Electrical Transport of Gate confined Quasi-one dimensional Wires

Shih-ying Hsu (許世英)

Department of Electrophysics, National Chiao Tung University
Hsinchu , Taiwan

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電子物理系
NCTU Electrophysics

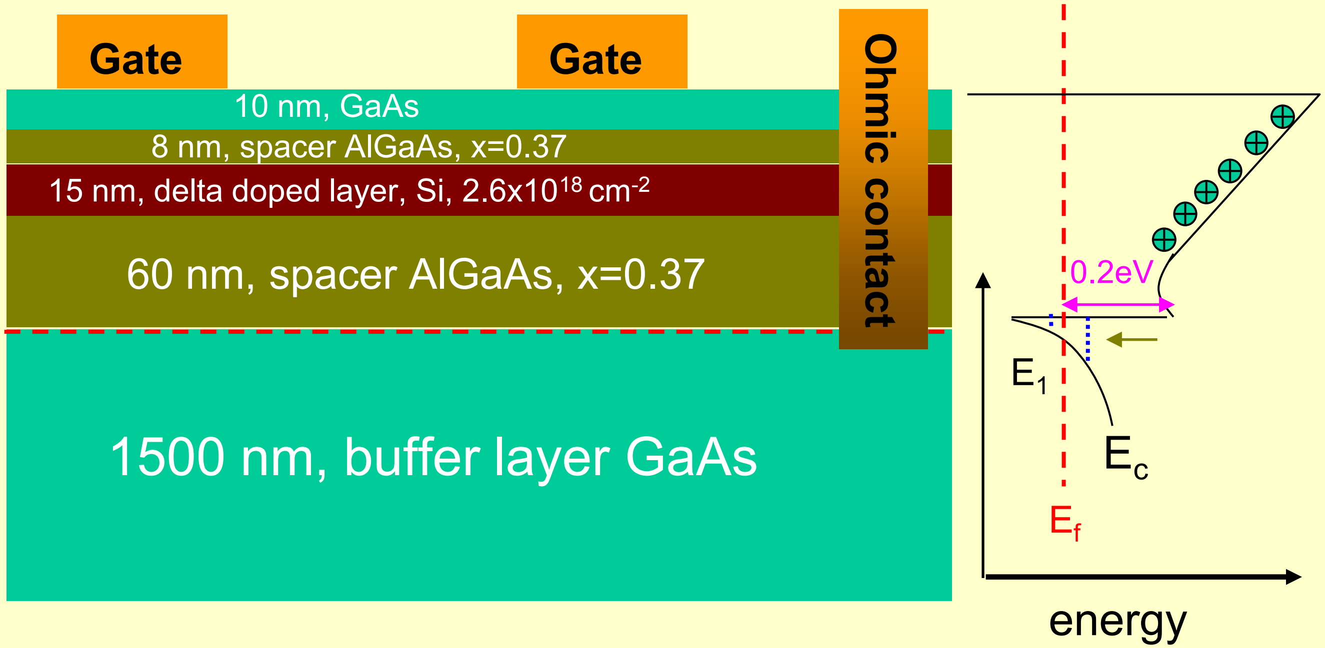
Outline

- Two dimensional and Quasi-one dimensional electron systems
- Experimental details
- Quantum transport of gate-confined nanostructures

  Zero-bias anomaly and conductance reduction in QWs
- Summary

Two dimensional electron gas (2DEG)

GaAs/AlGaAs heterostructure and band diagram

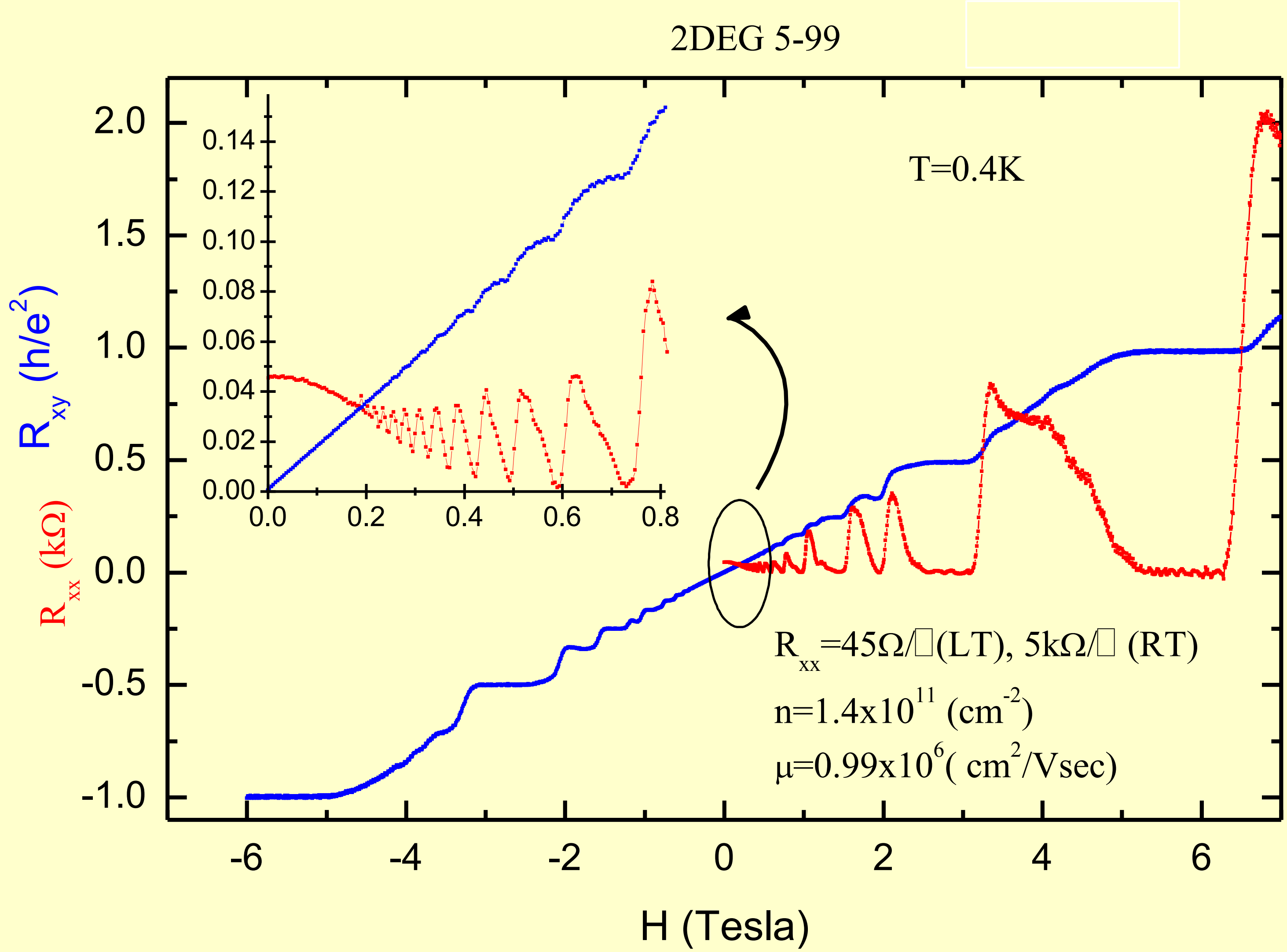


The 2DEG systems are generally formed by GaAs/AlGaAs heterostructure and contain a thin conducting layer in the interface.

Our wafers were grown by Dr.Umansky in Heiblum's group at the Wiezman Institute in Israel.

2DEG : 80~100 nm below surface
Sheet density, n_s = 1. ~2 x 10^{11} cm^{-2}
Mobility, μ = 0.8~2. x 10^6 cm^2 /Vs
Mean free path, ℓ_e = 3~15 μm

SdH Oscillation and Quantized Hall Conductance



A steady current of metallic film in the presence of E and B.

$$0 = e\left(E + v_d \times B\right) + \left(-\frac{m v_d}{\tau_m}\right)$$

Assuming $\vec{B} = B\hat{z}$ and film is in the x-y plane

$$\left(\frac{m}{n_s e^2 \tau_m}\right)\begin{bmatrix} 1 & -{eB\tau_m}/{m} \\ {eB\tau_m}/{m} & 1 \end{bmatrix}\begin{pmatrix} J_x \\ J_y \end{pmatrix} = \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

$$\boxed{\begin{aligned} \rho_{xx} &= \frac{m}{n_s e^2 \tau_m} \\ \rho_{yx} &= \left(\frac{m}{n_s e^2 \tau_m}\right)\left(\frac{eB\tau_m}{m}\right) \end{aligned}}$$

What happens at high magnetic field?

Experimental results :

Longitudinal resistivity ρ_{xx} shows pronounced oscillatory behavior.

-- ρ_{xx} can be zero between the peaks at higher B and at low T.

Shubnikov-de Haas oscillation

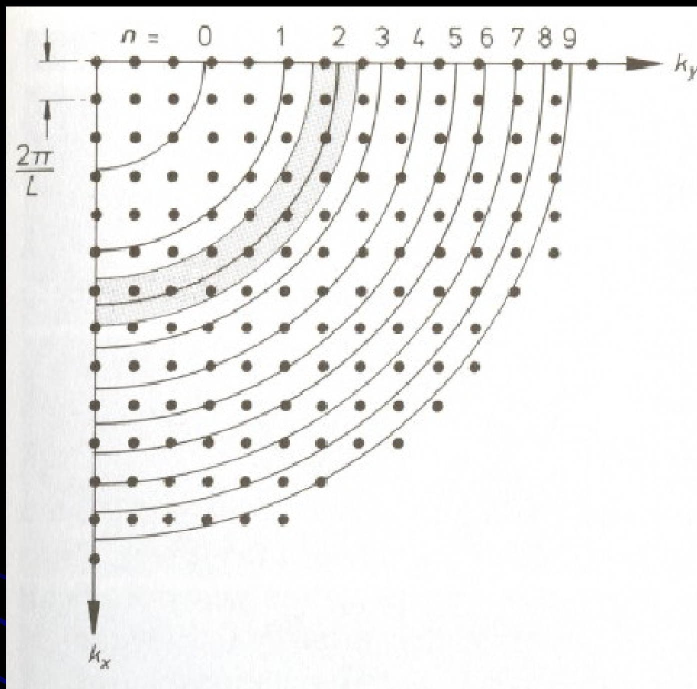
Hall resistivity ρ_{xy} exhibits plateaus corresponding to the minima in ρ_{xx}.

Quantized Hall conductance

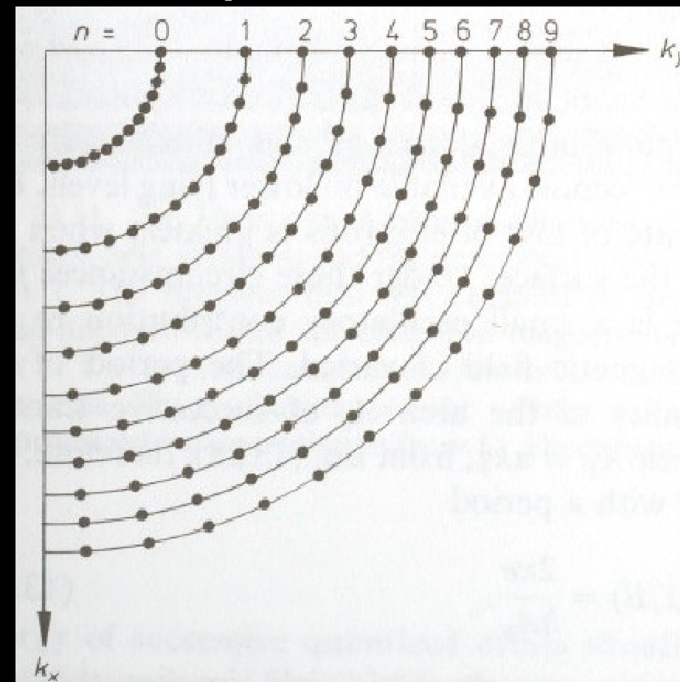
the quantization of Landau energy level due to B

The energies are quantized into discrete levels,
the Landau levels with energy $E=E_s+(n+1/2)\hbar\omega_c$

In the absence of B



In the presence of B



At the critical fields B_s, Landau levels are either fully occupied or completely empty.

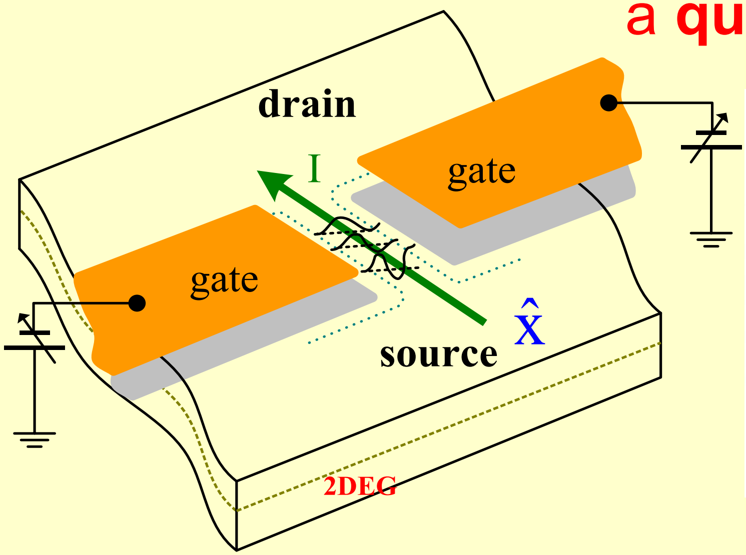
$$\boxed{N = s\frac{eA}{h}B_c}$$

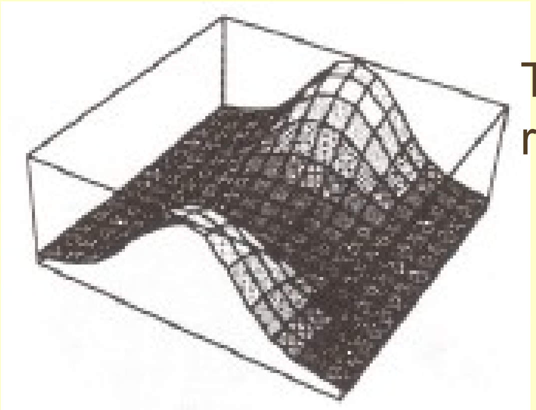
$$\rho_{yx} = \frac{h}{Ne^2}$$ **Plateaus**

$\sigma_{xx}=0$ and $\rho_{xx}=0$

Gate confined nanostructures

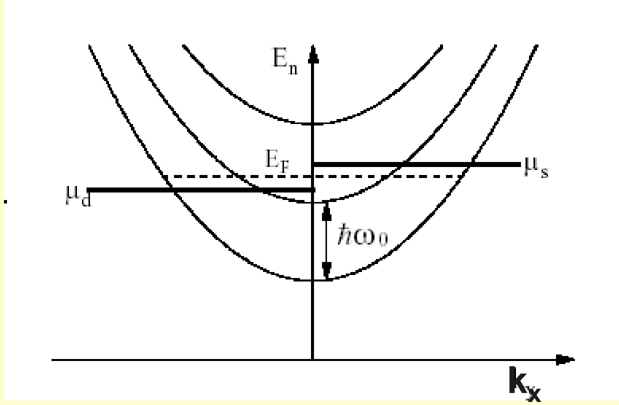
Applying negative voltages on the metal gates fabricated above a ***two dimensional electron gas(2DEG)***, a **quasi-1D quantum conductor** is formed.





Three dimensional representation of potential.

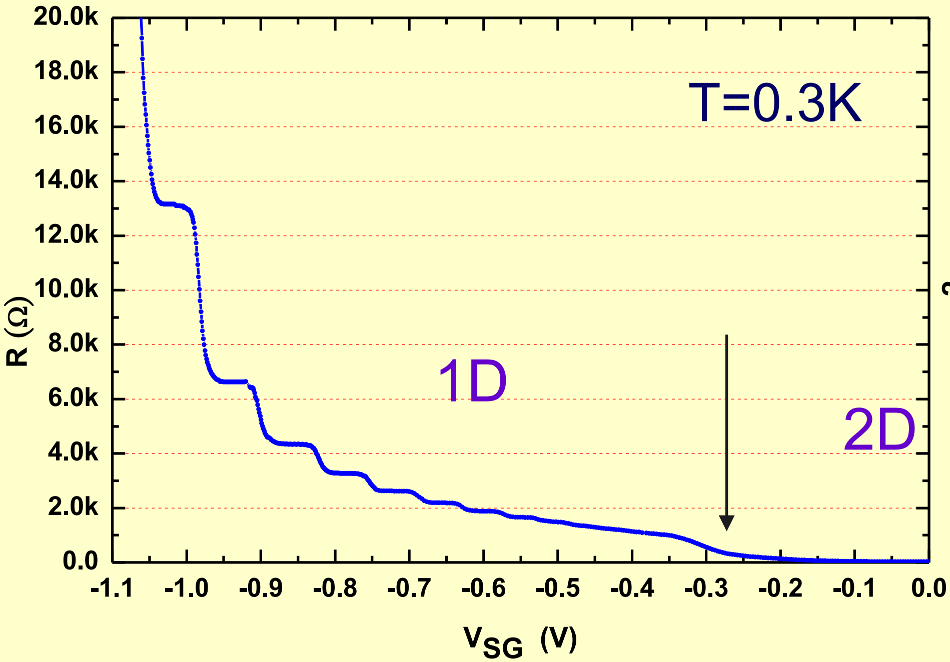
For a parabolic confining potential $V(y) = \frac{1}{2} m^* \omega_o^2 y^2$.

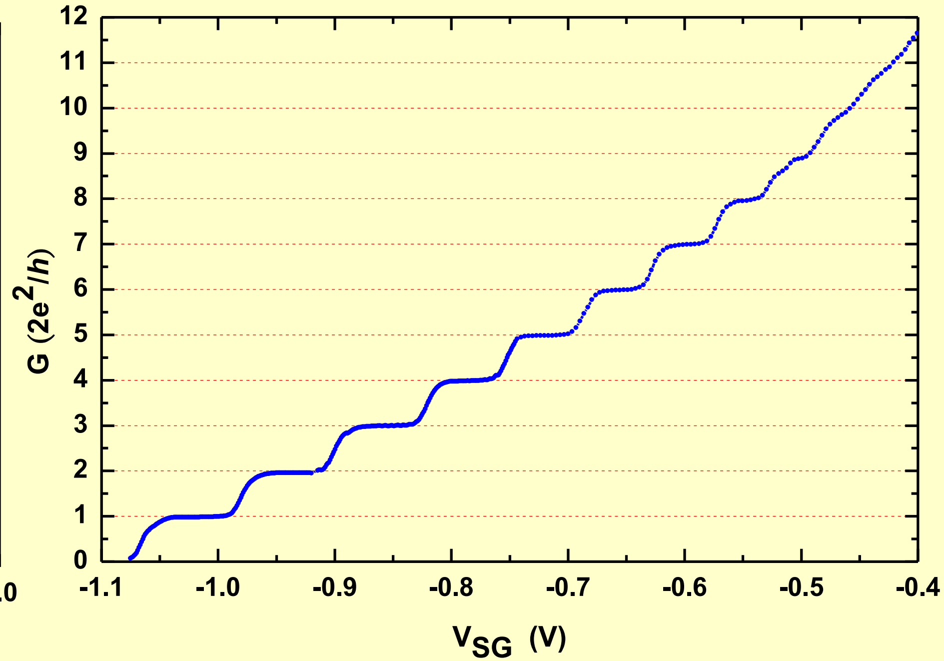


$$E_n(x) = \left(n - \frac{1}{2}\right)\hbar\omega_o + \frac{\hbar^2 k_x^2}{2m^*}$$

Energy dispersion for 1D channel E_n (for n=1,2,3) vs. longitudinal wavevector k_x. Electrons in the source and drain fill the available states up to chemical potentials μ_s and μ_d, respectively.

Split gates confined QW : W_{gap}=0.3μm and L=0.5 μm





$$G = \frac{I}{V_{sd}} = \frac{eI}{\mu_s - \mu_d}$$

van Wees *et. al.*, PRL 60, 848 (1988).
Wharam *et. al.*, J. Phys. C 21, L209 (1988).

$$G = \frac{2e^2}{h}\sum_{n=1}^{N} T_n(E_F) = N\,\frac{2e^2}{h}$$

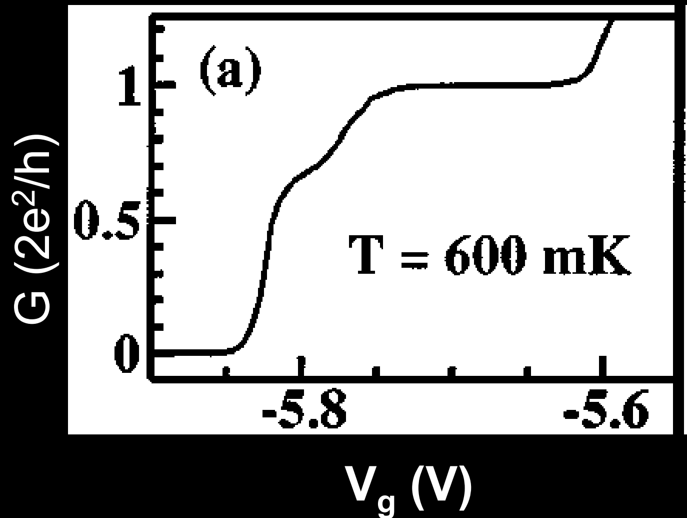
N: integer

Two terminal Landauer formula

Each plateau corresponds to an additional mode as ***integer multiples*** of ***half the Fermi wavelength***

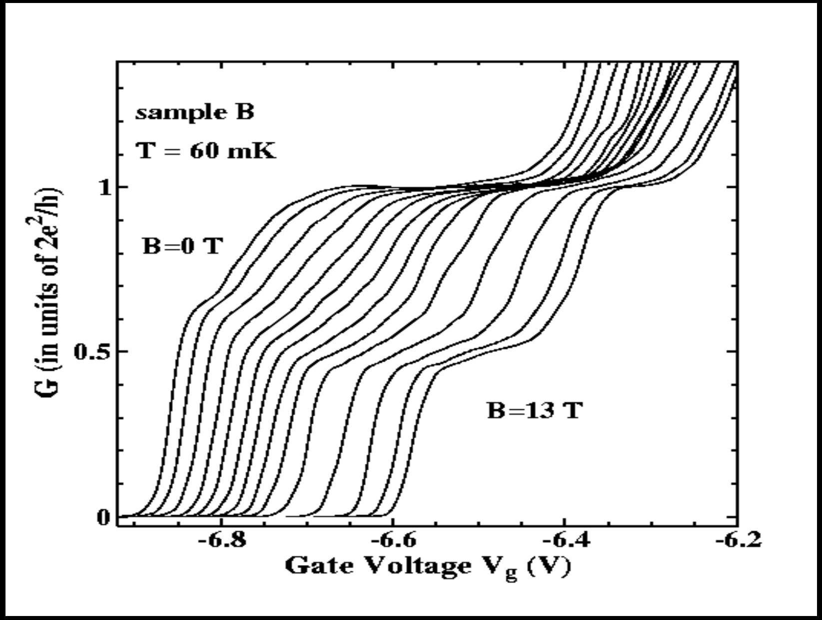
The 0.7 anomaly

In addition to the “integer” conductance plateaus, there is an anomalous structure close to $0.7(2e^2/h)$ in the clean one-dimensional constrictions.

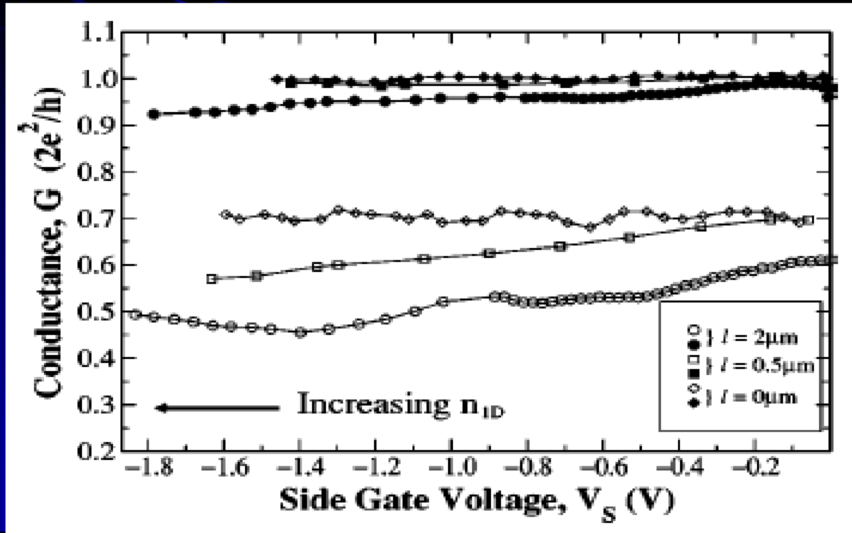


Possible Spin polarization ?

K. J. Thomas *et. al.*, PRL 77, 135 (1996).



The 0.7 structure continuously decreases with in-plane magnetic field and evolves into the spin-split plateau at e^2/h.

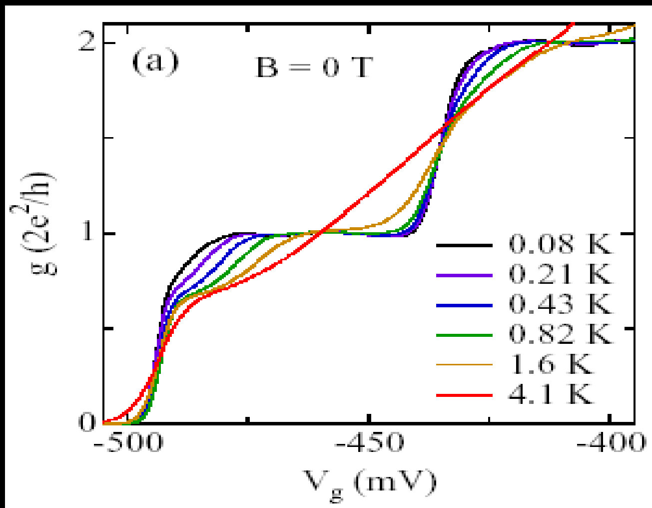


Similar evolution occurs in longer wires of high carrier concentration.

D. J. Reilly *et. al.*, PRB 63, 121311 (2001).

Kondo effect ?

Temperature dependent conductance



S. M. Cronenwett *et. al.*, PRL 88, 226805 (2002).

- The 0.7 structure becomes pronounced with temperature while the plateaus at N($2e^2/h$) are less visible due to the thermal smearing.
- Conductance reduction at high temperatures

Linear conductance g(T) for various V_g follows an universal equation:

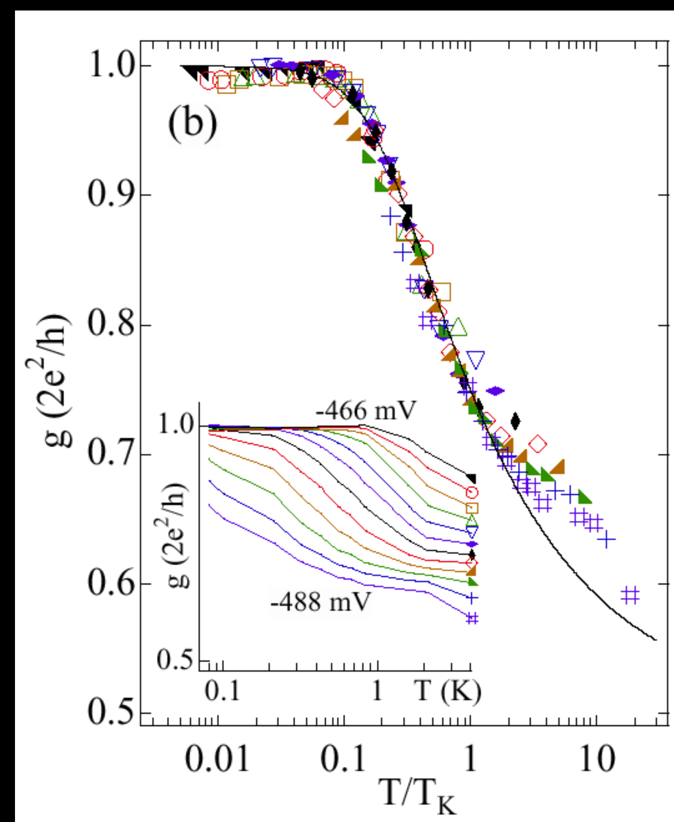
$$g(T) = \frac{2e^2}{h}\left[\frac{1}{2f\left(T/T_K\right)} + \frac{1}{2}\right]$$

The Kondo-type model for a QPC

$$f\left(T/T_K\right) \sim \left[1 + \left(2^{1/s} - 1\right)\left(T/T_K\right)^2\right]^{-s}$$

where s = 0.22

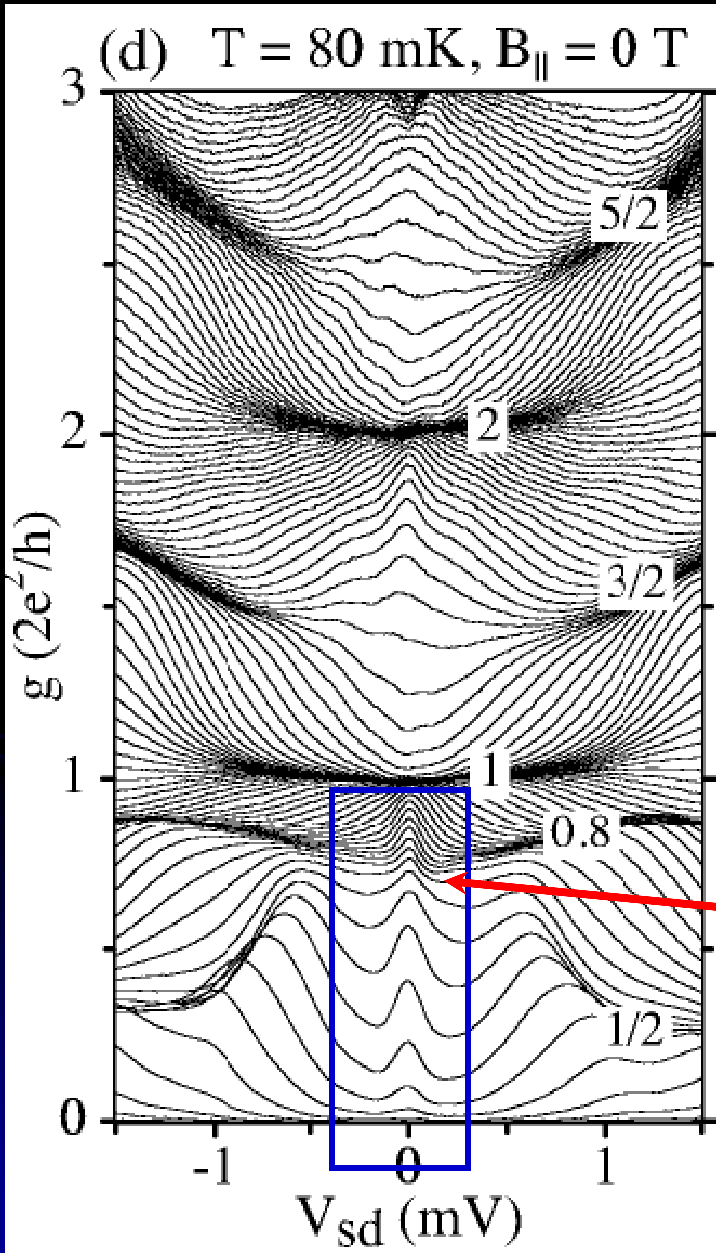
$$T_K \propto e^{V_g}$$



Source-drain bias spectroscopy

Differential conductance $g \equiv \left.\frac{dI}{dV}\right|_{V_{sd}}$ versus V_{sd} at sequential steps in gate voltage V_g.

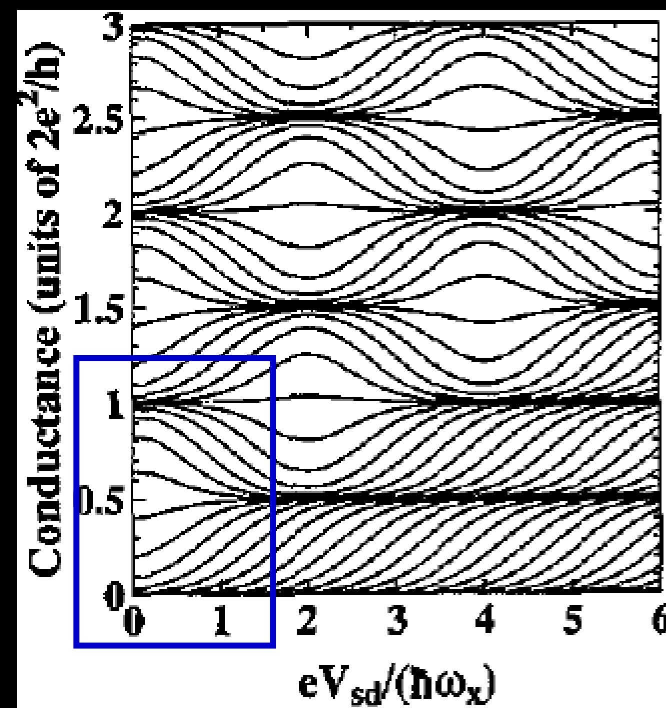
- Integer plateaus around V_{sd}~0 at g=1 and 2 ($2e^2/h$).
- Half plateaus around V_{sd}>~0.5mV at g~1/2, 3/2, and 5/2 ($2e^2/h$).



Zero-bias anomaly

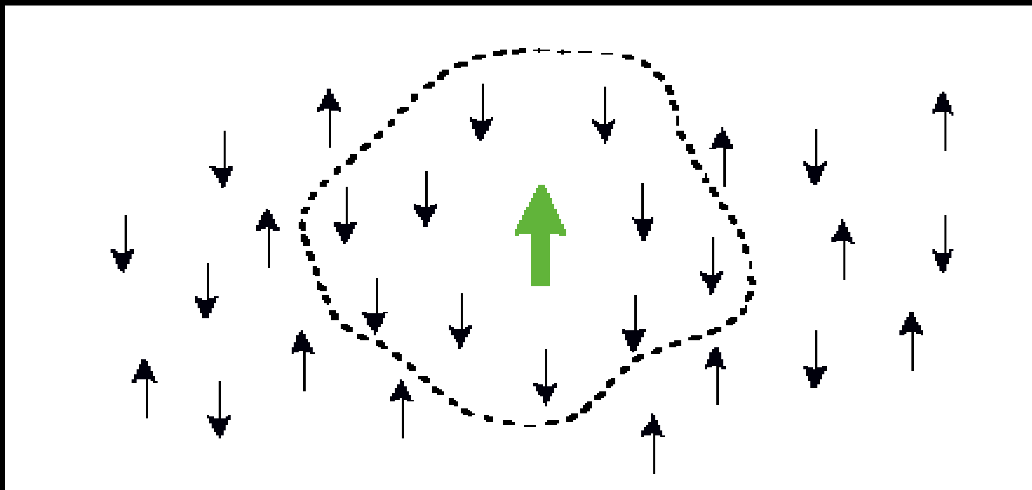
S. M. Cronenwett *et. al.*, PRL 88, 226805 (2002).

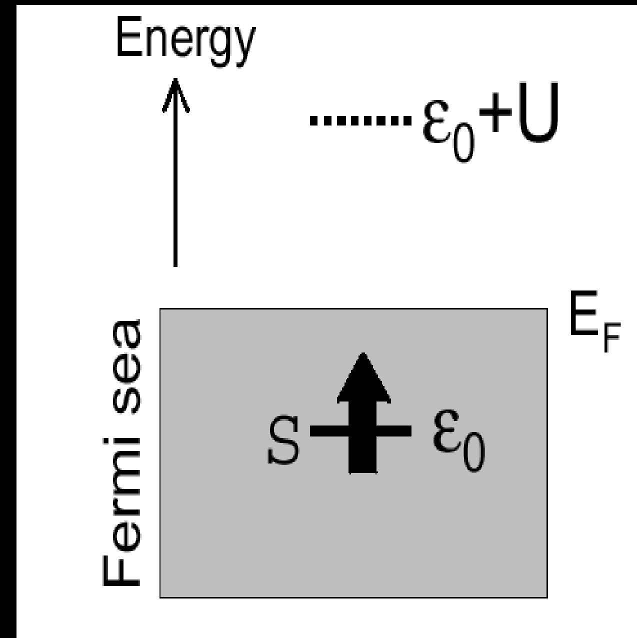
A numerical result for non-interacting electrons

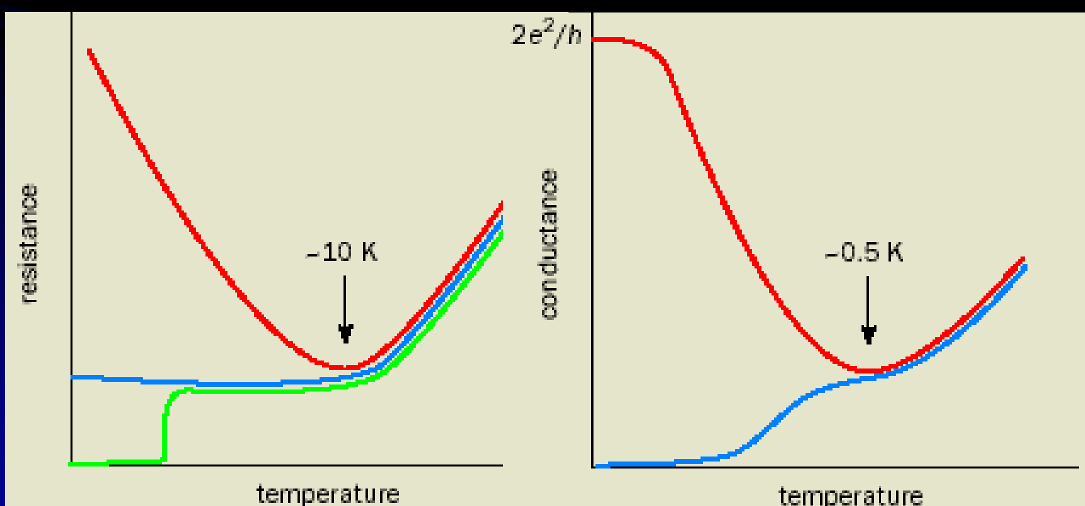


J. of Phys. :Condens. Matter. 4, 1323 (1992).

Kondo effect in metals : the screening of a localized spin by the formation of singlet correlations with the Fermi sea at low temperatures

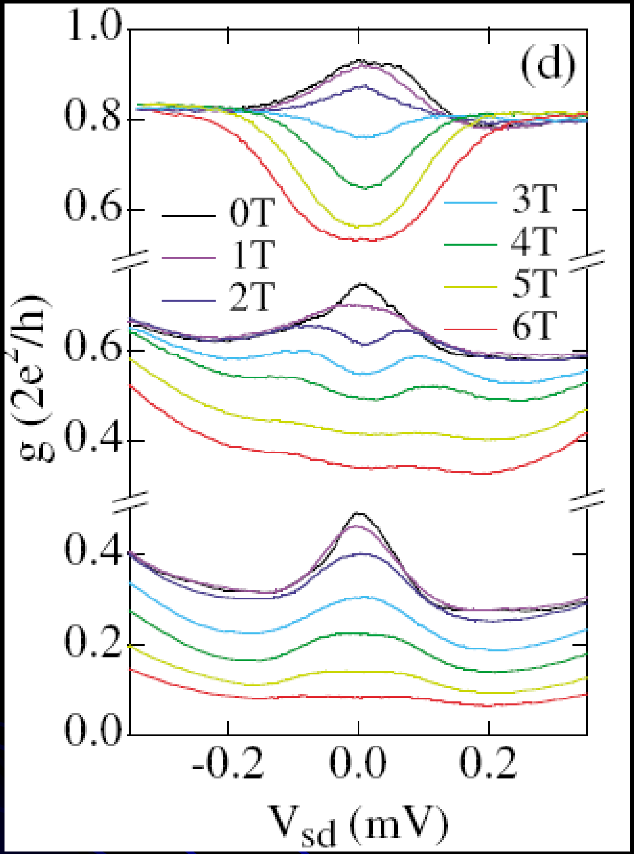






A peak
in the density of states at E_F

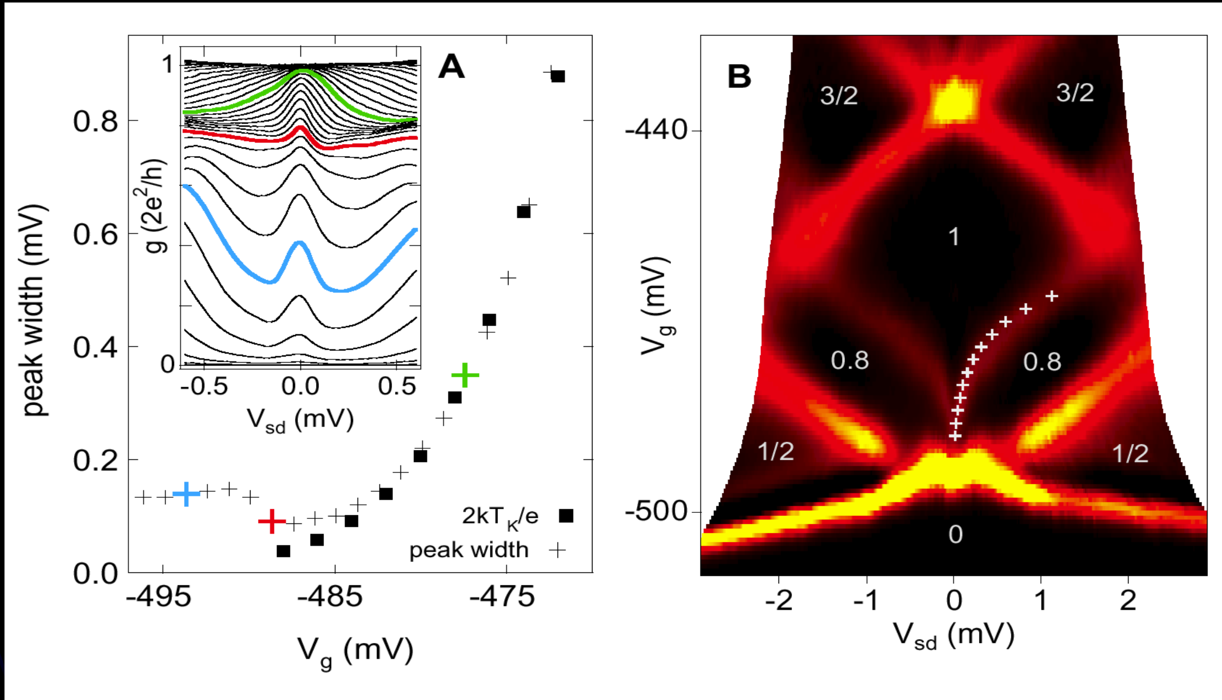
Splitting of ZBA with magnetic field



Near g~0.7, a clear splitting is present.

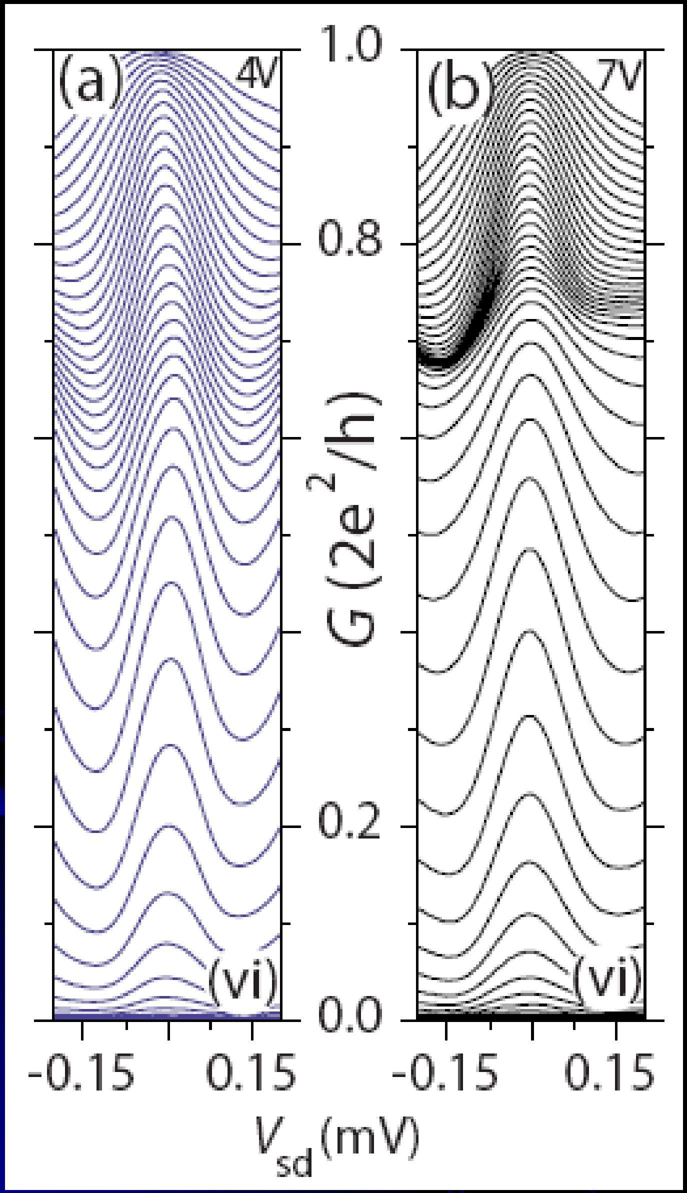
$$e\Delta V_{pp} = 2g^{*}\mu_{B}B$$

A correlated between ZBA width and T_k.



S. M. Cronenwett *et. al.*, PRL 88, 226805 (2002).

Story Ends? **A localized state near or in the QW.**



S. Sarkozy *et al.*, PRB 79, 161307 (2009).

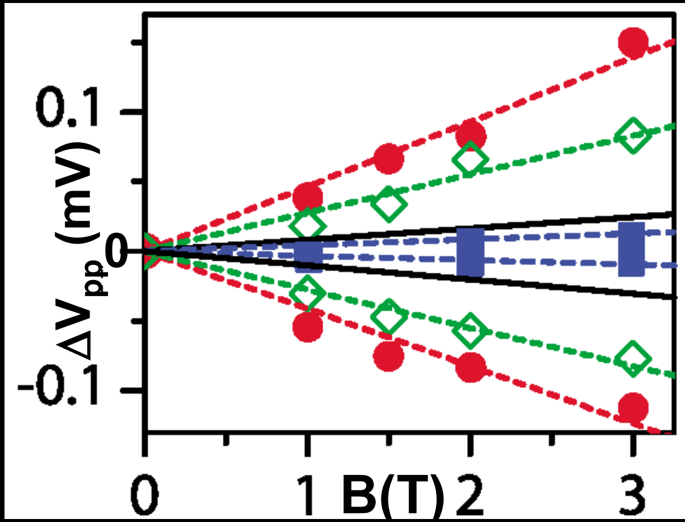
- ZBA is continuously present from $G \sim (2e^2/h)$ down to $G \sim (2e^2/h) \times 10^{-5}$.
- The width of ZBA does not scale with neither T_K nor T.

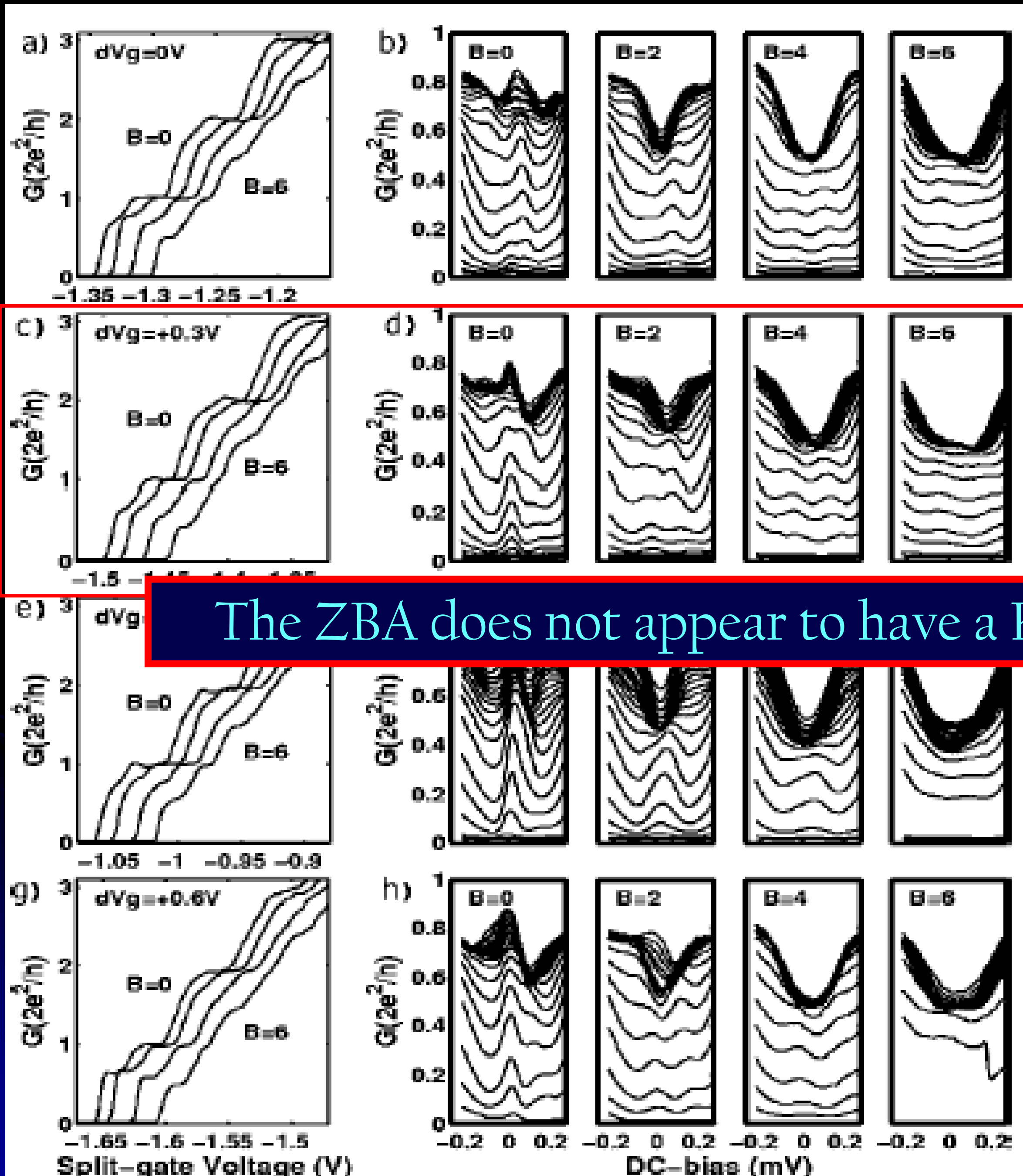
Y. Ren *et al.*, PRB 82, 045313 (2010).

- ZBA do not always split in magnetic fields .

TM Chen *et al.*, PRB 79, 153303 (2009).

- Peak_to_peak separation in ZBA splitting increases linearly with magnetic field.





The ZBA does not appear to have a Kondo origin.

ZBA does not spin split in $B_{||}$ (up to 10T).

Kondo expectation : $2g^{*}\mu_B$=120μV/T

(g^{*}=1.06 spin gap measurement)

ZBA is strongly affected by a disordered confining potential, dV_{sg}.

TM Chen *et al.*, PRB 79, 153303 (2009).

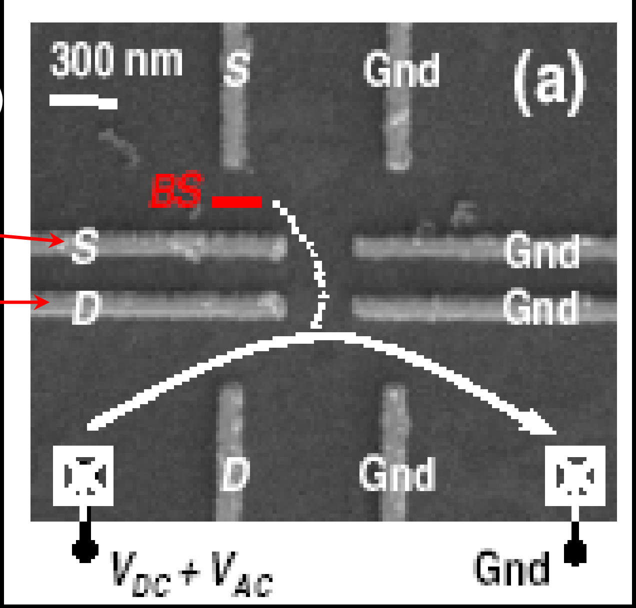
Self-consistent bound state?

Coupled QPCs to detect bound state.

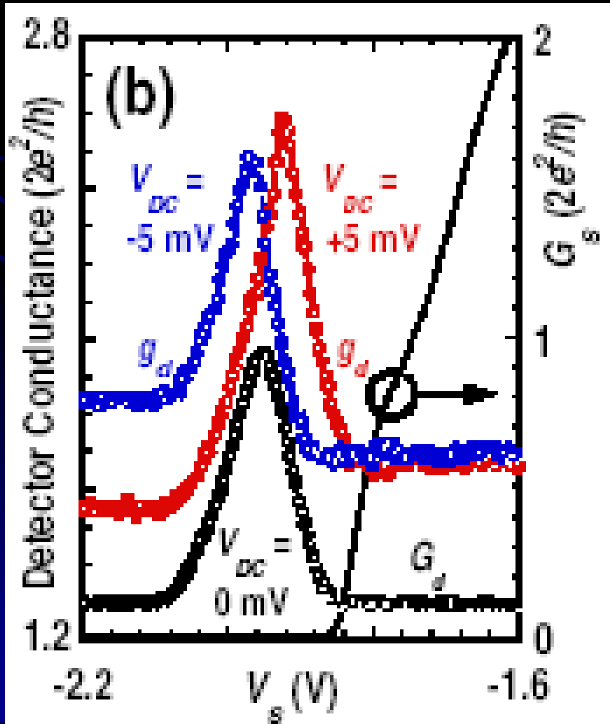
Y. Yoon *et al.*, APL 94, 213103 (2009)

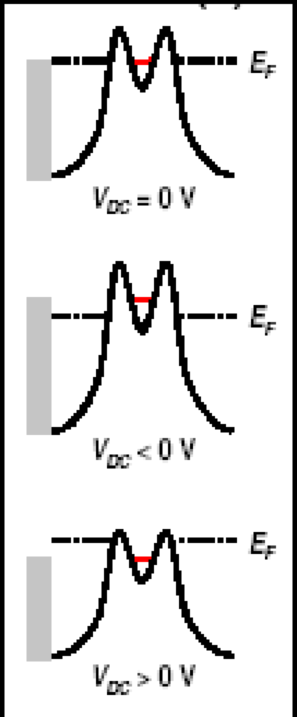
Swept QPC

Detector



Detector resonance occurs when the bound state is strongly confined.





Y. Yoon *et al.*, PRB 79, 121304 (2009)

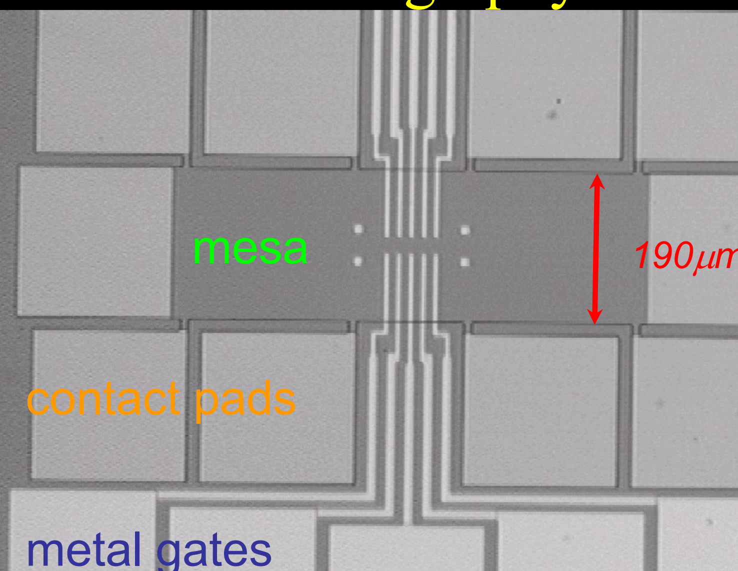
Experimental details

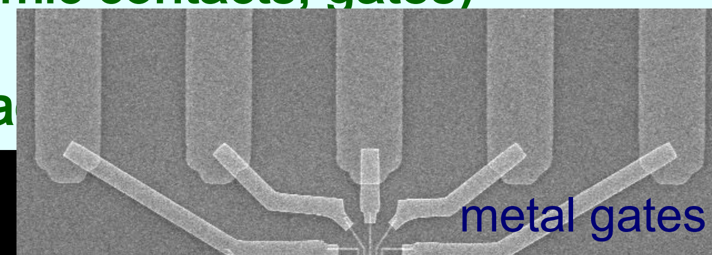
2DEG : high mobility GaAs/AℓGaAs heterostructure (by Umansky group)

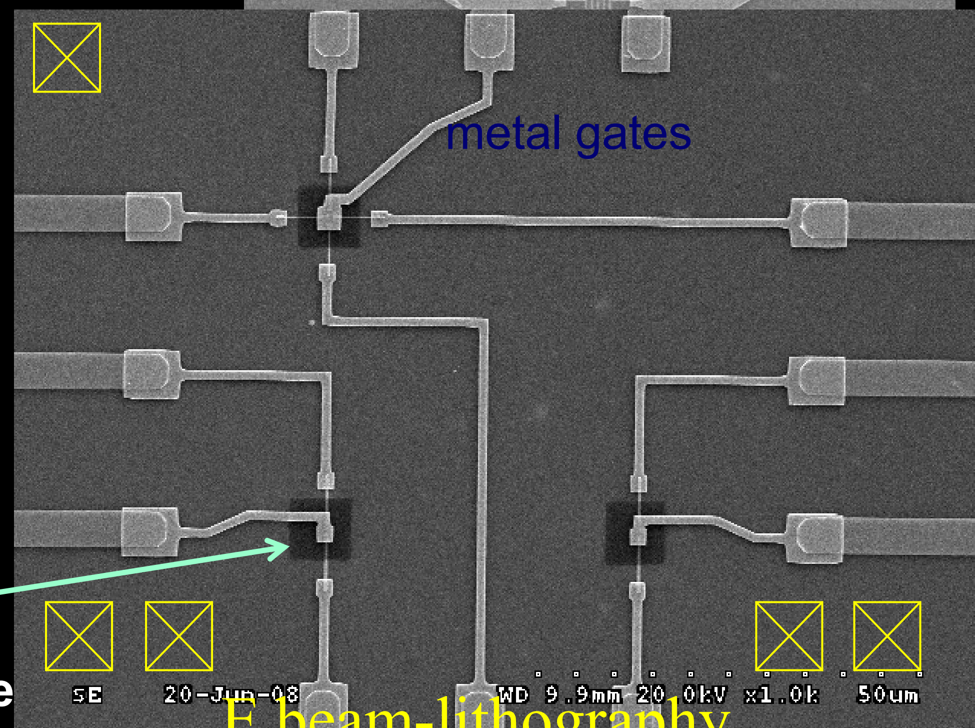
Device fabrication

- photolithography & e-beam lithography—patterning
- wet etching (mesa)
- thin-film deposition (Ohmic contacts, gates)
- lift-off
- annealing (Ohmic conta

Photo-lithography







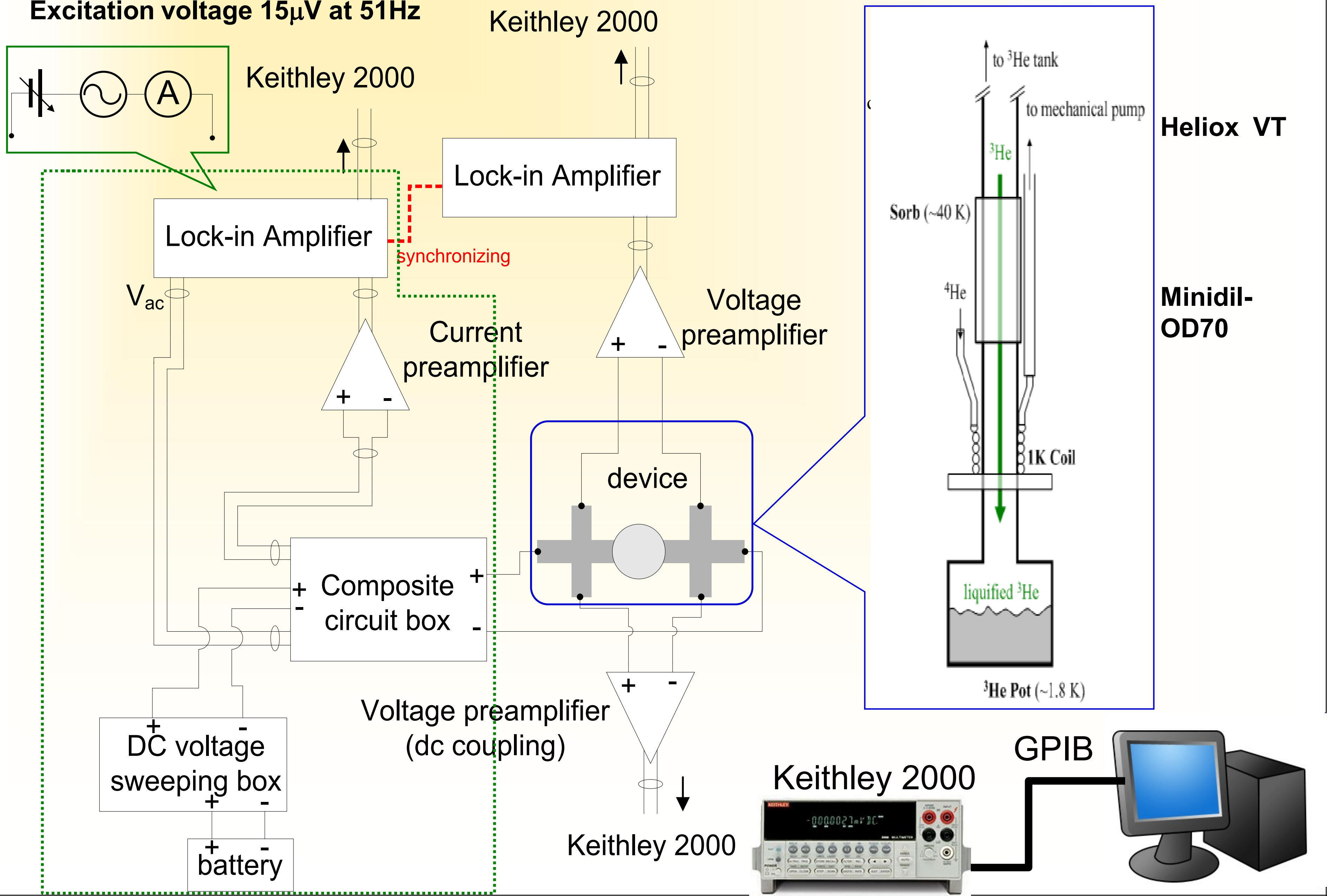
E beam-lithography

cross-linked PMMA
—isolating split gates and top gate

Electrical measurement

Differential resistance measurement (finite V_{sd} up to 3mV)

Excitation voltage 15μV at 51Hz

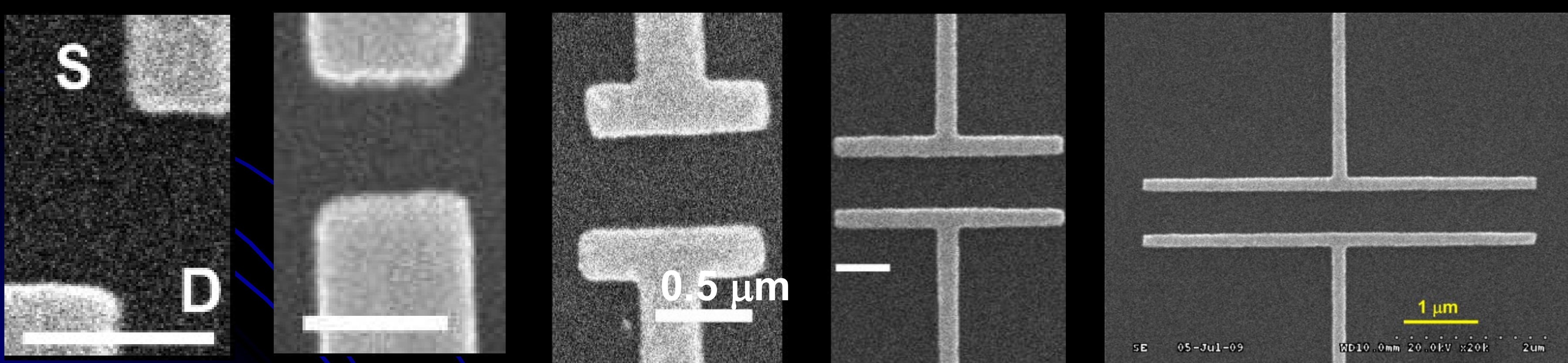


Zero-bias anomaly and conductance reduction in QWs

- What is the origin of ZBA?
- Does it have to do with any physical parameter, e.g. geometry and electron density?

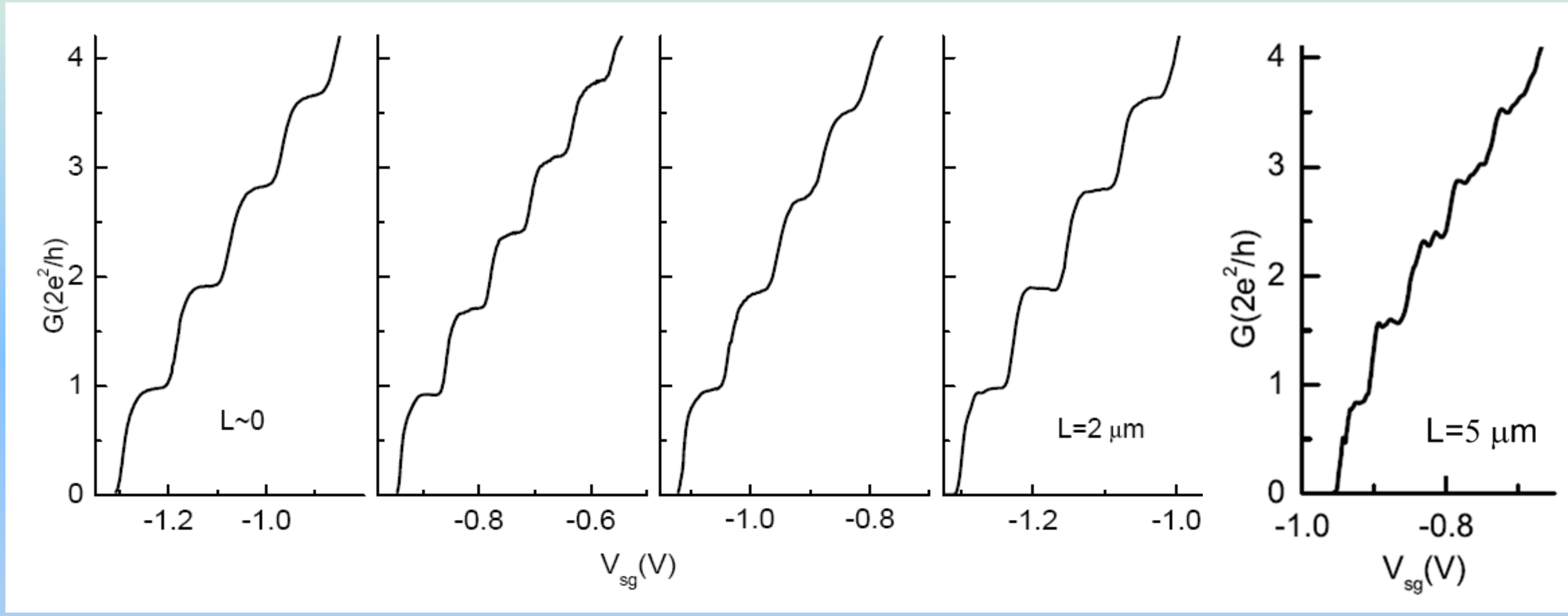
QW w/. various lengths L

L~0 L=0.5 μm L=0.8 μm L=2 μm L=5 μm



Top gate to control carrier concentration.

QW length dependence

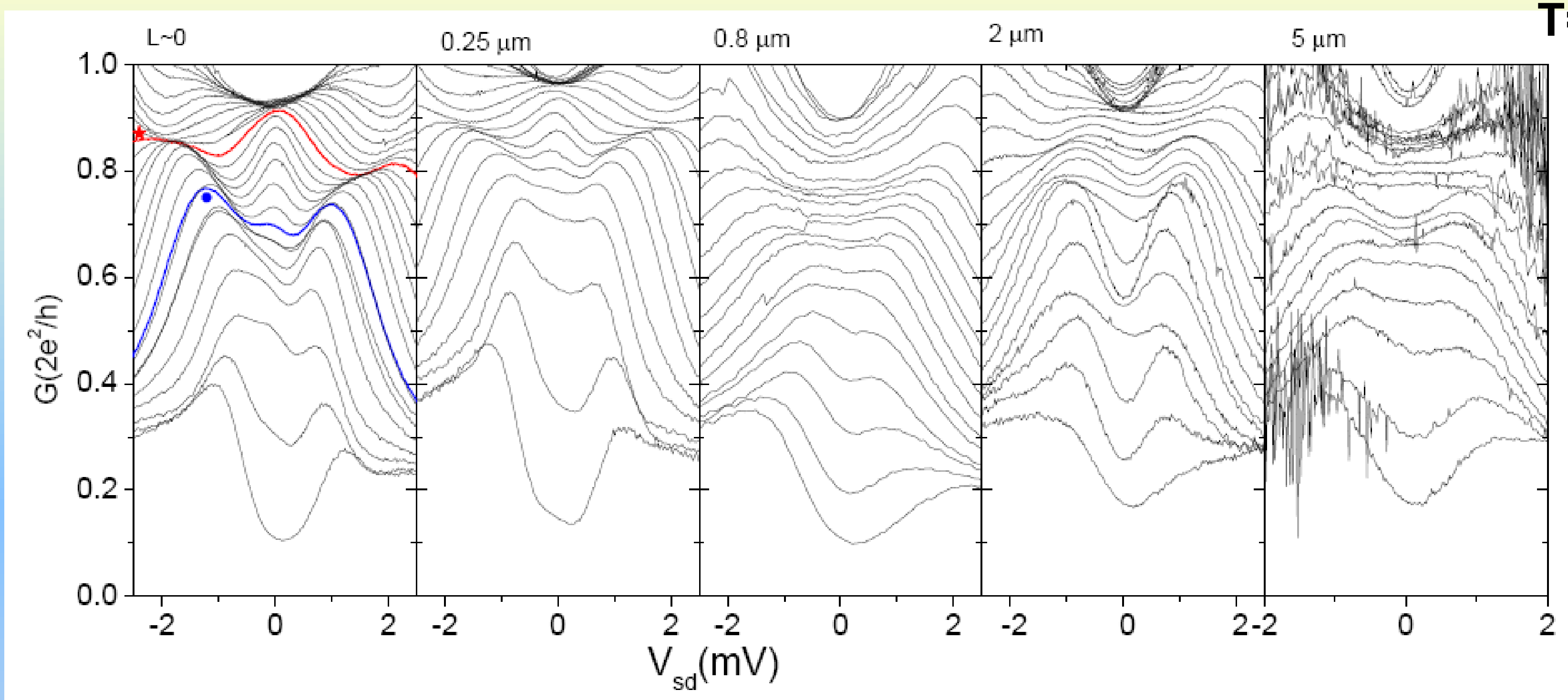


T=0.3 K

- For L $\leq$2 μm, conductance quantization remains robust. — ballistic
- For L=5 μm, plateaus conductance is lowered emerging with resonances.

— slightly diffusive

T=0.3 K



- A strong ZBA is present in the L~0 QW.
  (the differential conductance exhibits a series of single peak centered at V_{sd}=0)
- The ZBA is weaker for L=0.25 μm and completely suppressed for L≥0.8 μm.

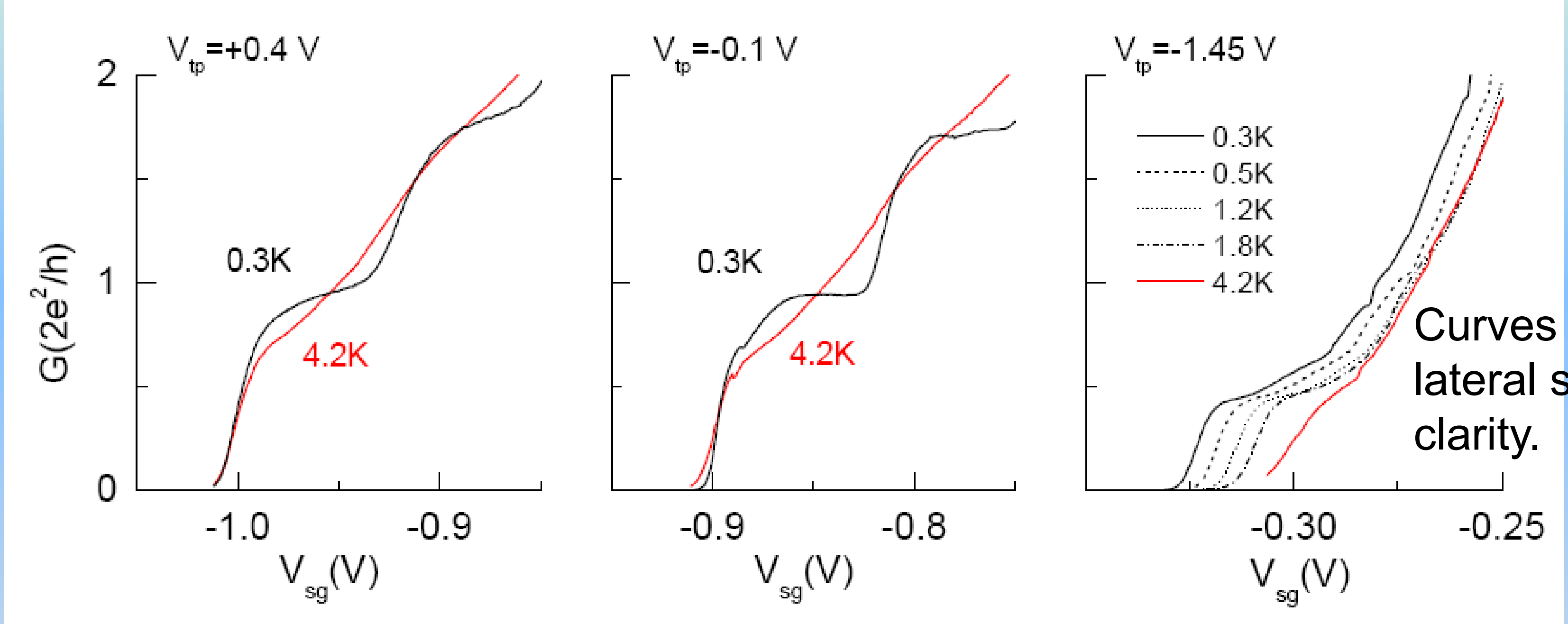
- differing from the conclusion by E. J. Koop, *et. al.*. J. Supercond. Nov. Magn. 20, 433 (2007).

- No splitting of ZBA peak in the long QW.

We suggest that the increase in QW length allows additional scattering of conduction electrons resulting in enhanced electron-electron interactions and correspondingly, a diminished ZBA.

Carrier density dependence

A QW w/. L=0.5 μm



Curves are lateral shifted for clarity.

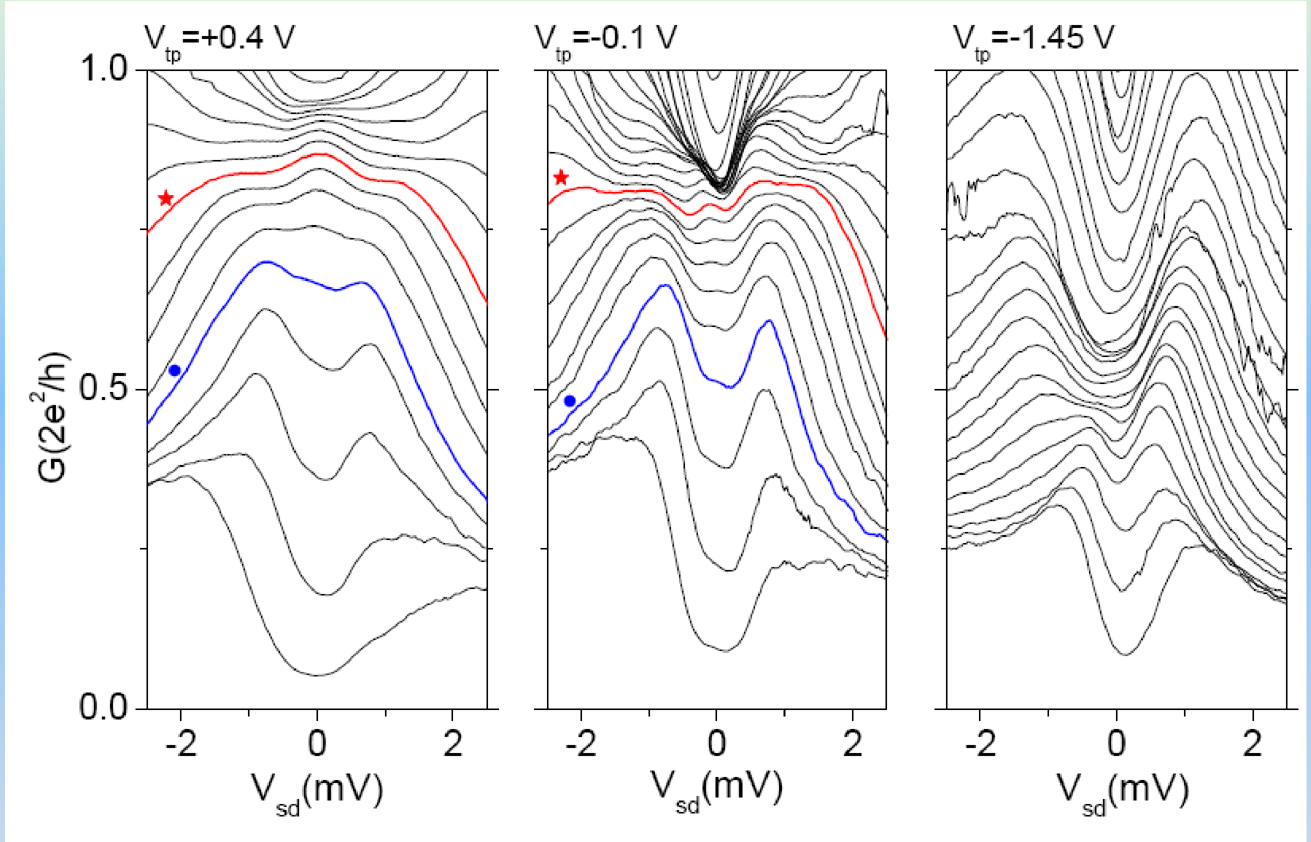
- The 0.7 anomaly evolves into a $0.5\times(2e^2/h)$ quasi-shoulder with reducing n.
- For V_{tp}=0.4 and $-$0.1V, a quasishoulder forms near $0.7G_o$ while the plateaus of NG_o are thermally washed out.

A clear temperature-induced condtance reduction around $0.7G_o$.

- The conductance is *insensitive* to temperature in lower carrier densities.

A QW w/. L=0.5 μm

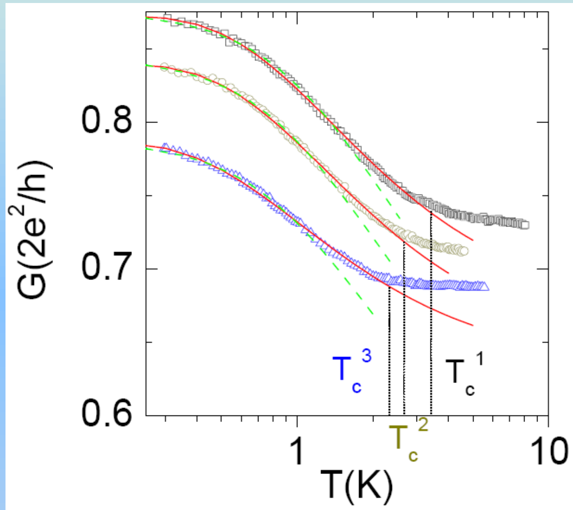
T=0.3 K



- The ZBA is weakened with decreasing carrier density, and completely suppressed in low carrier densities.

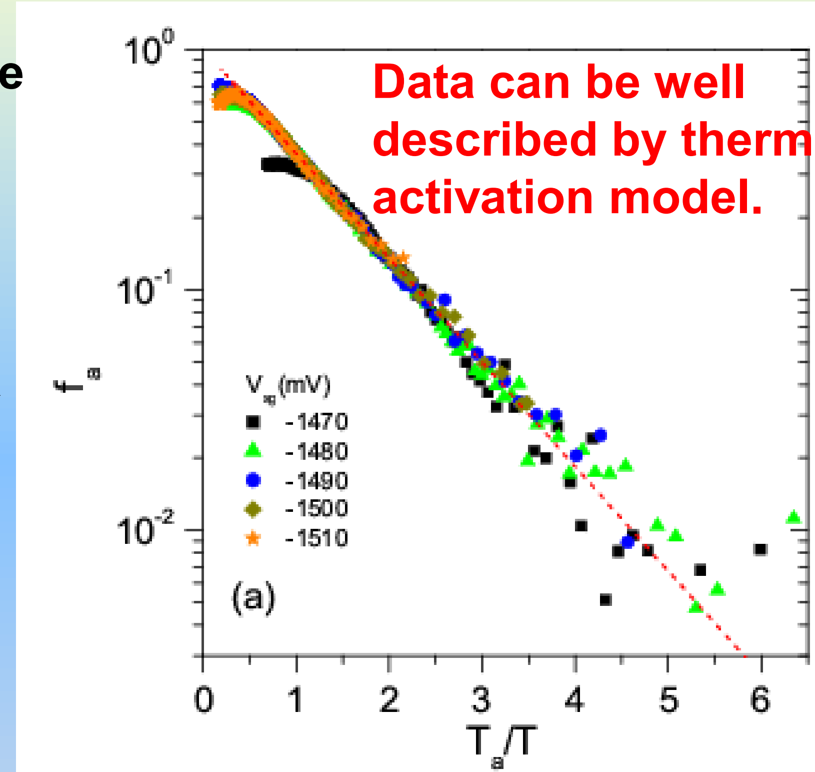
The conductance reduction with temperature

Typical temperature dependent conductance for a L~0 QW



$$f_a \equiv \frac{1}{C}\left(1-\frac{G(T)}{G(0)}\right)$$

Rearranging data



Data can be well described by thermal activation model.

comparing with two models,

Thermal Activation

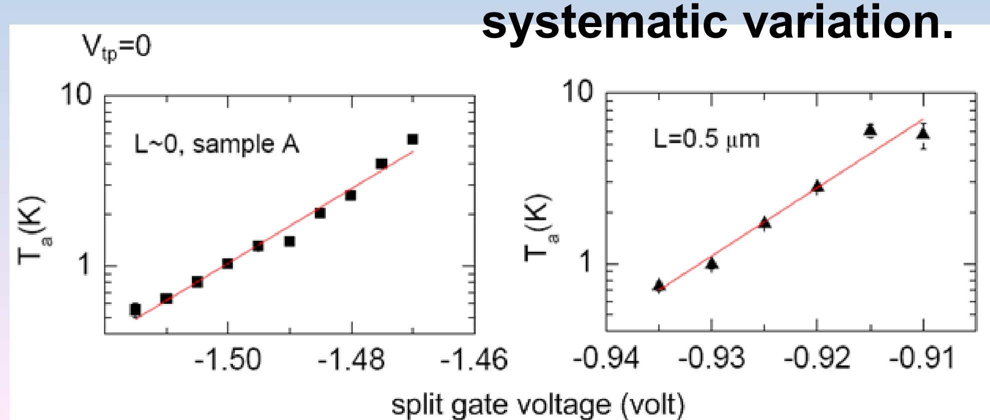
$$G(T)=G(0)\left(1-C\cdot e^{-T_a/T}\right)$$

Kondo-type

$$G_{KL}(T)=G(0)\left\{\frac{1}{2}\left[1+\left(2^{1/s}-1\right)\left(T/T_{KL}\right)^2\right]^{-s}+\frac{1}{2}\right\}$$

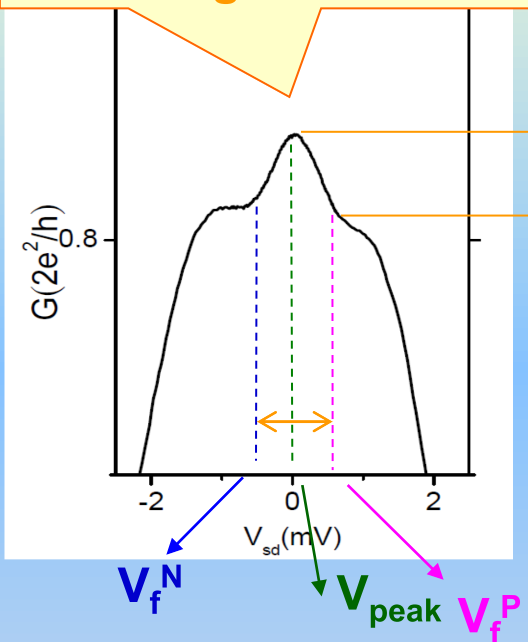
s=0.22

- **The applicable temperature range is wider.**
- **The fitting parameter T_a from the fit exhibits a systematic variation.**

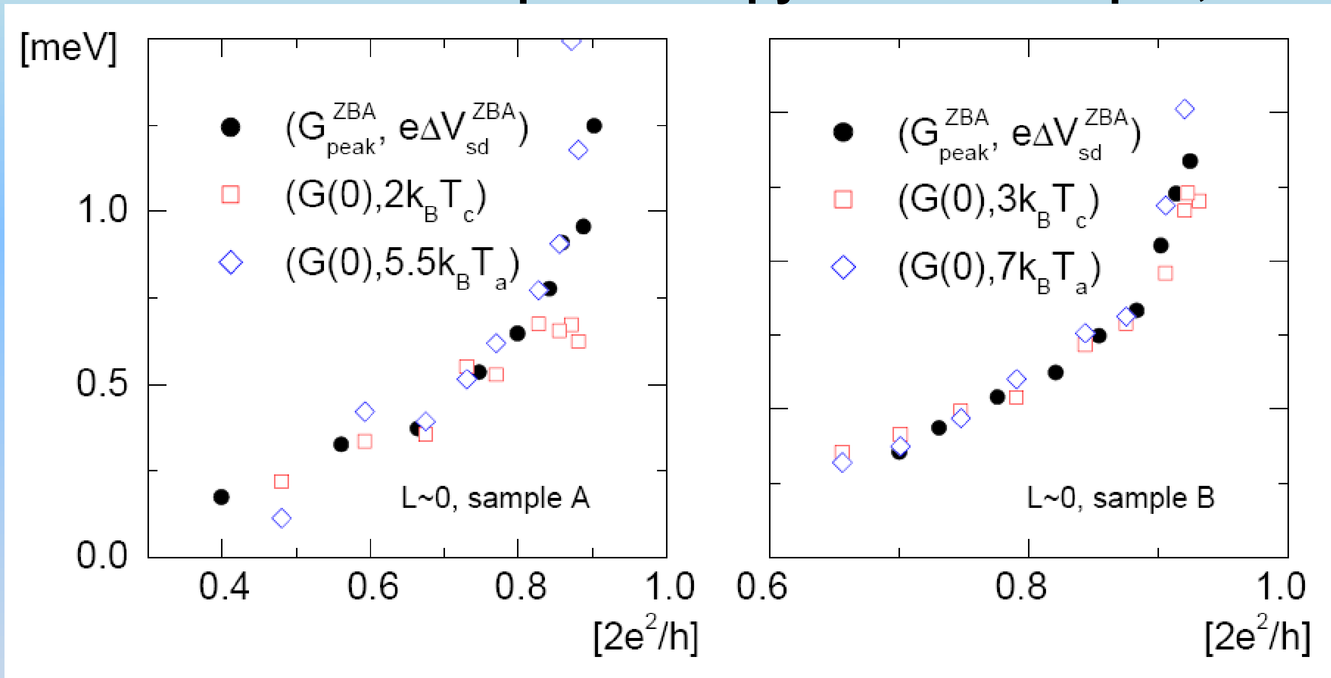


Correlation among T_a, T_c, and the ZBA width

Conductance decreases with increasing bias at low temperatures



Scaling [G(0), T_c], [G(0), T_a] extracted from G(T) and [G^{ZBA}_{peak}, ΔV^{ZBA}_{sd}] extracted from source-drain bias spectroscopy on the same plot,



- **Three traces collapse onto one curve.**

Width of the ZBA:

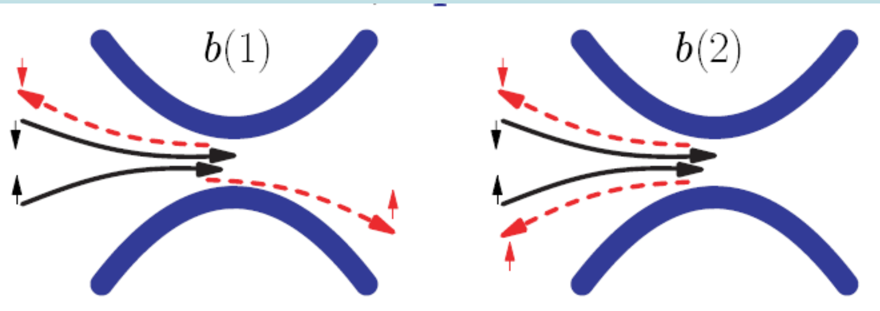
$$e\Delta V_{sd}^{ZBA} \equiv \frac{e}{2}\left(V_f^P - V_f^N\right)$$

- **Three characteristic quantities Tc, Ta, and ΔV^{ZBA}_{sd} decrease monotonically with decreasing zero bias differential conductance.**
- **The temperature- and bias- induced conductance reductions are strongly correlated.**

Inelastic backscattering in QWs

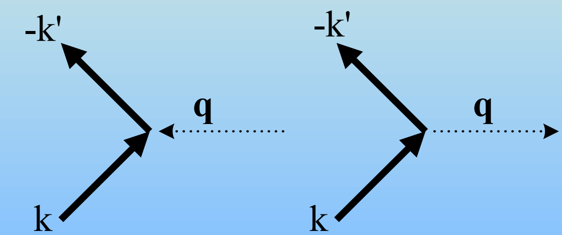
electron-electron scattering

A. M. Lunde *et al.*, New J. Phys. 11, 023031 (2009).



electron-phonon scattering

G. Seelig and K. A. Matveev, PRL 90, 176804 (2003).



Consider backscattered current using Fermi's golden approach

Fermi-Dirac distribution

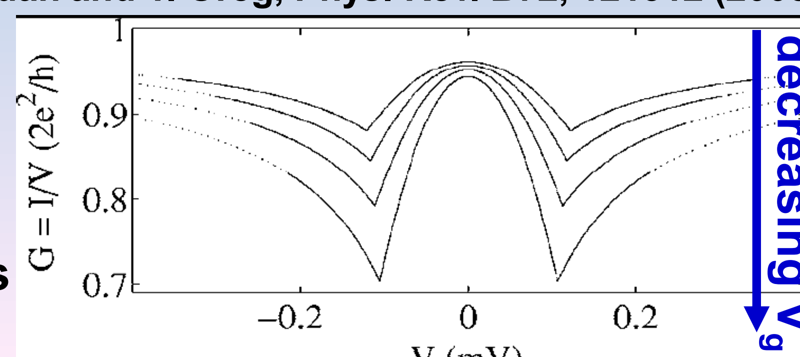
$$\delta I = -2e\int_{-\infty}^{\infty}\left[\tau_R^{-1}(E)f_R(E) - \tau_L^{-1}(E)f_L(E)\right]dE$$

Backscattering rate of left-going electrons

- ***Negative*** **conductance correction with either *bias* or *temperature* due to increased allowable electrons for backscattering.**
- ***Thermal activated*** **conductance behavior.**

D. Meidan and Y. Oreg, Phys. Rev. B72, 121312 (2005)

- **Model a normal QPC by an interacting spinful Luttinger Liquid.**
- ***Two-electron scattering*** **arisen from strong Coulomb interaction at high biases**



Summary

- The ZBA is weakened with either decreasing carrier density or increasing channel length.
- The temperature dependent conductance reduction follows the thermal activation form.
- Cutoff energy, activation energy, and the ZBA width are correlated.

The temperature- and bias- induced conductance reductions are affected by the same physics.

Our results are consistent with some theoretical works.

Multiple backscattering becomes frequent with increasing source-drain bias leading to a reduced conductance, manifesting as ZBA, whereas enhanced electron-electron interaction prompts multiple scatterings to weaken the ZBA.

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