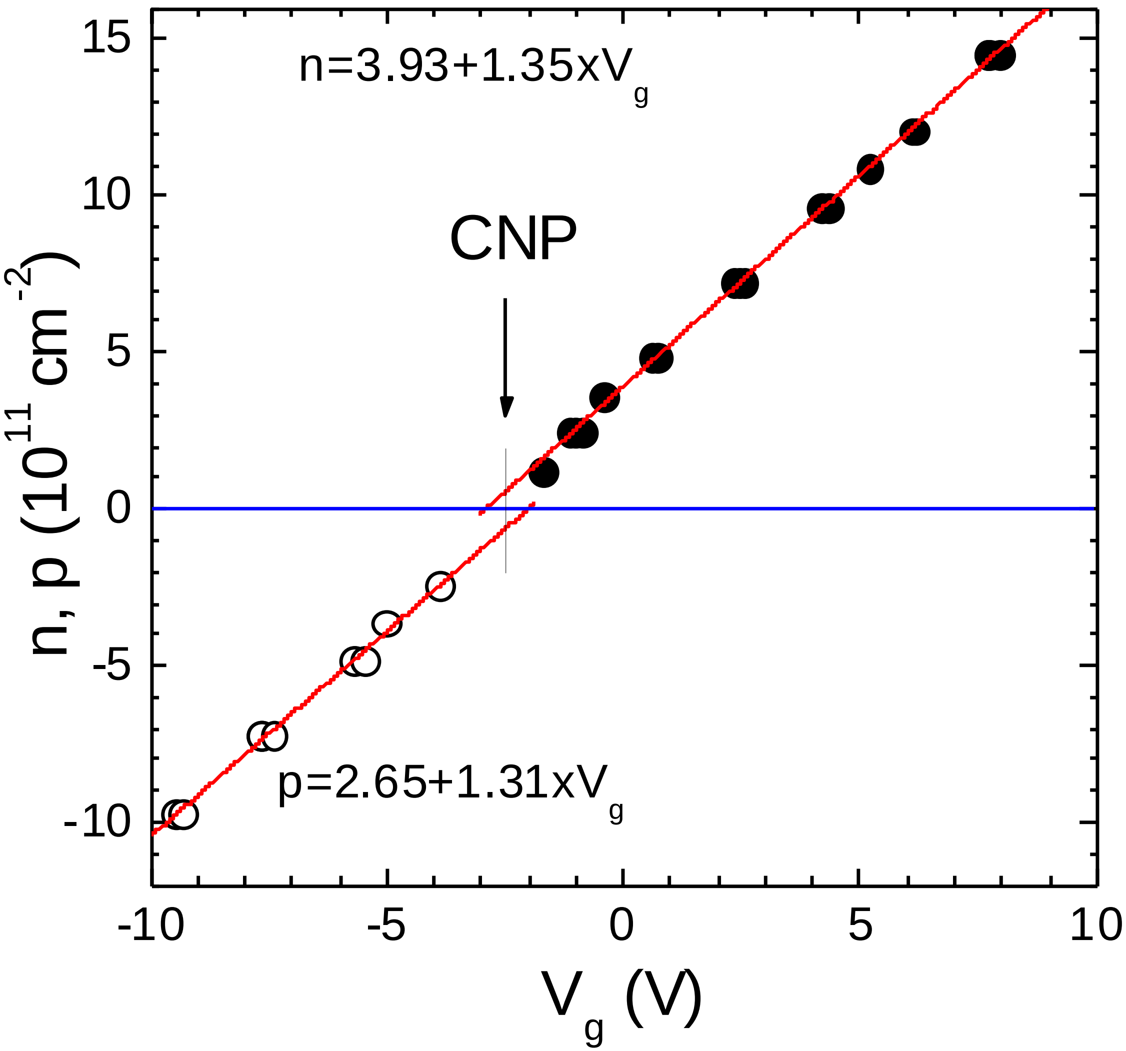
$G^{th}_{xx} = 5\ e^2/h \sim 4\ e^2/h$



L.J. Cooper et al, Phys. Rev. B 57 11915 (1998)

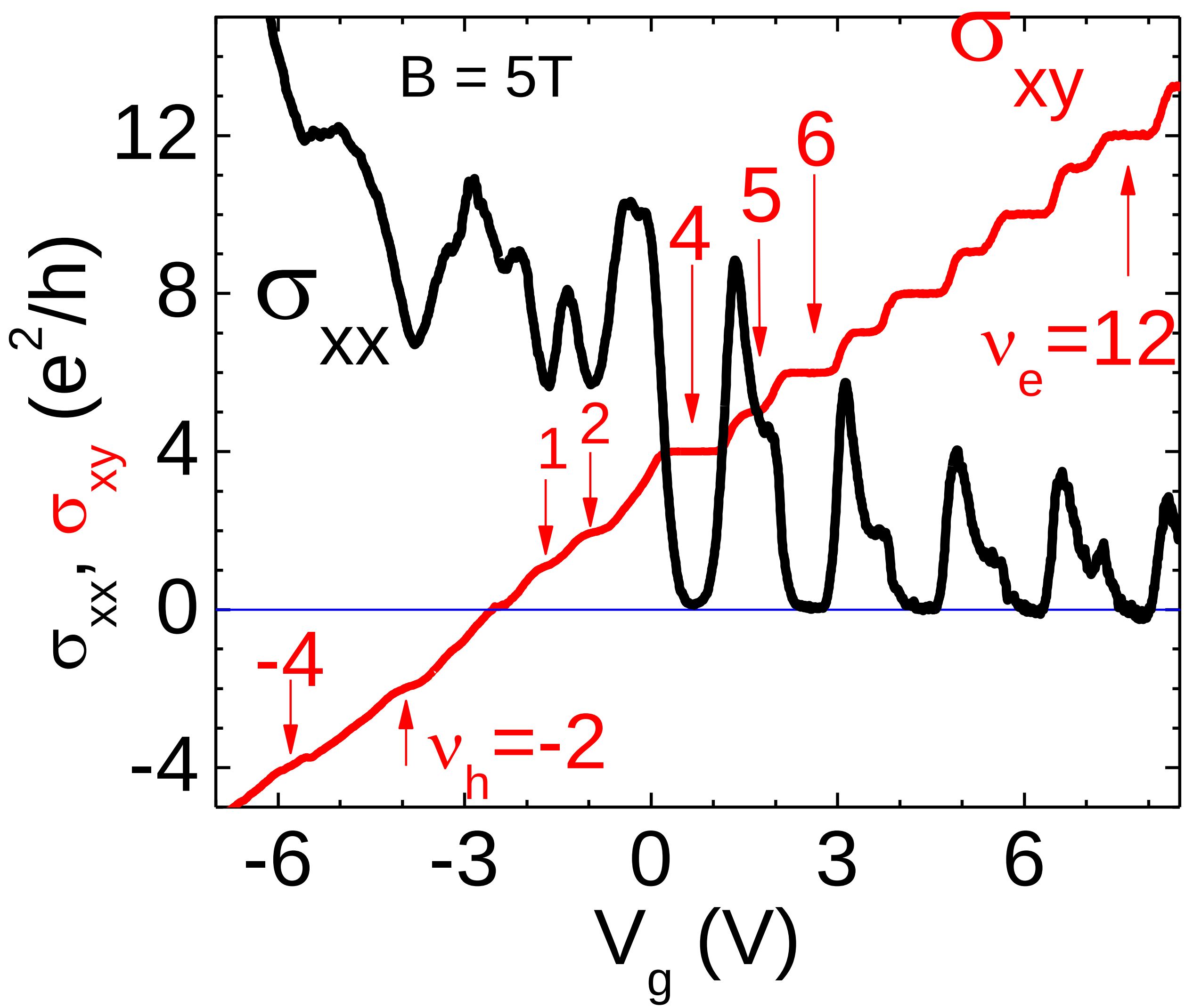
Electron transport at low magnetic fields:





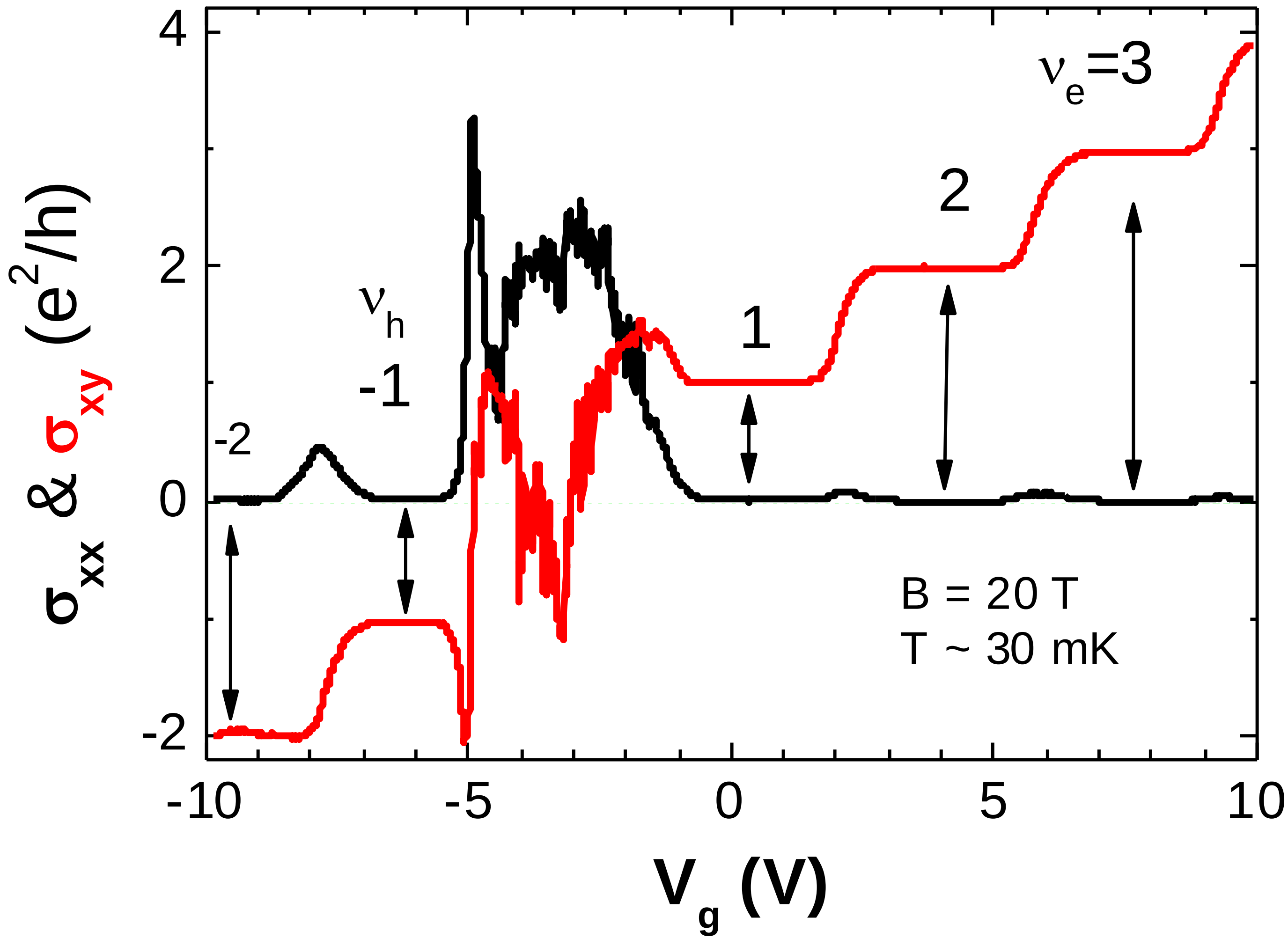
At charge neutrality point CNP (n + p =0)

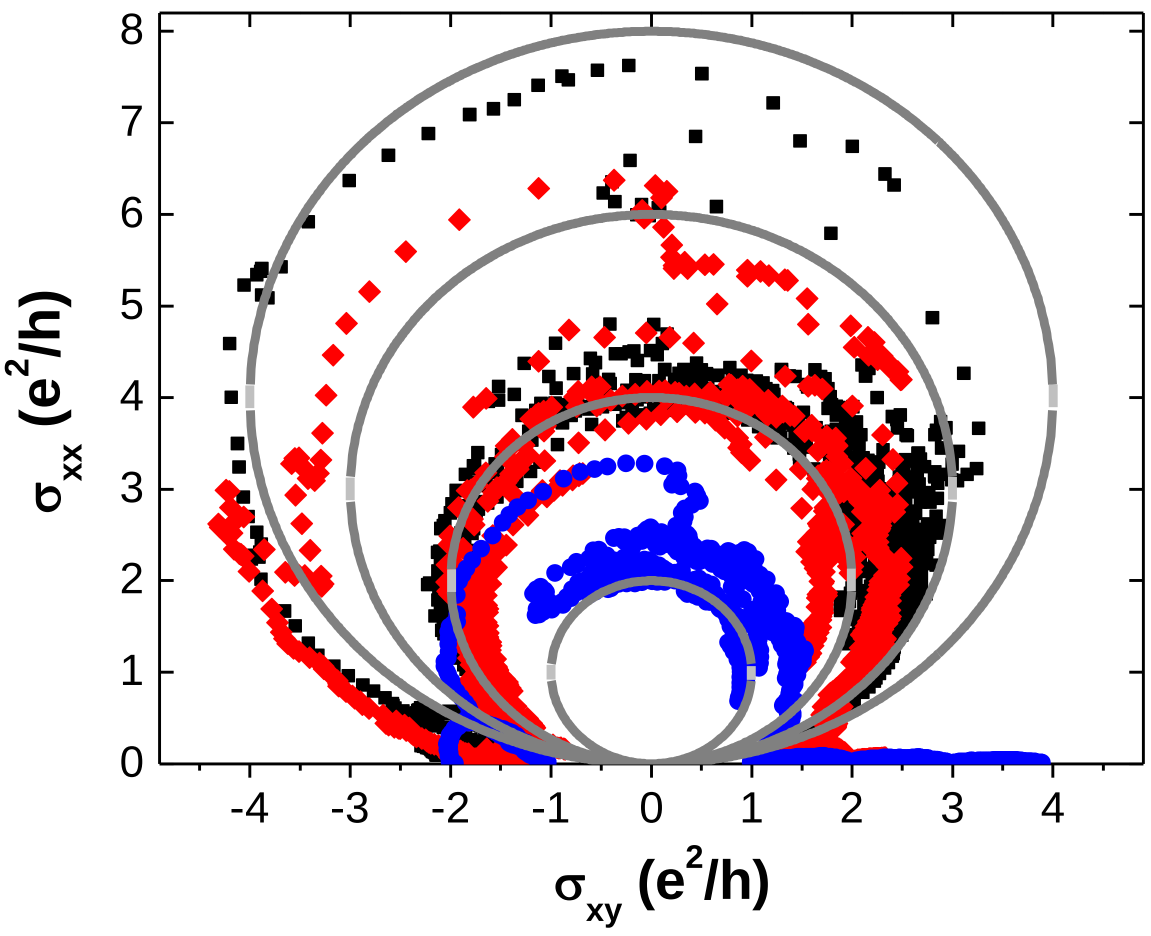
$|n| = |p| \sim 0.6\times10^{11}$ cm^{-2}



B = 5T
σxx
σxy
σxx, σxy (e2/h)
Vg (V)
12
8
4
0
-4
-6
-3
0
3
6
1
2
4
5
6
-4
νh=-2
νe=12

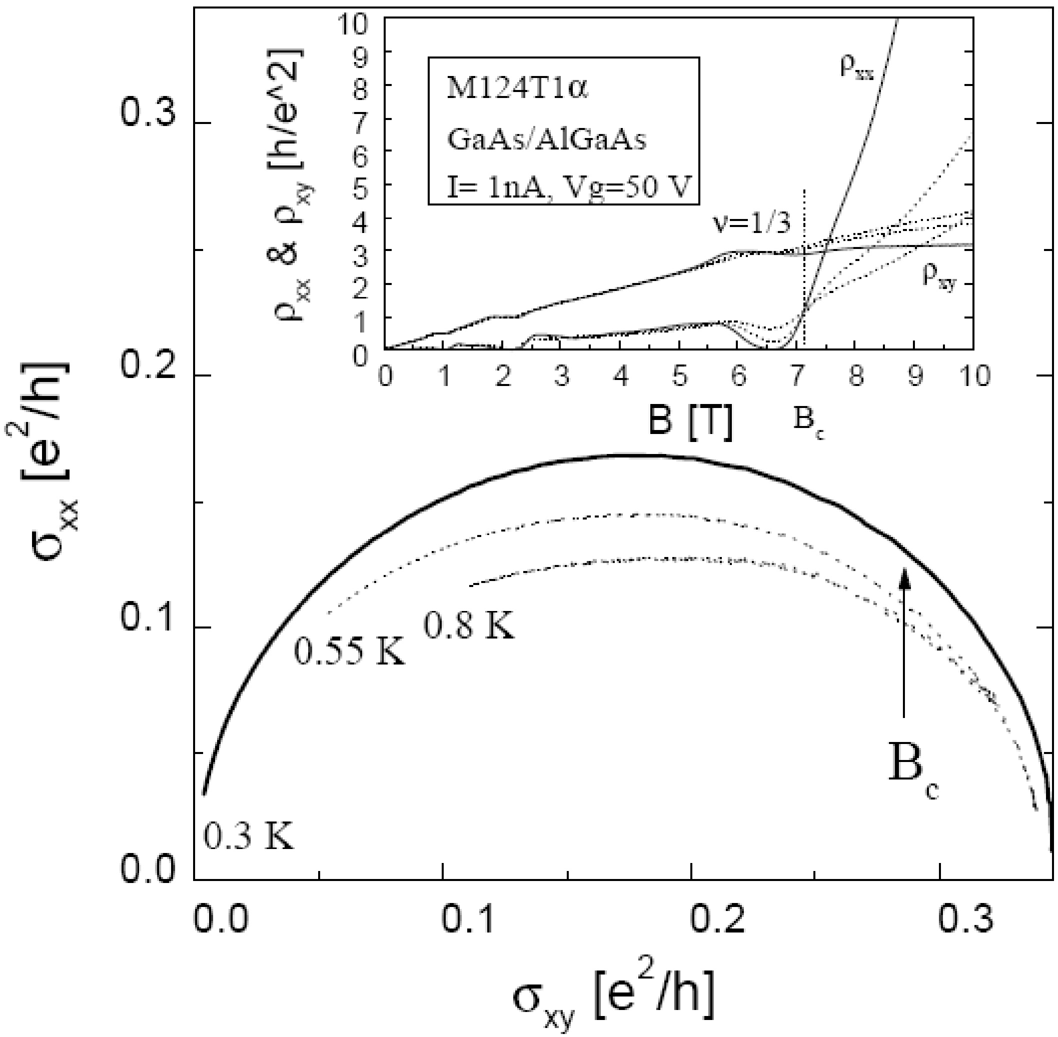
Electron transport at high magnetic fields:





$$(\sigma_{xx} - N)^2 + \sigma_{xy}{}^2 = N^2$$

Semi-Circular conductivity law in quantum Hall plateau transition



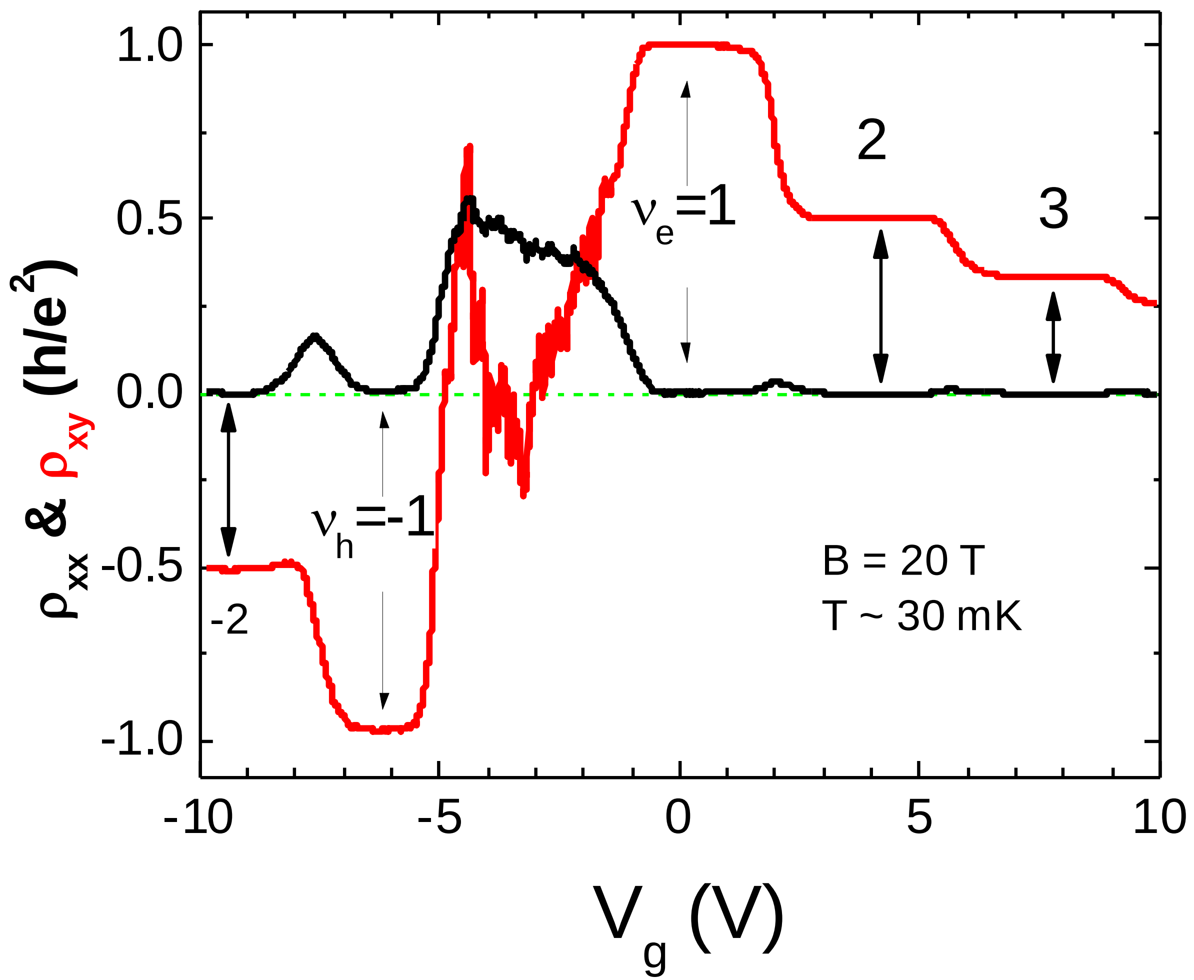
$$(\sigma_{xy} - \nu/2)^2 + \sigma_{xx}^2 = (\nu/2)^2$$

independently of ρ_{xx}

M. Hilke et al, Nature (1998)

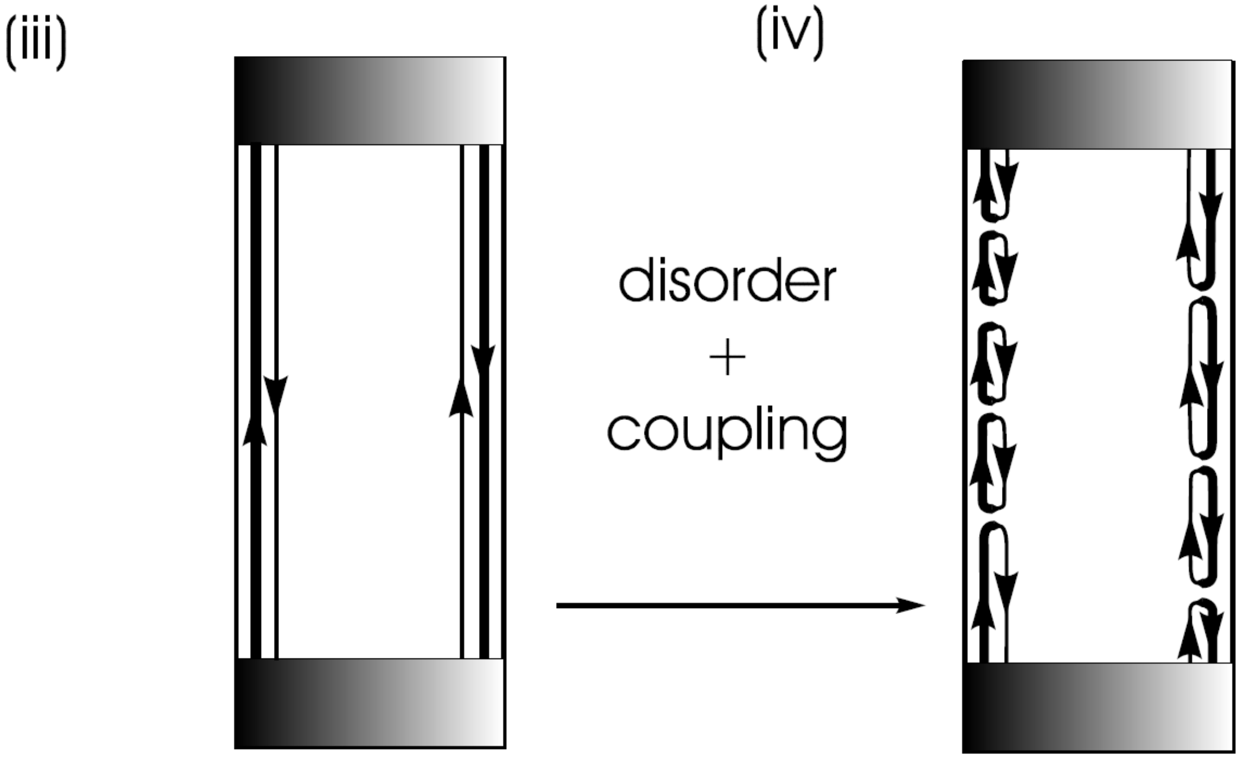
$$(\sigma_{xx} - N)^2 + \sigma_{xy}{}^2 = N^2$$

$$\rho_{xx} = h/e^2/(2N)$$



The circular conductivity law due to co-existence of both electrons and holes and their interactions

- In the CN regime, electron density and hole density low.
- Landau level filling factors for electrons and holes small
- Without e-h interactions, 2D electrons and holes in high magnetic field induced insulating phase, $\sigma_{xx} = 0$ and $\sigma_{xy} = 0$.



R.J. Nicolas et al, Phys. Rev. Lett. **85**, 2364 (2000)

- Breakup of perfect dissipationless edge states due to disorder and e-h interactions.

- Breakup of stable orbits can give rise to chaotic motions.

[G. Müller, G.S. Boebinger et al, Phys. Rev. Lett. **75**, 2875 (1995).]

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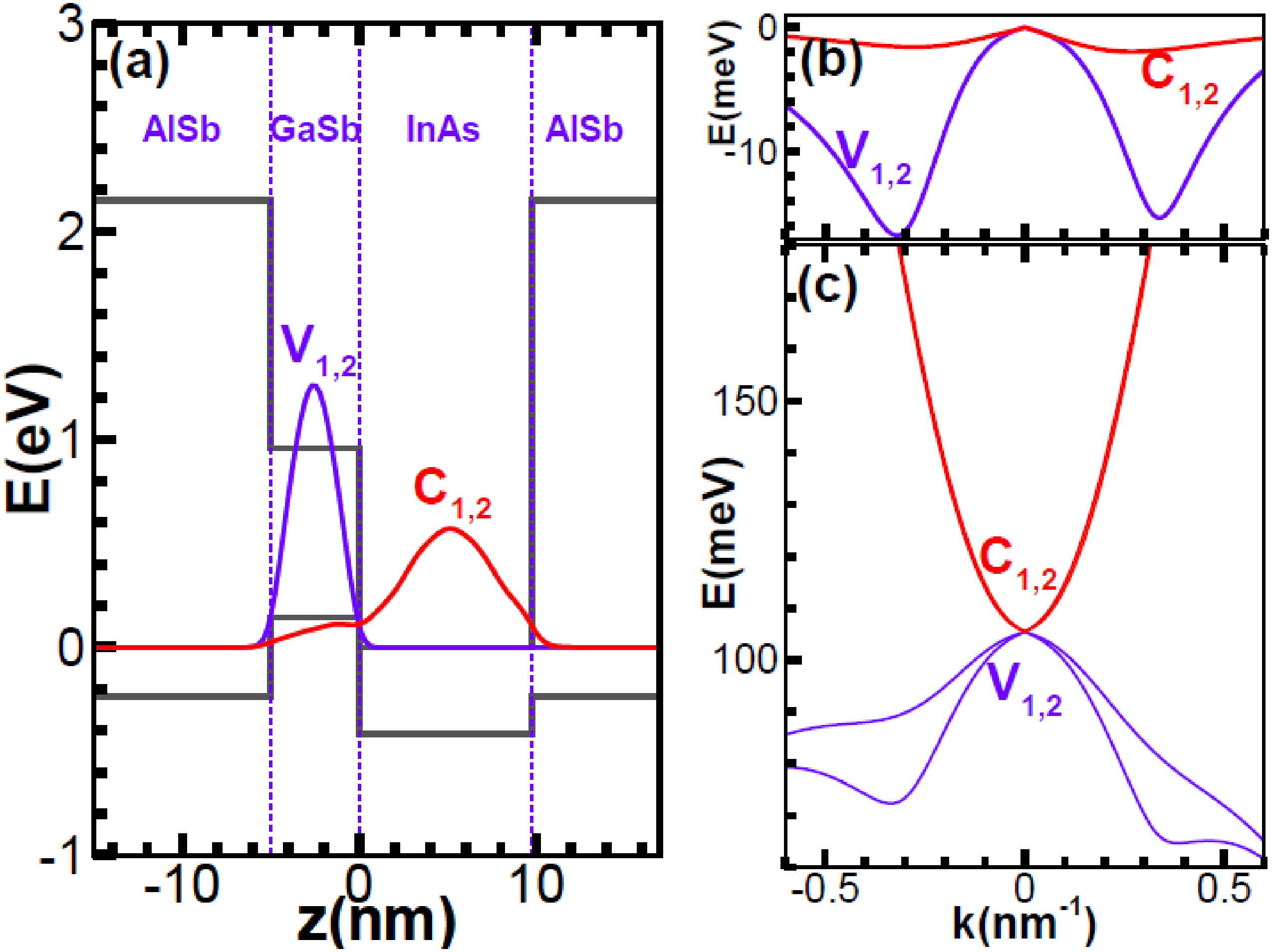


8-band k.p calculations with QW widths (GaSb 5 nm; InAs 10 nm)

K. Chang, unpublished

Z. Liu et al., Acta Phys. Sin. 2012, 61, 217303

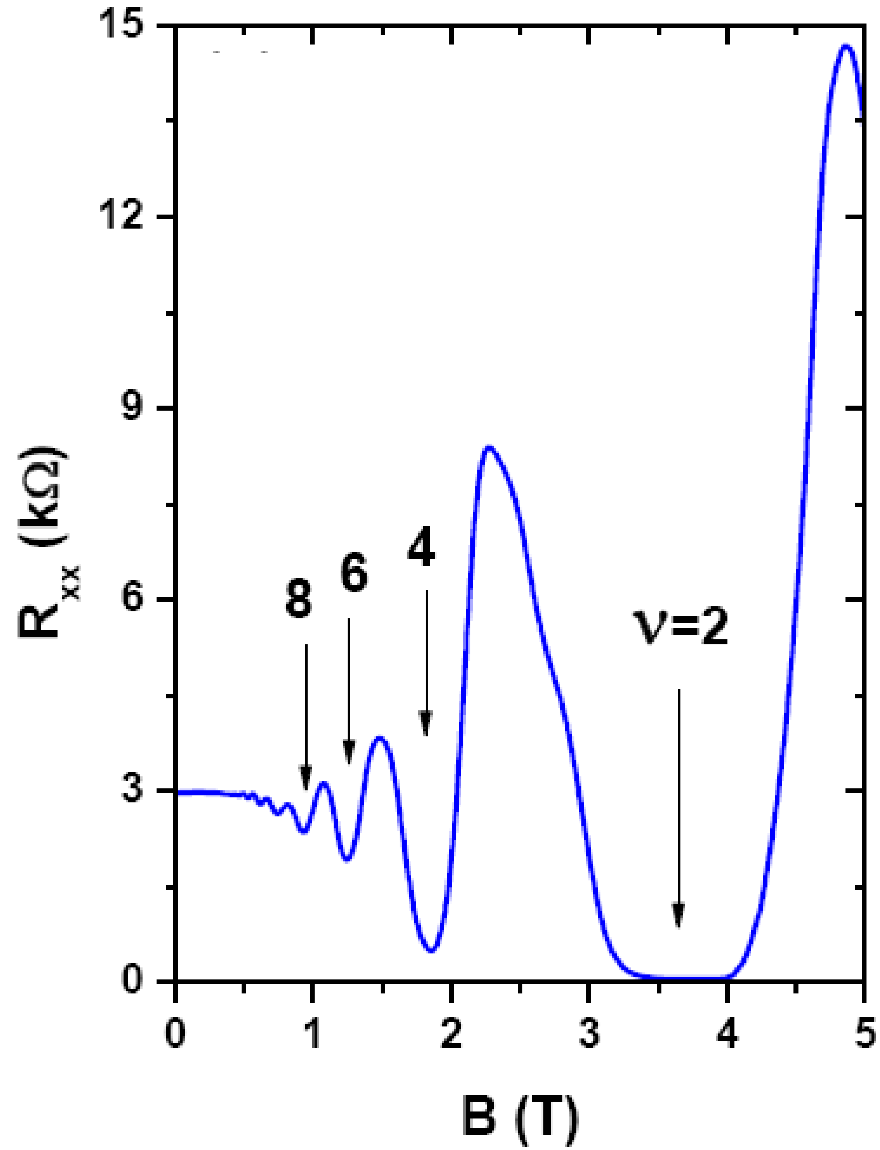
Density n = 1.8x10^{11} cm^{-2}

Mobility μ = 1.2x10^{5} cm^{2}/Vs

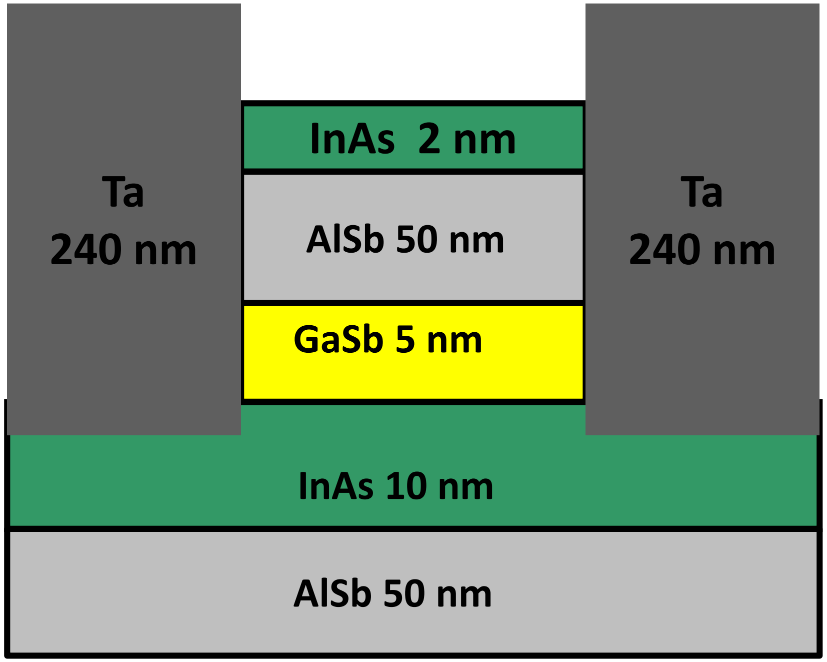
E_F = 18.7 meV

l_{mfp} = 0.8 μm

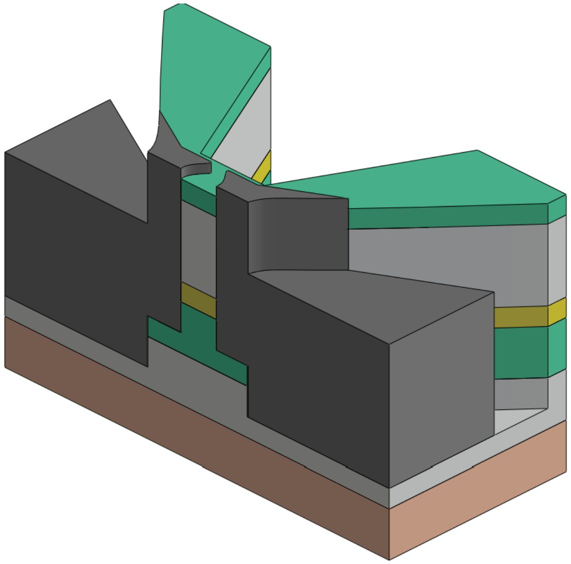
V_F = 5.4x10^{5} m/s

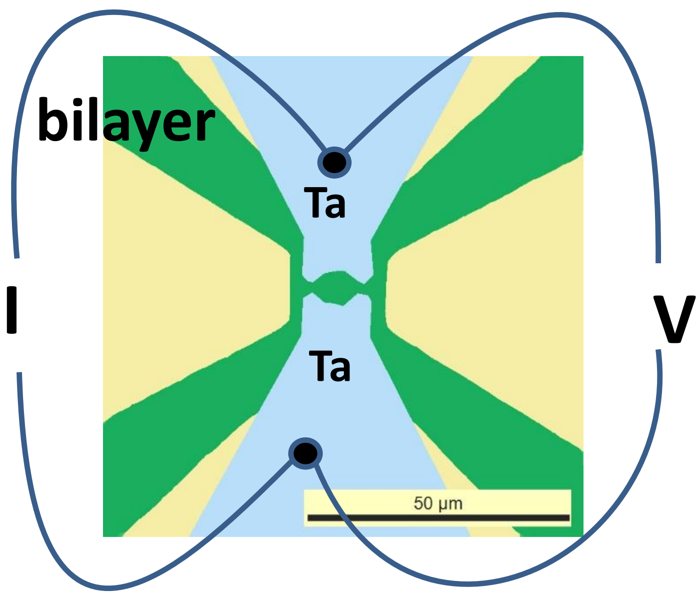


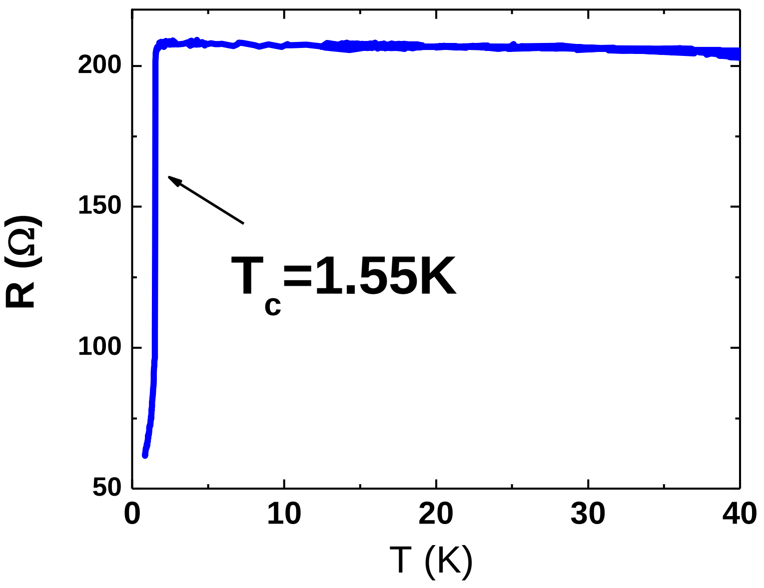
Ta-InAs/GaSb-Ta junction

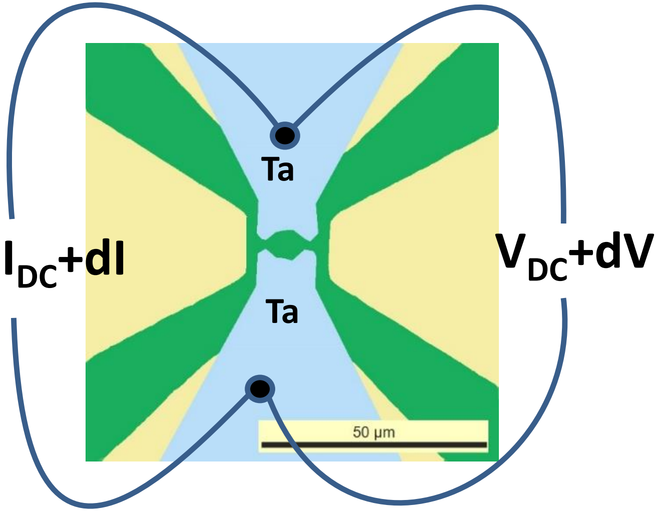


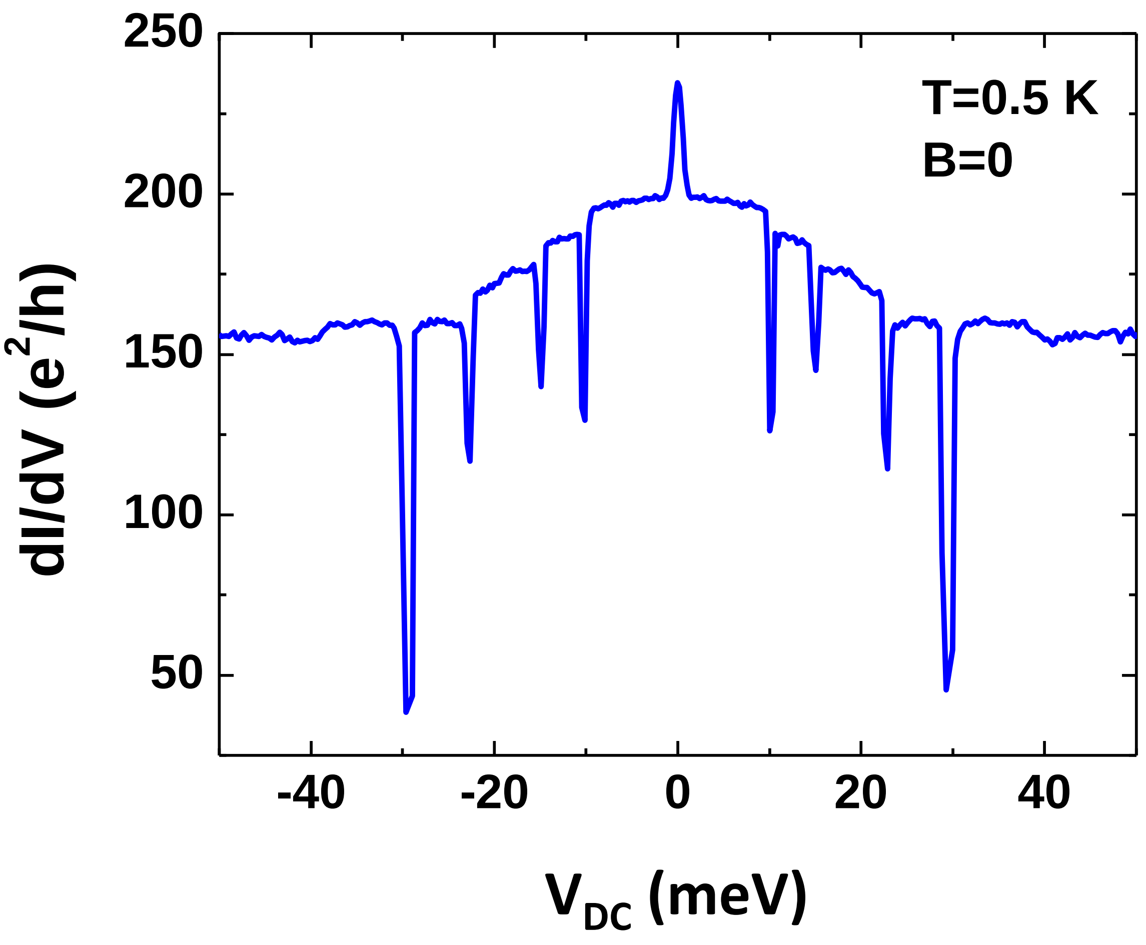
- Junction: W=10 μm L= 2 μm





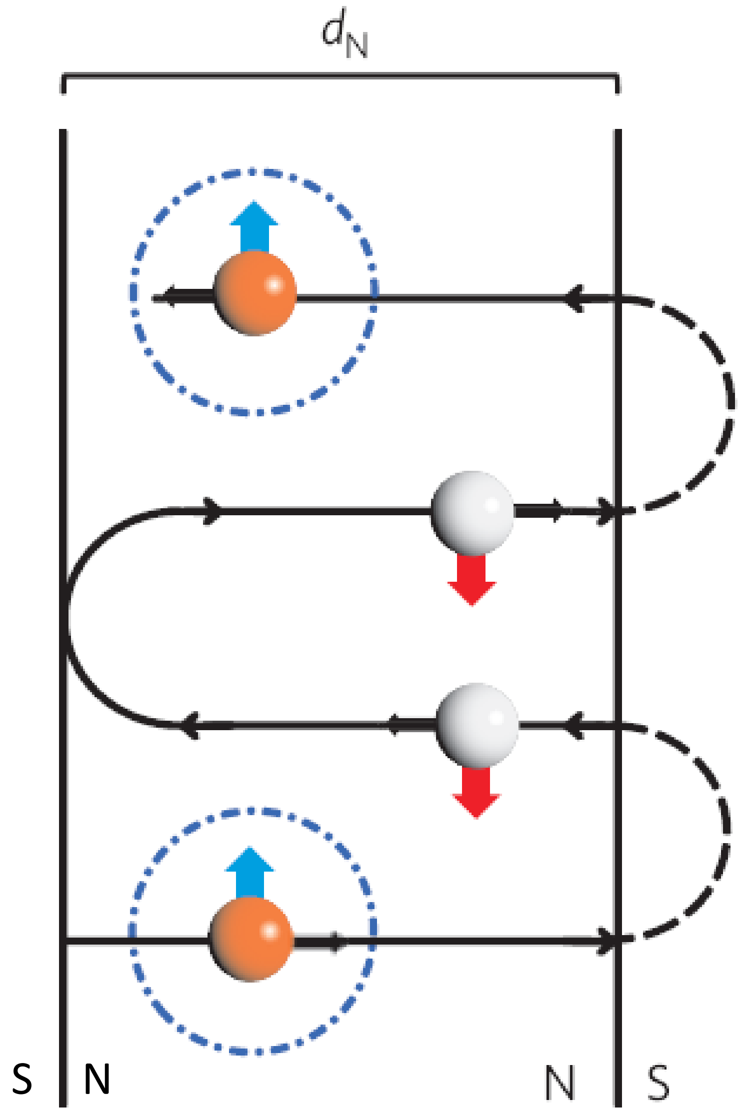






Zero bias conductance peak + multiple equally spaced dips

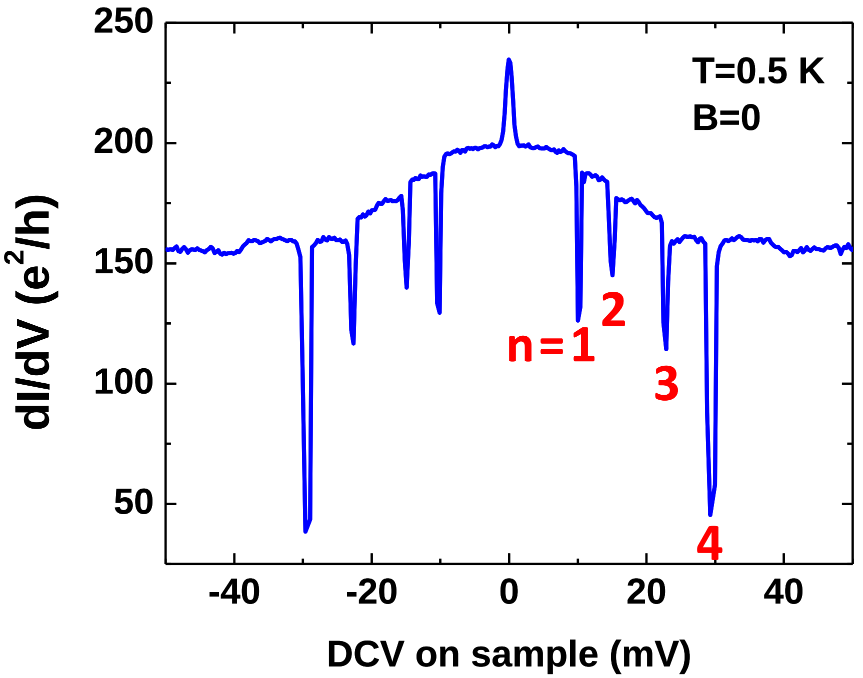
McMillan-Rowell Oscillations (MRO)

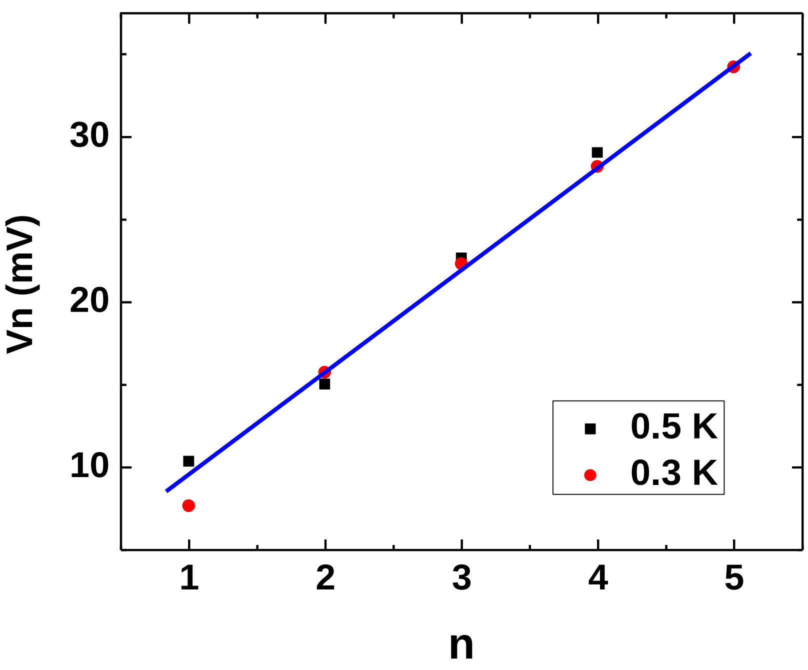


$$V_n = V_0 + n \times hV_F/4d_N$$

J. M. Rowell and W. L. McMillan, Phys. Rev. Lett. **16**, 453 (1966).
C. Visanli et al, Nature Physics 8, 539 (2012).
B. Wu et al, arXiv:1305.5140.

McMillan-Rowell like Oscillations





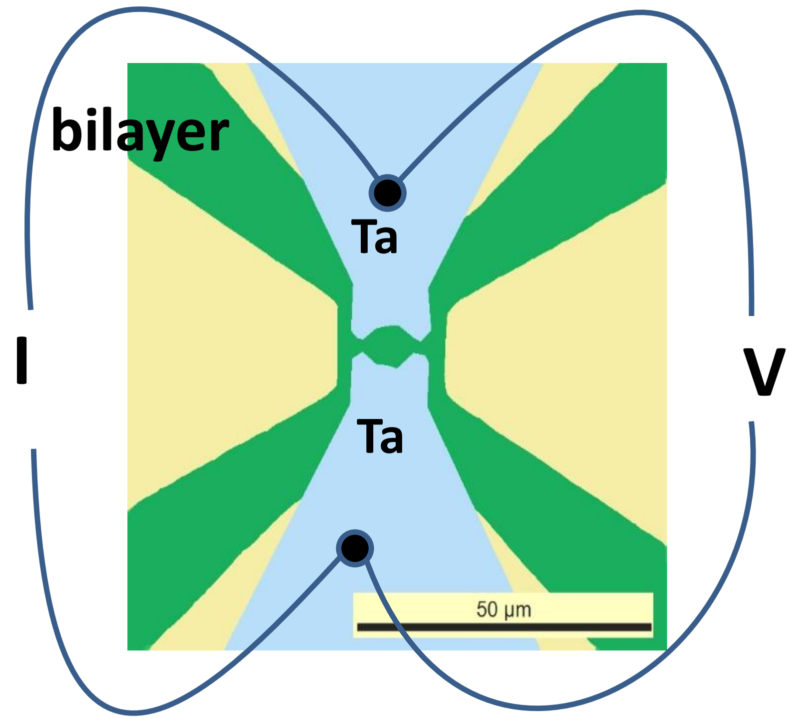
$$V_n = V_0 + n \times hV_F/4d_N$$

One serious issue with MRO explanation:

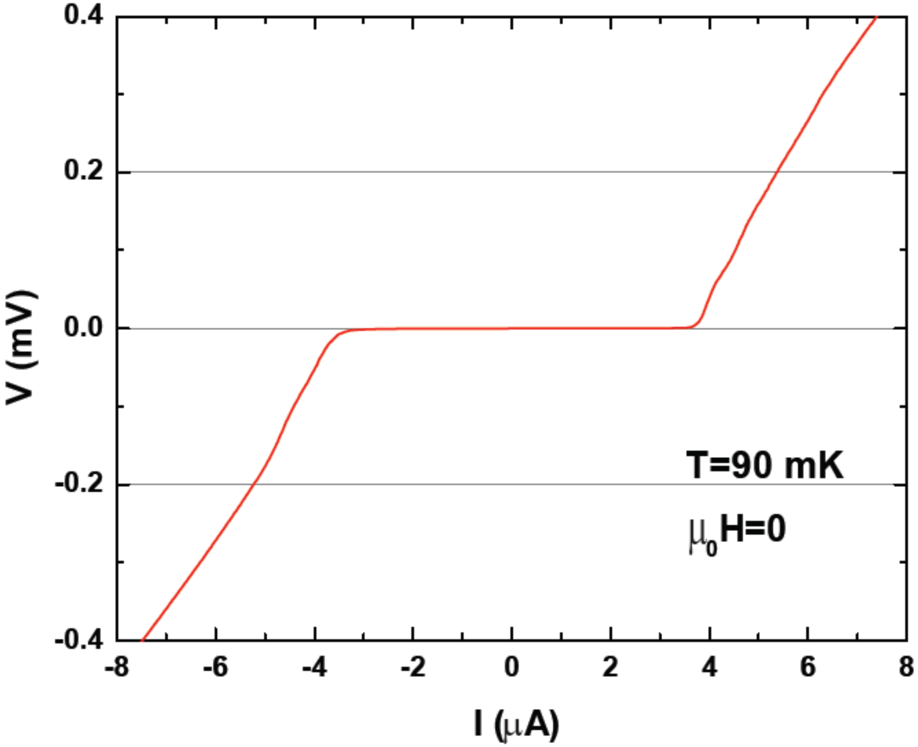
From the slope of MRO plot, a Fermi velocity of V_F = $1.3x10^7$ m/s is obtained.

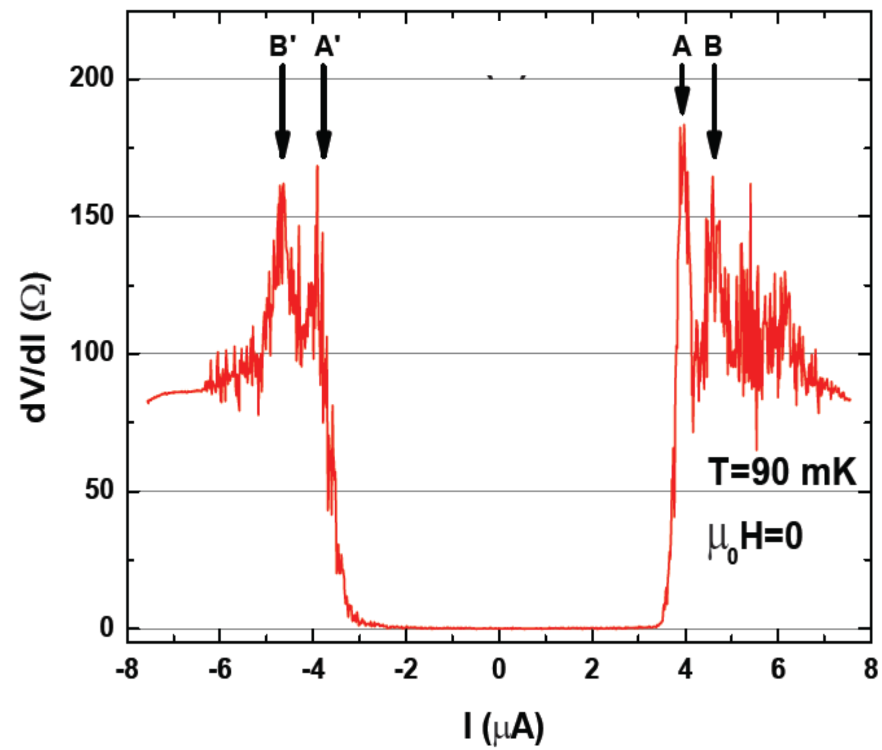
This value is much larger than that (V_F= $5.4x10^5$ m/s) obtained fro SdH oscillations.

Giant super-current in Ta-InAs/GaSb-Ta junction

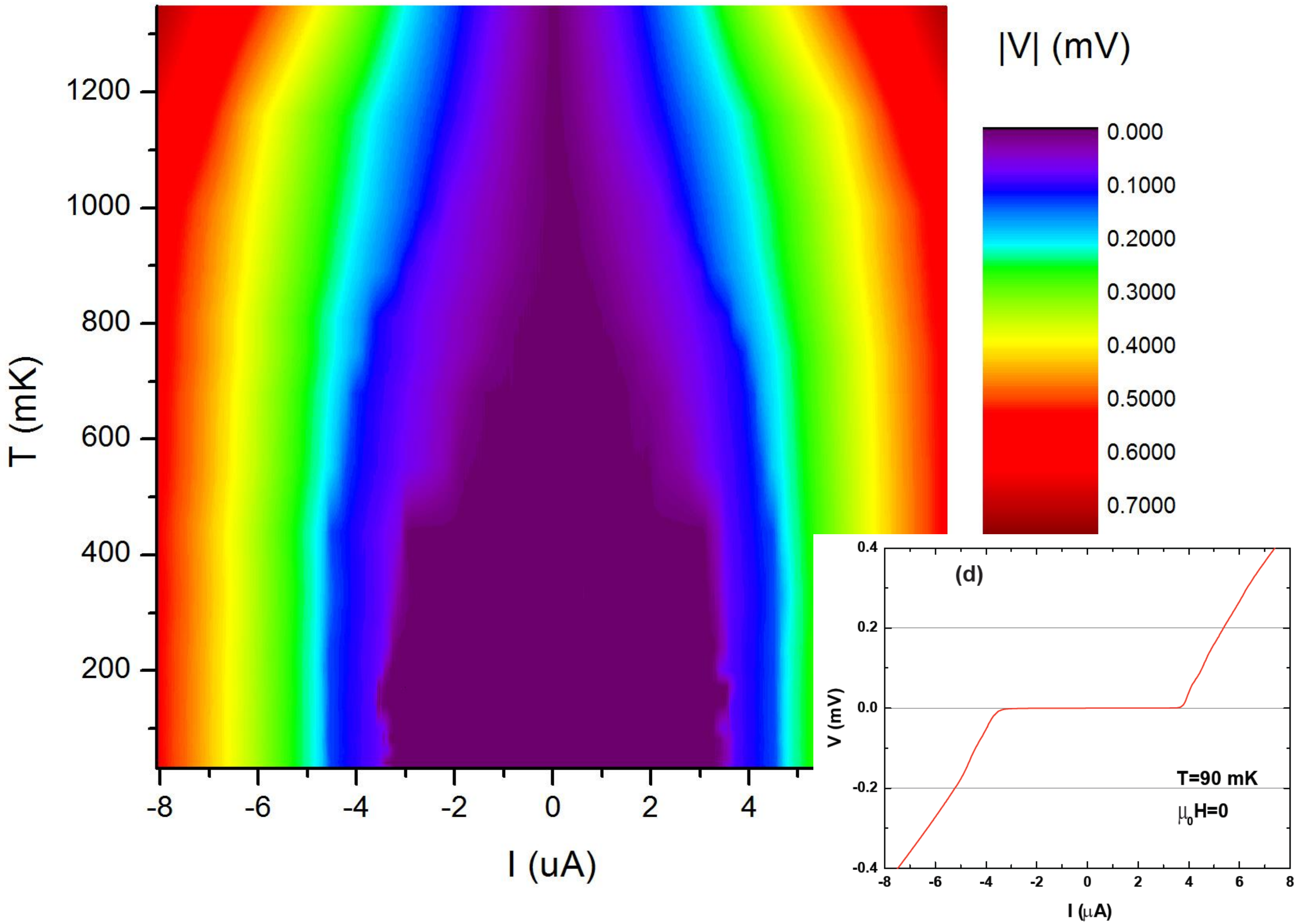


Giant super-current observed

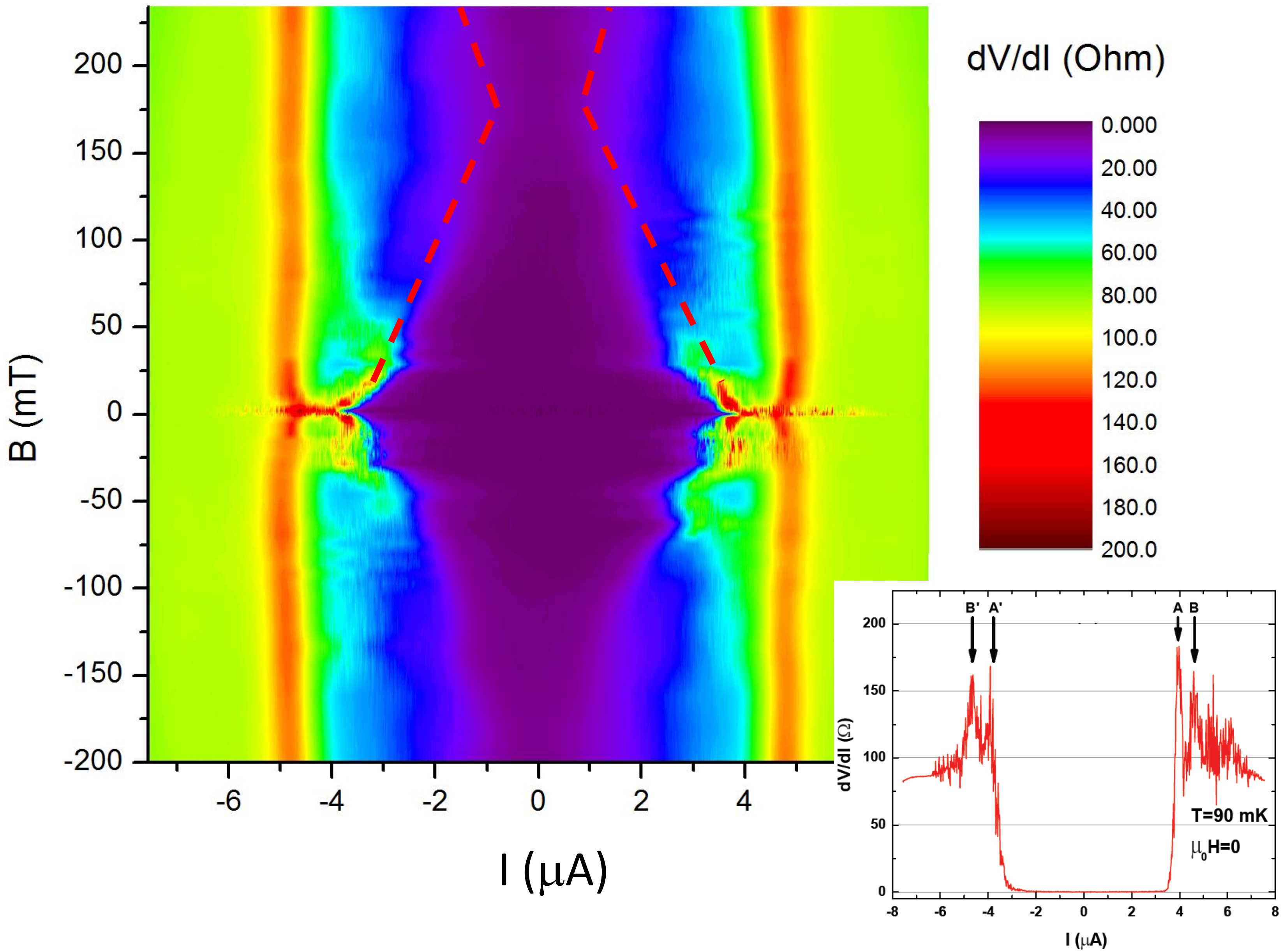




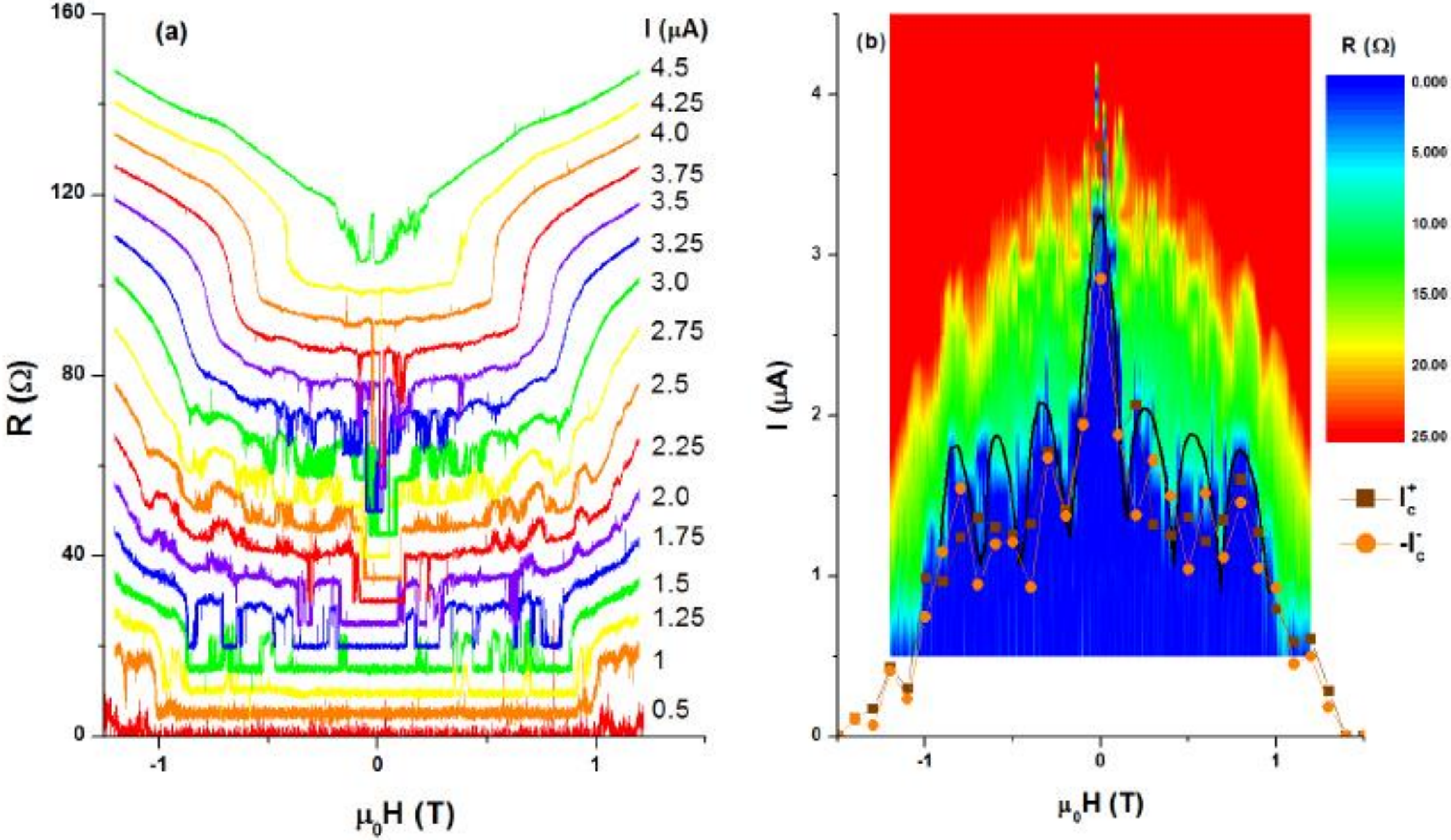
Large T_c



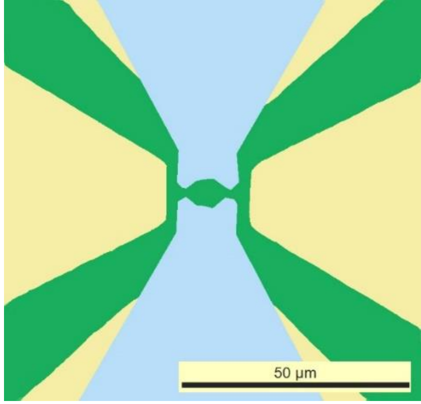
|V| (mV)
0.000
0.1000
0.2000
0.3000
0.4000
0.5000
0.6000
0.7000
T (mK)
1200
1000
800
600
400
200
-8
-6
-4
-2
0
2
4
I (uA)
(d)
T=90 mK
μ0H=0
V (mV)
0.4
0.2
0.0
-0.2
-0.4
-8
-6
-4
-2
0
2
4
6
8
I (μA)



dV/dI (Ohm)
0.000
20.00
40.00
60.00
80.00
100.0
120.0
140.0
160.0
180.0
200.0
B (mT)
200
150
100
50
0
-50
-100
-150
-200
-6
-4
-2
0
2
4
I (μA)
B'
A'
A
B
T=90 mK
μ0H=0
dV/dI (Ω)
I (μA)



(a)
I (μA)
4.5
4.25
4.0
3.75
3.5
3.25
3.0
2.75
2.5
2.25
2.0
1.75
1.5
1.25
1
0.5
R (Ω)
160
120
80
40
0
-1
0
1
μ0H (T)
(b)
R (Ω)
0.000
5.000
10.00
15.00
20.00
25.00
I (μA)
4
3
2
1
0
-1
0
1
μ0H (T)
Ic+
-Ic-



A couple of details:

1) Very large Jc, Jc = 350 nA/μm >> ~15 nA/μm reported by other groups.
(considering L = 2μm, ξ_{sc} ~ 80nm (bulk Ta) and l_{mfl} = 0.8μm)

2) Large number of flux per lobe ~ 300 Φ_0 >>1.
A large value of flux per lobe was also observed in S-GaAs-S junction by Rokhinson et al.

Summary:

(1) Well-developed integer quantum Hall effect states at Landau level fillings ν=1, 2 in the hole regime and ν=1, 2, 3… in the electron regime.

(2) Chaotic quantum transport behavior at extremely high magnetic fields around the charge neutrality point.

(3) Circular conductivity law in σ_{xx} versus σ_{xy}.

(4) MRO in Ta-InAs/GaSb-Ta junction device

(5) Giant supercurrent in Ta-InAs/GaSb-Ta junction

Collaborators:

Sandia:

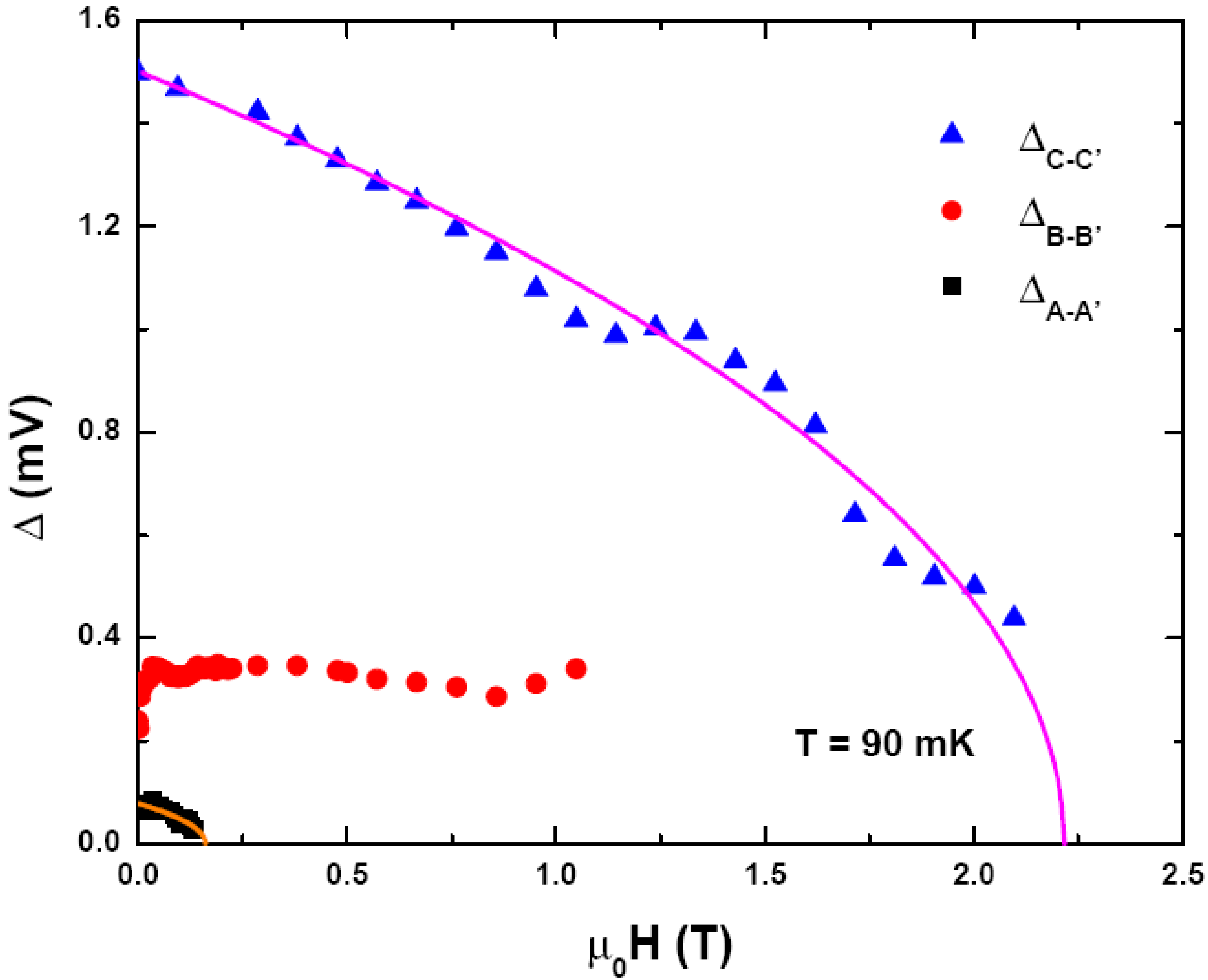
- **John Klem**
- **Sam Hawkins**
- **Ken Lyo**
- **Jin Kim**
- **Mike Cich**
- **Madhu Thalakulam**
- **Wenlong Yu**
- **Xiaoyan Shi**

Princeton:

- **Jian Li**
- **Andrei Berniverg**

Georgia Tech:

- **Wenlong Yu**
- **Zhigang Jiang**



1.6
1.2
0.8
0.4
0.0
Δ (mV)
0.0
0.5
1.0
1.5
2.0
2.5
μ0H (T)
ΔC-C'
ΔB-B'
ΔA-A'
T = 90 mK