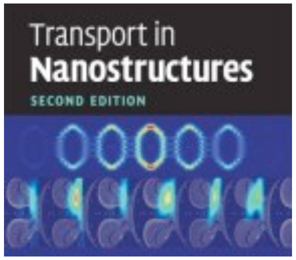
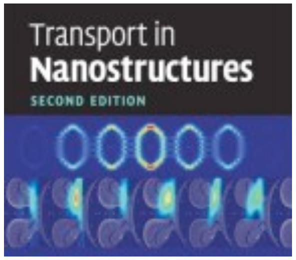


GENERAL ASPECTS OF MESOSCOPIC TRANSPORT: III

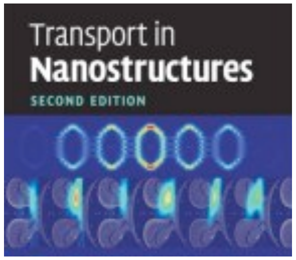
Jonathan Bird
Electrical Engineering, University at Buffalo, Buffalo NY, USA



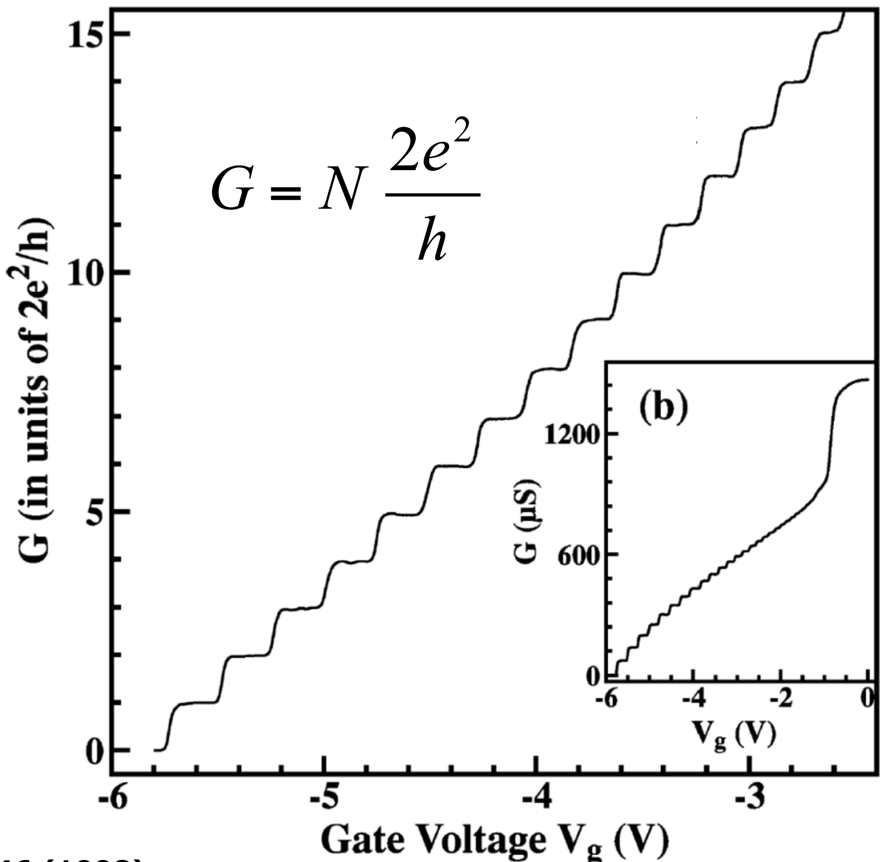
GENERAL ASPECTS OF MESOSCOPIC TRANSPORT III

- 1-D Conductance Quantization … Revisited
- Non-Linear Conductance of QPCs
- Bias-Spectroscopy Techniques*
- Breakdown of Conductance Quantization*
- And Now for Something Completely … New

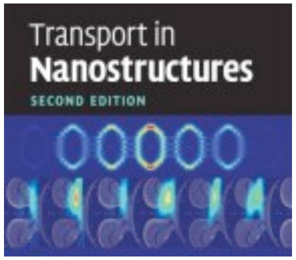
* UNFORTUNATELY, NO TIME FOR THIS TODAY



LINEAR Conductance of QPCs QUANTIZED in units of $2e^2/h$



K. J. Thomas et al.
Phys. Rev. B 58, 4846 (1998)



LINEAR Conductance of QPCs QUANTIZED in units of $2e^2/h$

Take excess charge per unit length PER OCCUPIED SUBBAND:

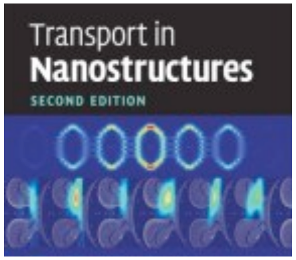
$$\delta Q \approx e \times eV_{sd} \times \frac{1}{2} g_{1D}(E_F) = e^2 V_{sd} \left[\frac{m^*}{2\pi^2 \hbar^2 E} \right]^{1/2}$$

ASSUMES SMALL V_{sd} TO AVOID NEED TO INTEGRATE OVER DoS!

This allows us to obtain the CURRENT:

$$I_{pc} = \delta Q \times v_g = e^2 V_{sd} \left[\frac{m^*}{2\pi^2 \hbar^2 E} \right]^{1/2} \times 2\sqrt{\frac{E}{2m^*}} = \frac{2e^2}{h} V_{sd}$$

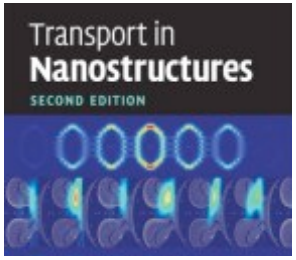
But What About LARGE Voltages?



GENERAL ASPECTS OF MESOSCOPIC TRANSPORT III

- **1-D Conductance Quantization … Revisited**
- **Non-Linear Conductance of QPCs**
- **Bias-Spectroscopy Techniques***
- **Breakdown of Conductance Quantization***
- **And Now for Something Completely … New**

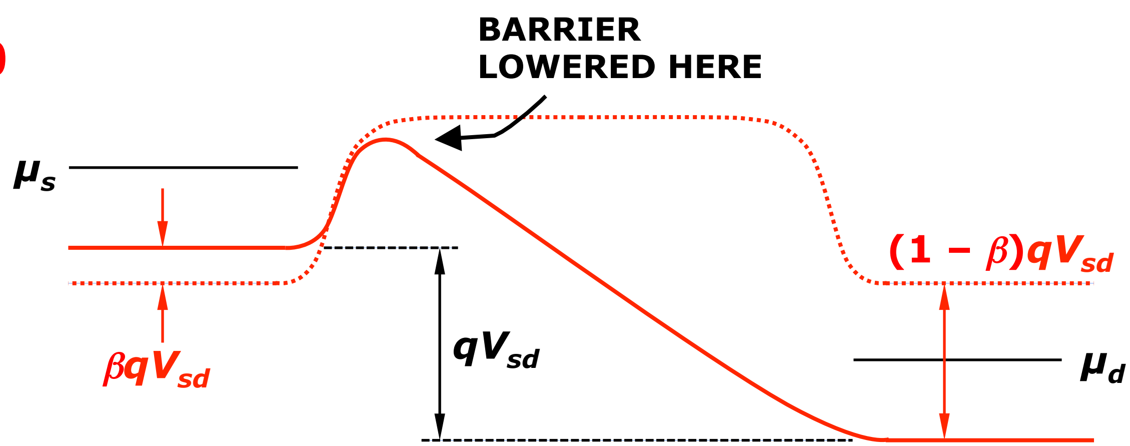
*** UNFORTUNATELY, NO TIME FOR THIS TODAY**

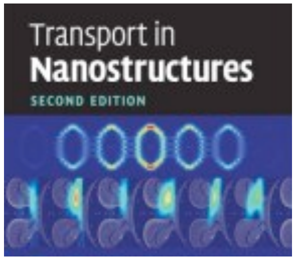


A Model for the VOLTAGE DROP Across a QPC

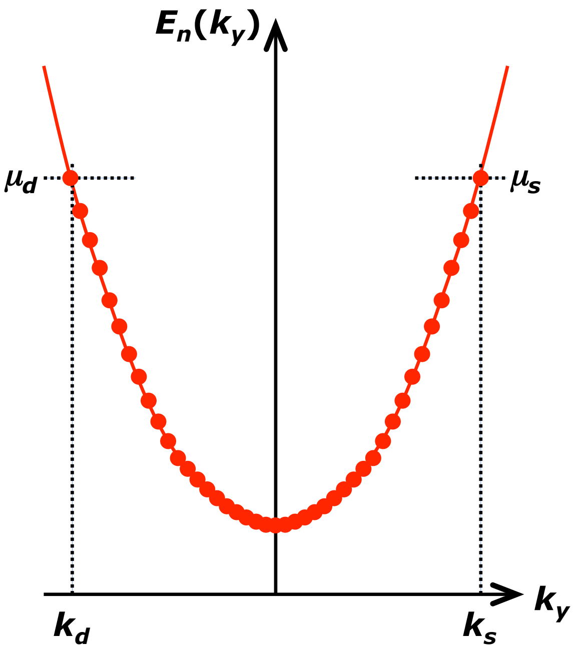
1. $V_{sd} = 0$

2. $V_{sd} > 0$





QPC Current For SINGLE Subband Under Bias



1. Current due to SINGLE electron is ev_g/L

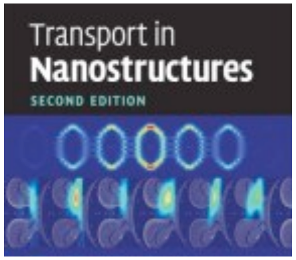
2. Current due to ALL electrons between k & $k + \mathrm{d}k$

$$e\frac{v_g}{L}\frac{2dk}{2\pi / L} = 2e\frac{v_g}{2\pi}$$

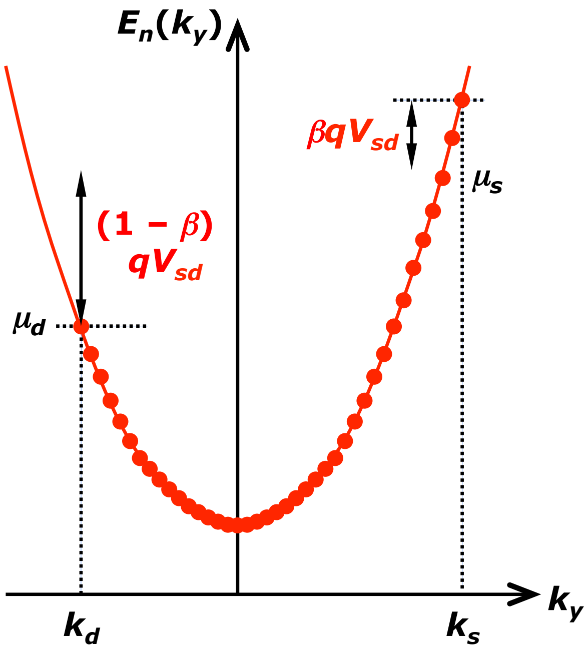
3. Thus the TOTAL current

$$I = 2e\int_{k_d}^{k_s} v_g(k)\,\frac{dk}{2\pi}$$

= 0 WHEN V_{sd} = 0
SINCE $k_d = -k_s$



QPC Current For SINGLE Subband Under Bias



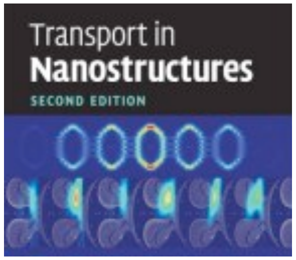
1. With V_{sd} applied the integral becomes

$$I = 2e \int_{k_d}^{k_s} v_g(k)\,\frac{dk}{2\pi} = \frac{2e}{h} E(k)\Big|_{k_d}^{k_s}$$

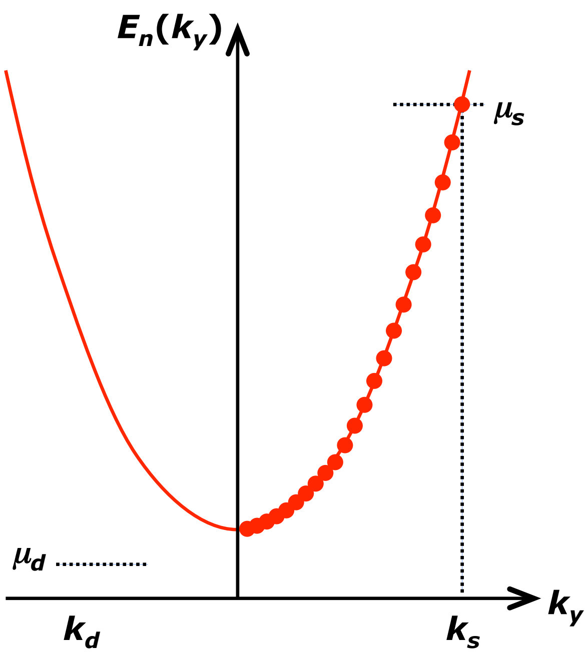
2. Since the integrand is just eV_{sd} the DIFFERENTIAL CONDUCTANCE

$$\frac{\partial I}{\partial V_{sd}} = \frac{2e^2}{h}$$

JUST WHAT WE HAD BEFORE!



QPC Current For SINGLE Subband Under STRONG Bias



1. Now only carriers from ONE reservoir contribute to the current

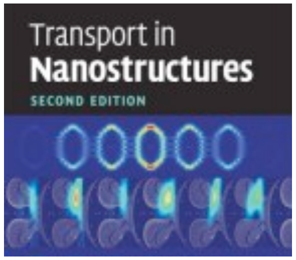
2. The current is then written as

$$I = \frac{2e}{h} E(k)\Big|_0^{k_s} = \frac{2e}{h}(\mu_s + \beta e V_{sd})$$

3. So the corresponding differential conductance becomes

$$\frac{\partial I}{\partial V_{sd}} = \beta \frac{2e^2}{h}$$

NO LONGER QUANTIZED!



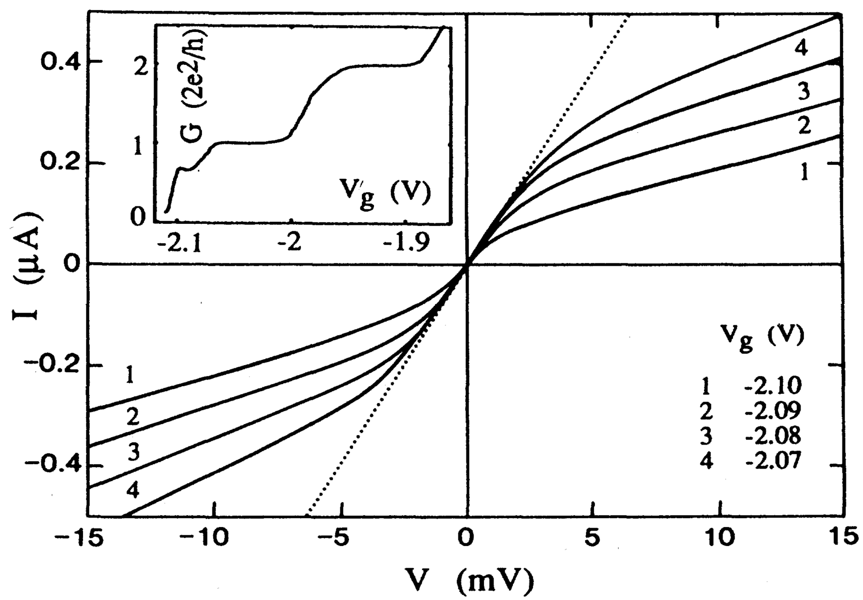
QPC Current For SINGLE Subband Under STRONG Bias

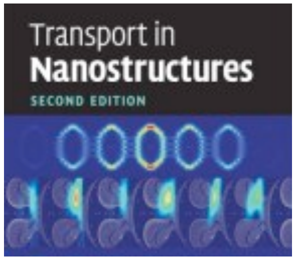
RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 39, NUMBER 11 15 APRIL 1989-I

Nonlinear conductance of quantum point contacts

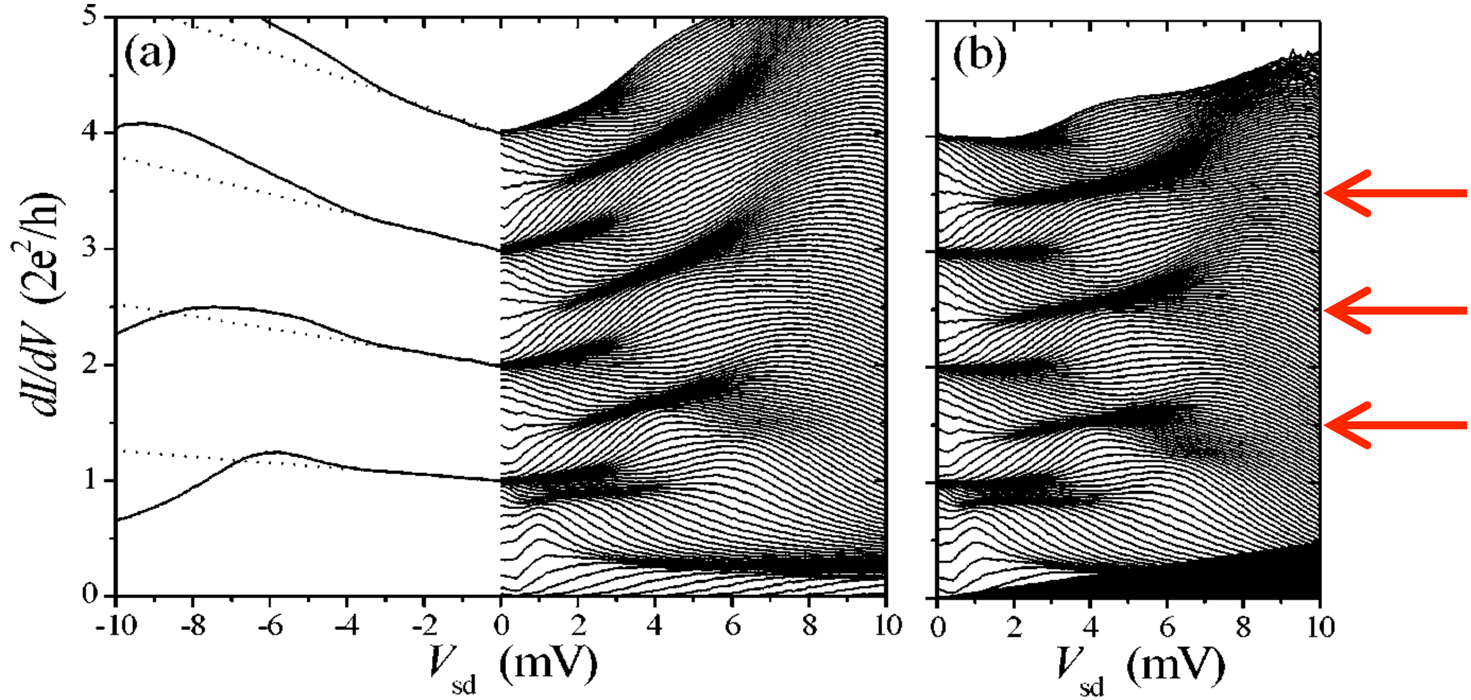
L. P. Kouwenhoven, B. J. van Wees, and C. J. P. M. Harmans
Department of Applied Physics, Delft University of Technology, P. O. Box 5046, 2600 GA Delft, The Netherlands



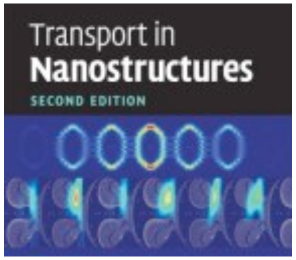


HALF-PLATEAUS For A SYMMETRIC Voltage Drop (β = ½)

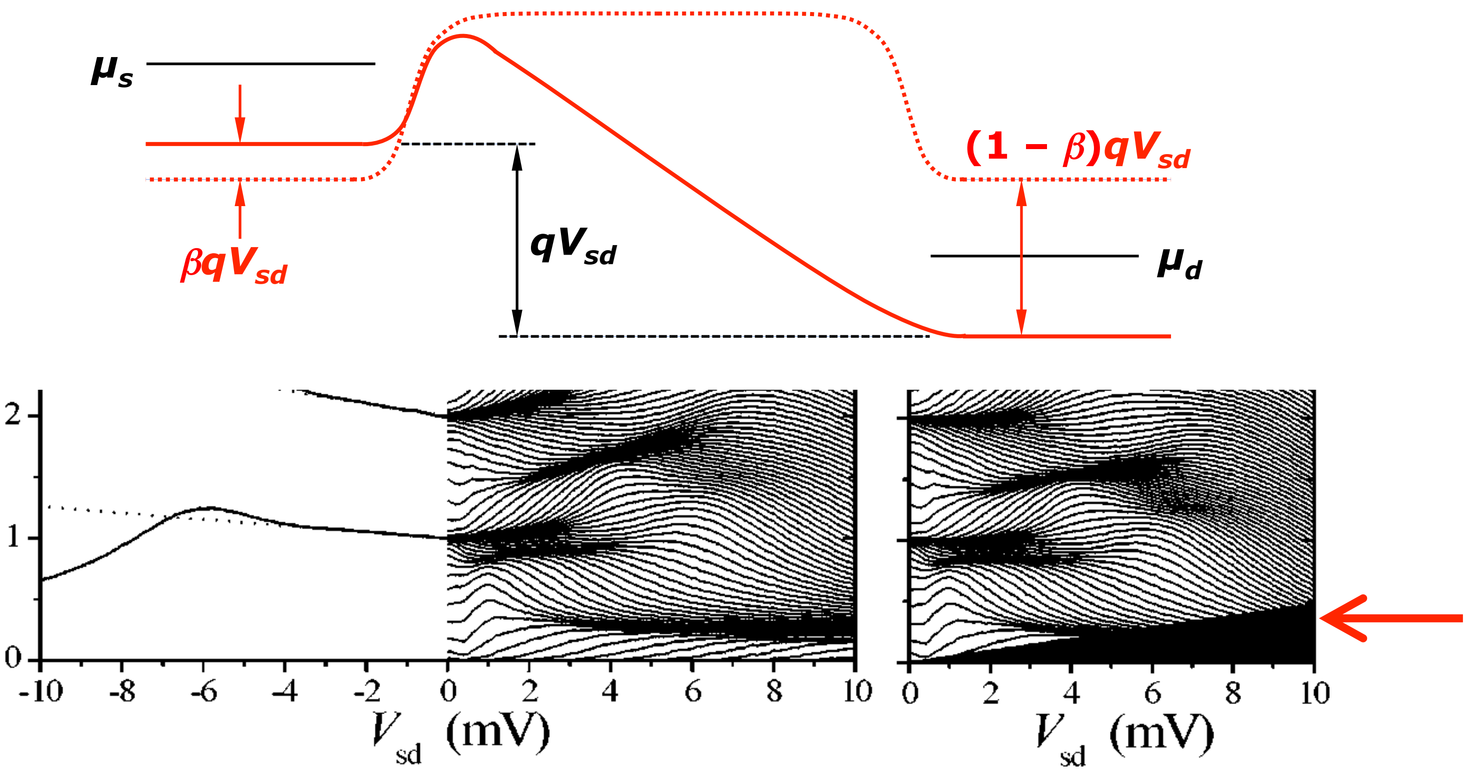
$$\frac{\partial I}{\partial V_{sd}} = \frac{1}{2}\frac{2e^2}{h}$$



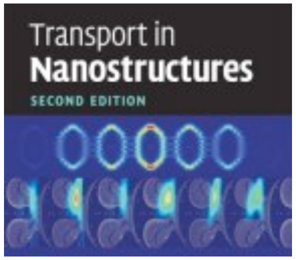
A. Kristensen et al., Phys. Rev. B 62, 10950 (2000)



HALF-PLATEAUS Near PINCH-OFF (β << ½)



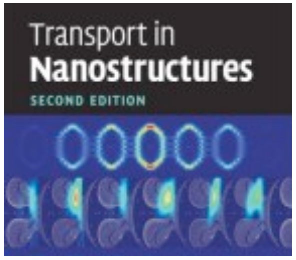
A. Kristensen et al., Phys. Rev. B 62, 10950 (2000)



GENERAL ASPECTS OF MESOSCOPIC TRANSPORT III

- **1-D Conductance Quantization … Revisited**
- **Non-Linear Conductance of QPCs**
- **Bias-Spectroscopy Techniques***
- **Breakdown of Conductance Quantization***
- **And Now for Something Completely … New**

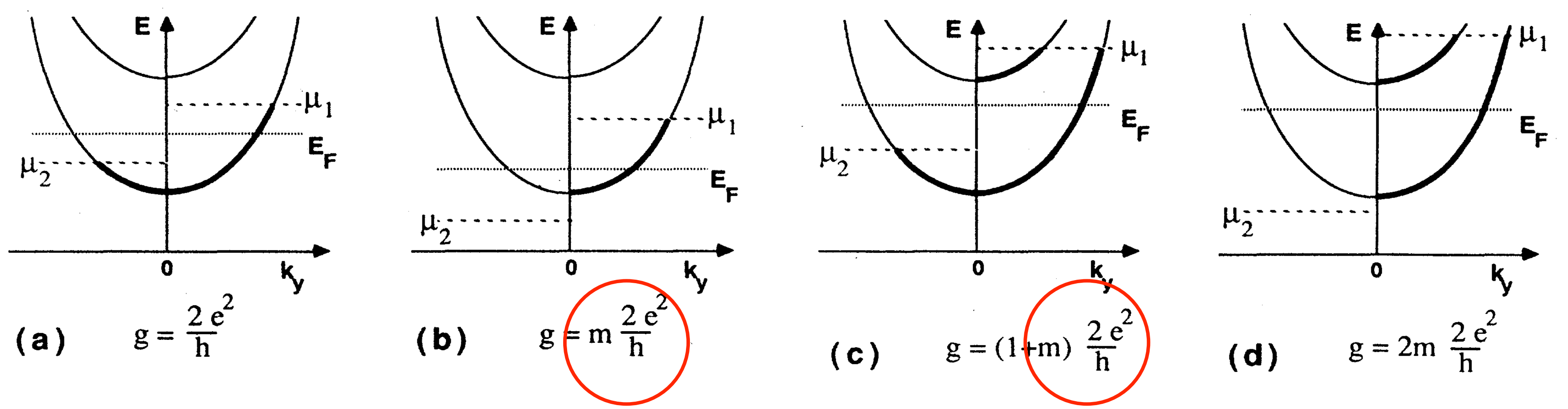
*** UNFORTUNATELY, NO TIME FOR THIS TODAY**



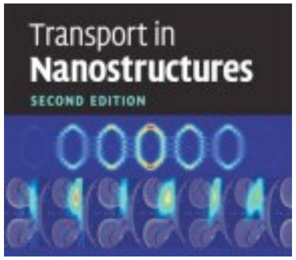
Determination of 1-D Subband SPACING

The half plateaus appear when the number of conducting subbands for the two directions of transport differs by 1.

N. K. Patel et al., Phys. Rev. B 44, 13549 (1991)



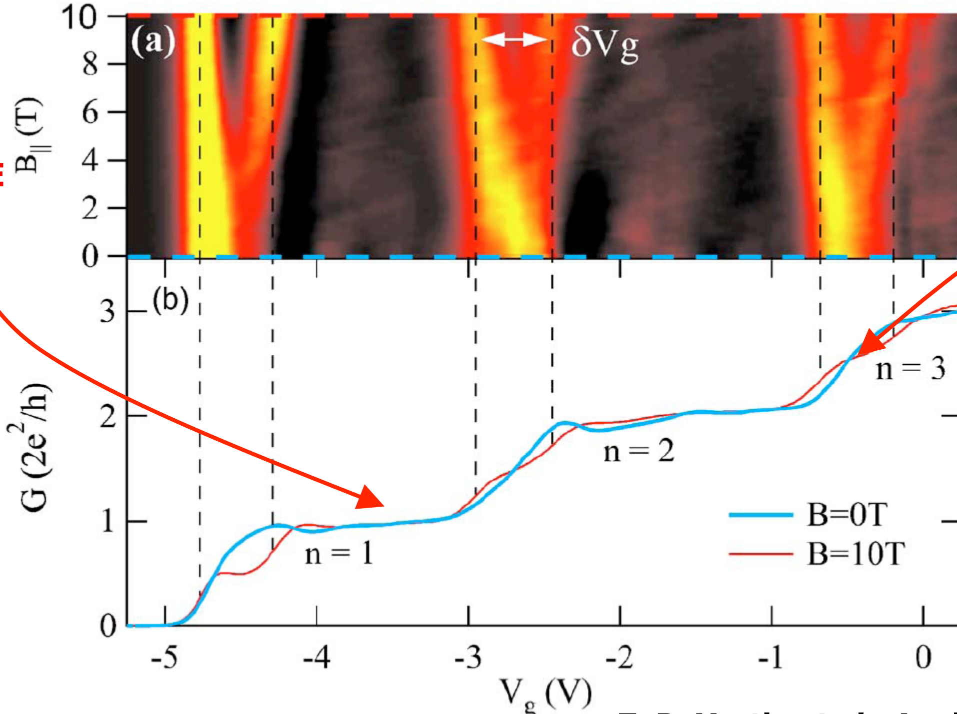
L. P. Kouwenhoven et al., Phys. Rev. B 39, 8040 (1991)



Determination of 1-D Subband SPACING

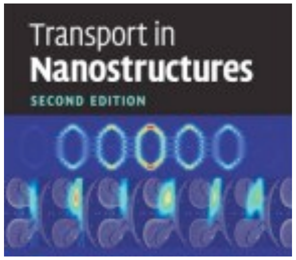
LOW TRANS-CONDUCTANCE

HIGH TRANS-CONDUCTANCE



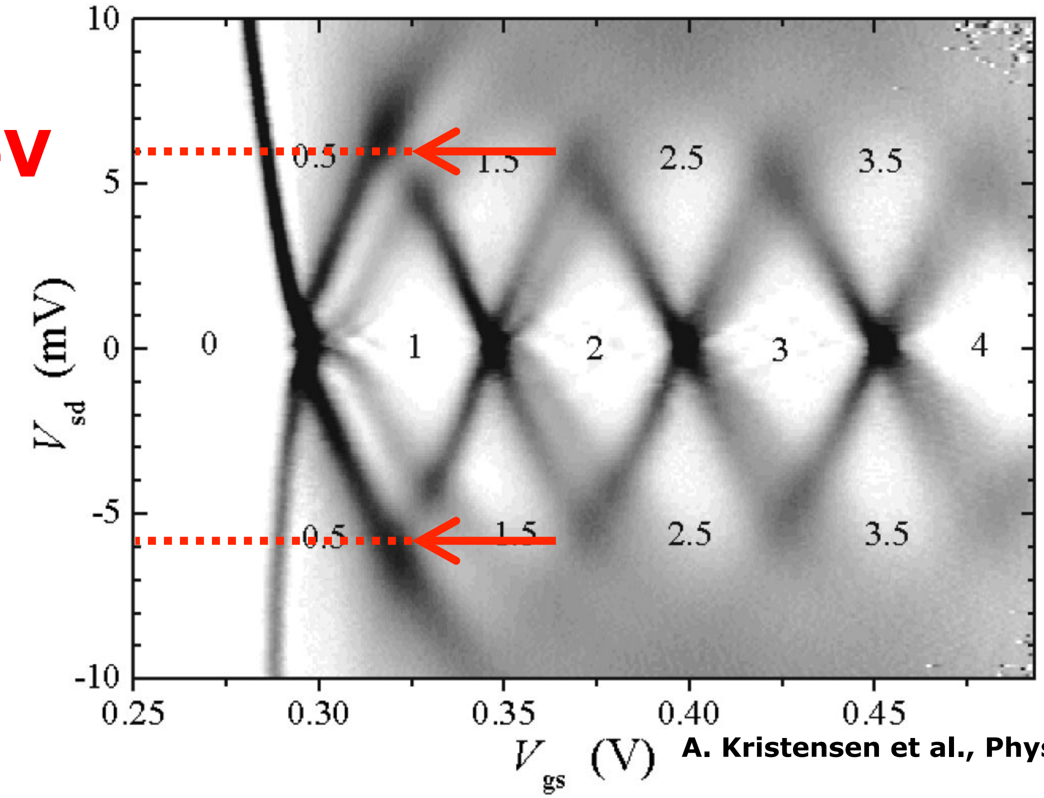
T. P. Martin et al., Appl. Phys. Lett. 93, 012105 (2008)

Make Use of TRANSconductance



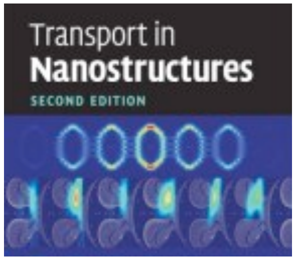
Determination of 1-D Subband SPACING

Δ = 6 meV



A. Kristensen et al., Phys. Rev. B 62, 10950 (2000)

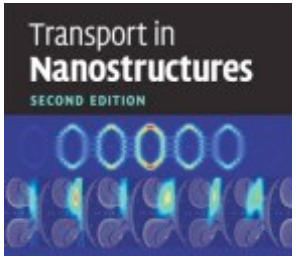
Make Use of TRANSconductance



Determination of 1-D Subband SPACING

- **Typical subband spacings in the range of a FEW meV – dependent on STRUCTURE**
- **Subband spacing typically INCREASES as gate confinement is made stronger**
- **Bias-Spectroscopy can also be used to investigate ZEEMAN splitting of the subbands**

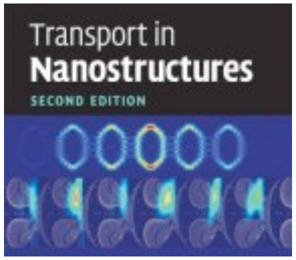
MORE NEXT WEEK FROM ADAM MICOLICH!



GENERAL ASPECTS OF MESOSCOPIC TRANSPORT III

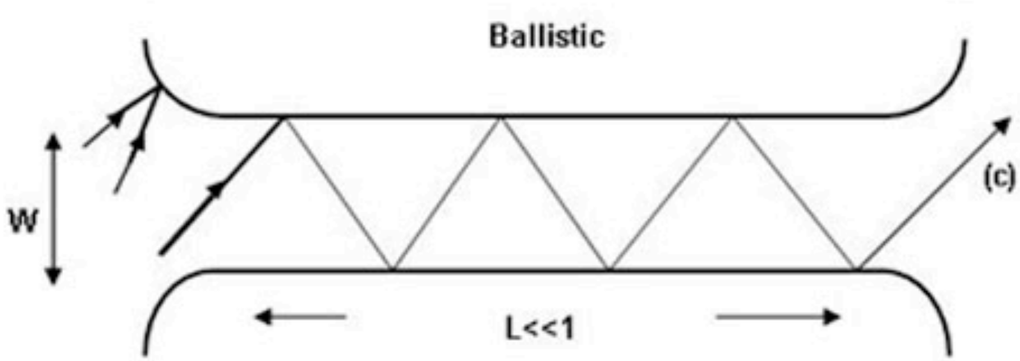
- **1-D Conductance Quantization … Revisited**
- **Non-Linear Conductance of QPCs**
- **Bias-Spectroscopy Techniques***
- **Breakdown of Conductance Quantization***
- **And Now for Something Completely … New**

*** UNFORTUNATELY, NO TIME FOR THIS TODAY**



So Far We Have ASSUMED NO Scattering Within the QPC

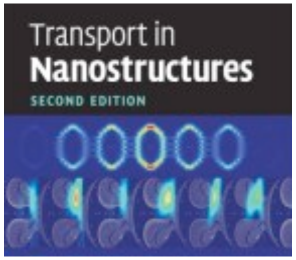
SOURCE RESERVOIR



DRAIN RESERVOIR

1. ELECTRONS TRAVELING TO RIGHT MUST COME FROM SOURCE
2. ELECTRONS TRAVELING TO LEFT MUST COME FROM DRAIN

Allowed SIMPLISTIC Assumption of PERFECT Transmission



Disorder in QPCs Causes SCATTERING Between Subbands

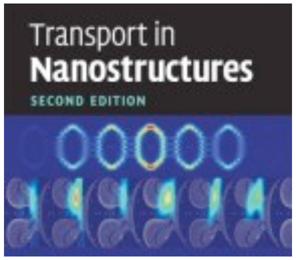
Current in EACH channel now determined by TRANSMISSION COEFFICIENT

$$I_n = \frac{2e^2}{h} V T_n \,, \quad T_n = \sum_{m=1}^{N} T_{nm}$$

PROBABILITY FOR TRANSMISSION VIA *n*th SUBBAND

PROBABILITY FOR TRANSMISSION FROM SUBBAND "*n*" TO SUBBAND "*m*"

Current Now SAMPLE Dependent



Disorder in QPCs Causes SCATTERING Between Subbands

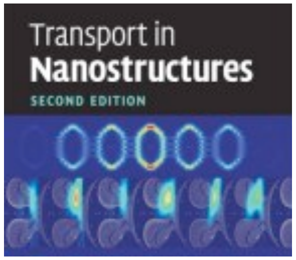
Calculating TOTAL Current Yields LANDAUER FORMULA

$$G = \frac{I}{V} = \frac{2e^2}{h}\sum_{n=1}^{N} T_n = \frac{2e^2}{h} T$$

SAMPLE DEPENDENT TRANSMISSION PROBABILITY

1. **TRANSMISSION PROBABILITY DEPENDS STRONGLY ON THE NATURE OF THE DISORDER INSIDE THE QPC AND IS ALSO STRONGLY ENERGY DEPENDENT**

2. **CONSEQUENTLY THE CONDUCTANCE IS NO LONGER NECESSARILY QUANTIZED**



A Simple Limit – FIXED Transmission Per Subband

$$\frac{1}{G}=\frac{h}{2e^2}\frac{1}{NT_{pc}}=\frac{h}{2e^2}\frac{1}{N}+\frac{h}{2e^2}\frac{1}{N}\left[\frac{1-T_{pc}}{T_{pc}}\right]=\frac{1}{G_C}+\frac{1}{G_D}$$

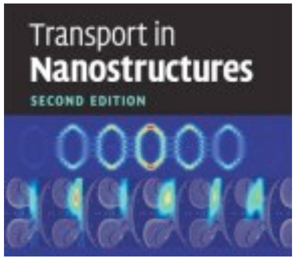
CONTACT-RELATED RESISTANCE

DISORDER-RELATED RESISTANCE

CAN NEVER BE ZERO (G_C)

CAN BE ZERO (G_D)

1. RESISTANCE G_C^{-1} IS AN UNAVOIDABLE QUANTUM CONTACT RESISTANCE
2. RESISTANCE G_D^{-1} IS A SAMPLE-DEPENDENT CONTRIBUTION TO THE TOTAL RESISTANCE

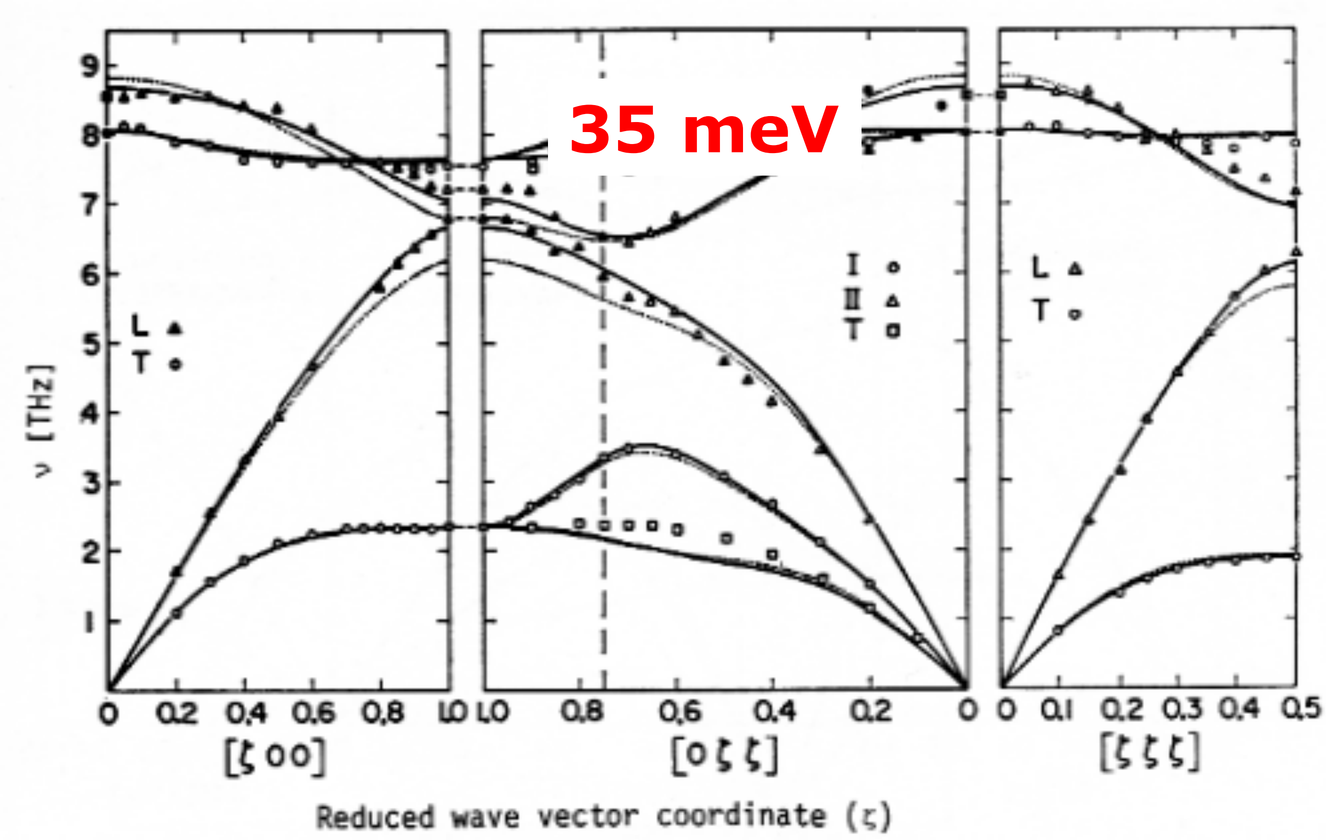


GENERAL ASPECTS OF MESOSCOPIC TRANSPORT III

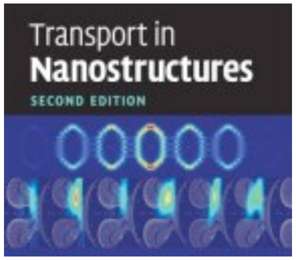
- **1-D Conductance Quantization … Revisited**
- **Non-Linear Conductance of QPCs**
- **Bias-Spectroscopy Techniques***
- **Breakdown of Conductance Quantization***
- **And Now for Something Completely … New**

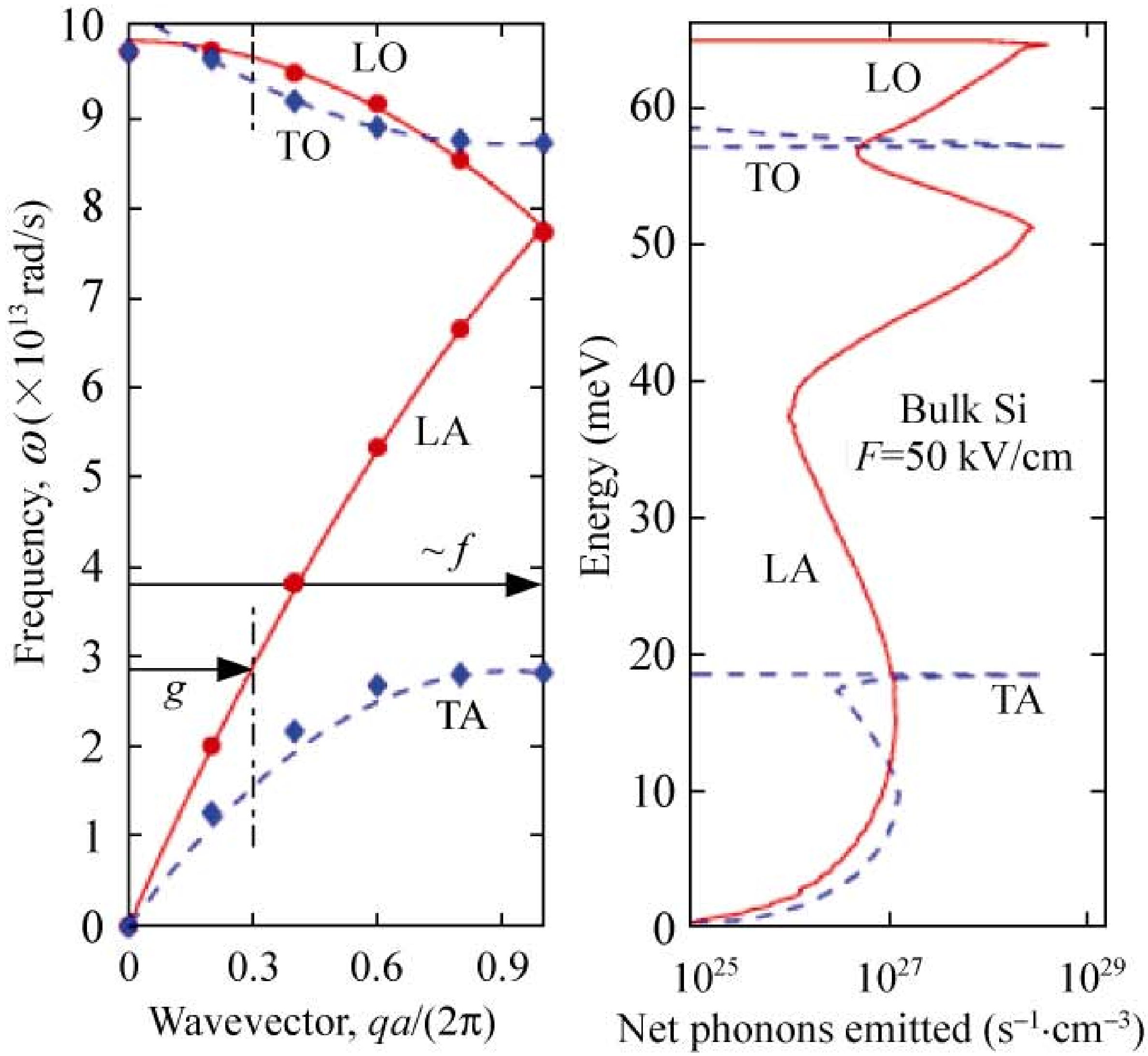
*** UNFORTUNATELY, NO TIME FOR THIS TODAY**

OPTICAL Phonon Emission at LARGE Voltages

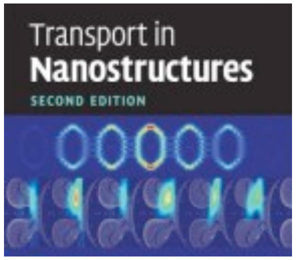


GaAs PHONON SPECTRUM





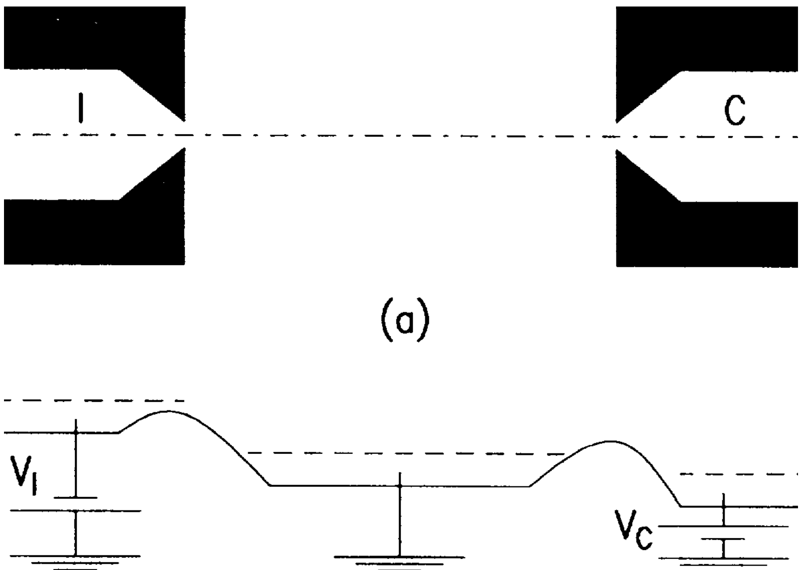
PHONON EMISSION FOR Si
E. Pop, Nano. Res. 3, 147 (2010)

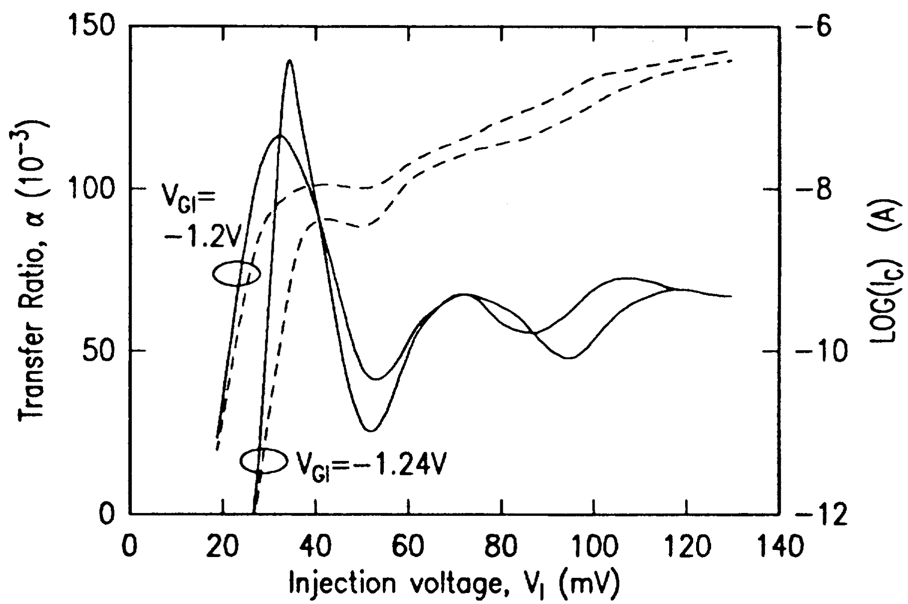


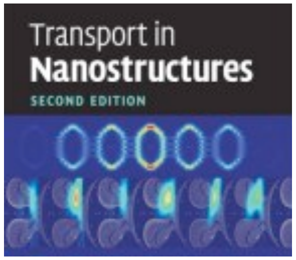
VOLUME 63, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1989

Hot Ballistic Transport and Phonon Emission in a Two-Dimensional Electron Gas

U. Sivan, M. Heiblum, and C. P. Umbach
IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598



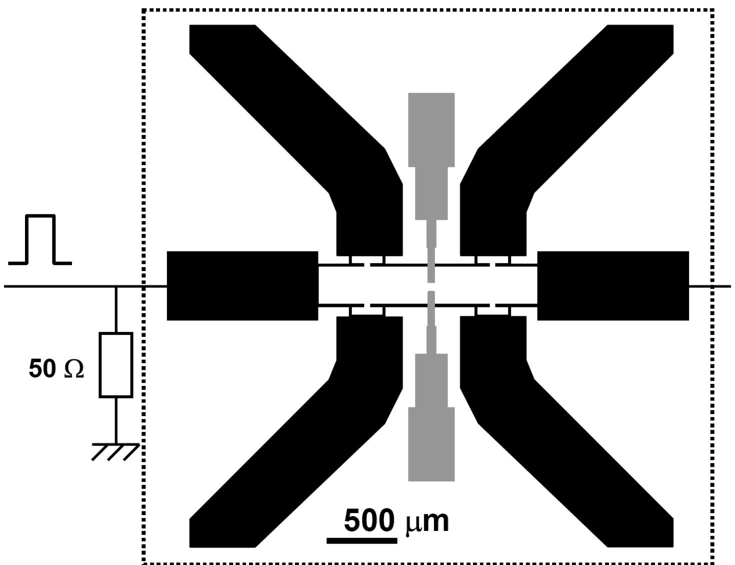


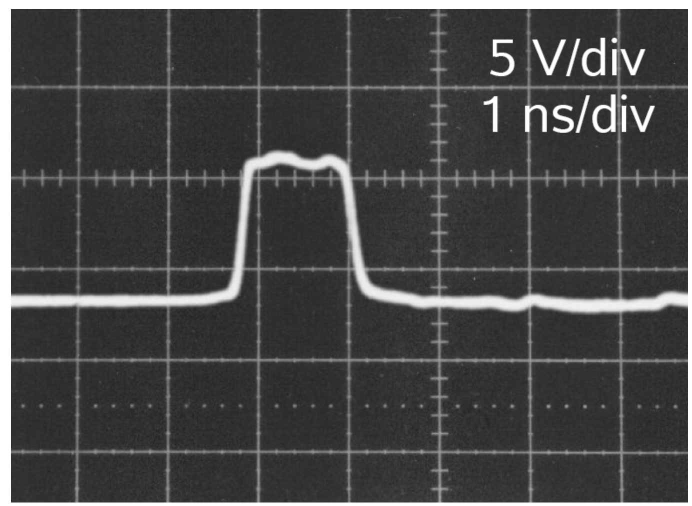


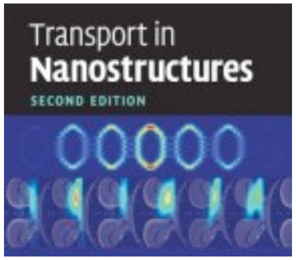
Our Study - TRANSIENT NON-LINEAR Transport in QPCs

REVIEW OF SCIENTIFIC INSTRUMENTS **76**, 113905 (2005)

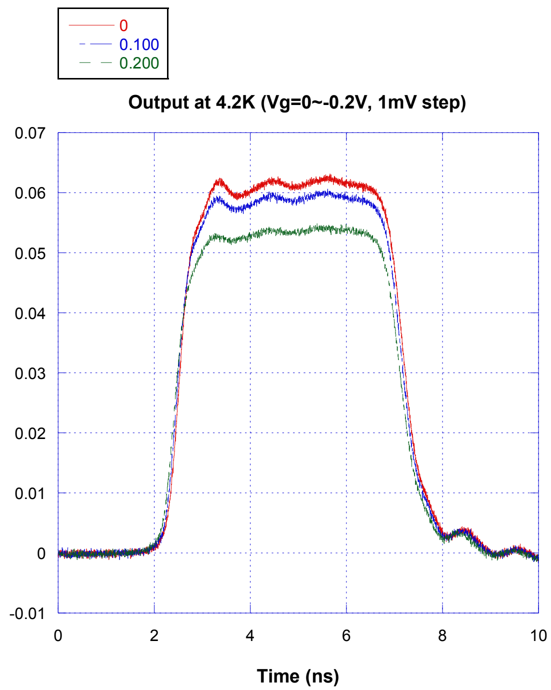
50-Ω-matched system for low-temperature measurements of the time-resolved conductance of low-dimensional semiconductors



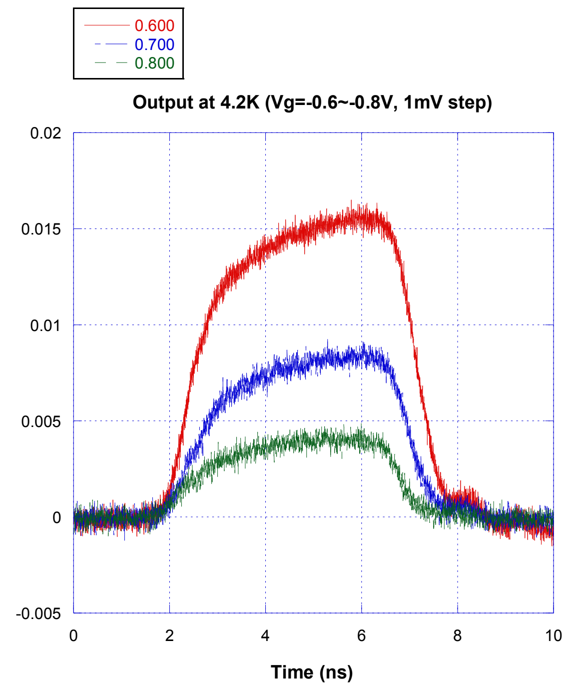




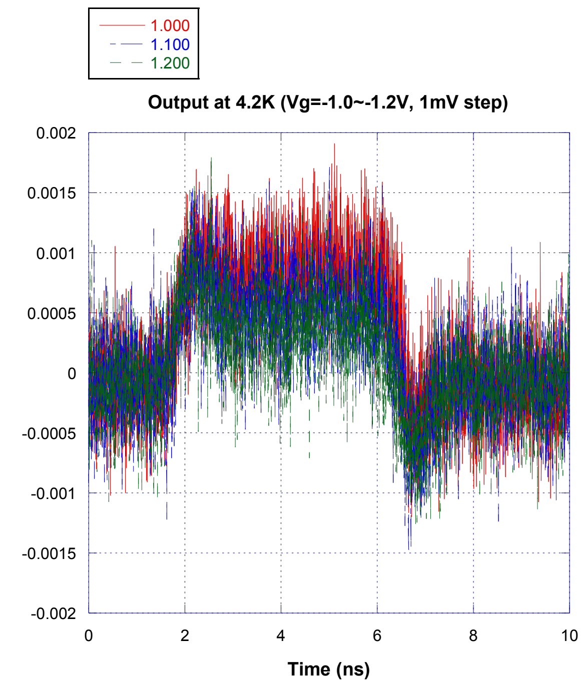
Our Observations:
1. REGIMES of Transient Response



QUASI-2D LIMIT

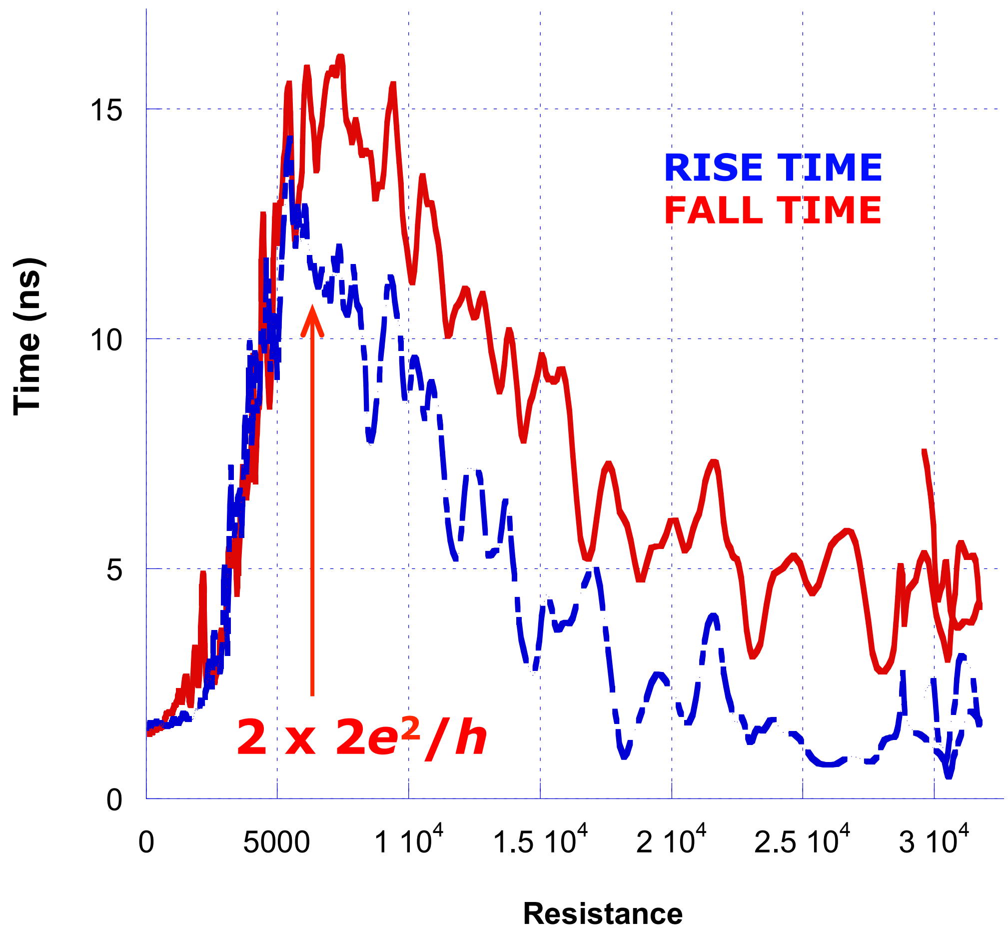


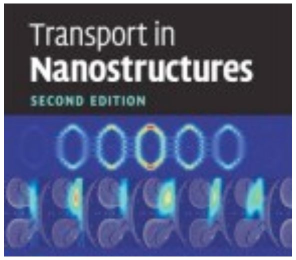
QUASI-1D LIMIT



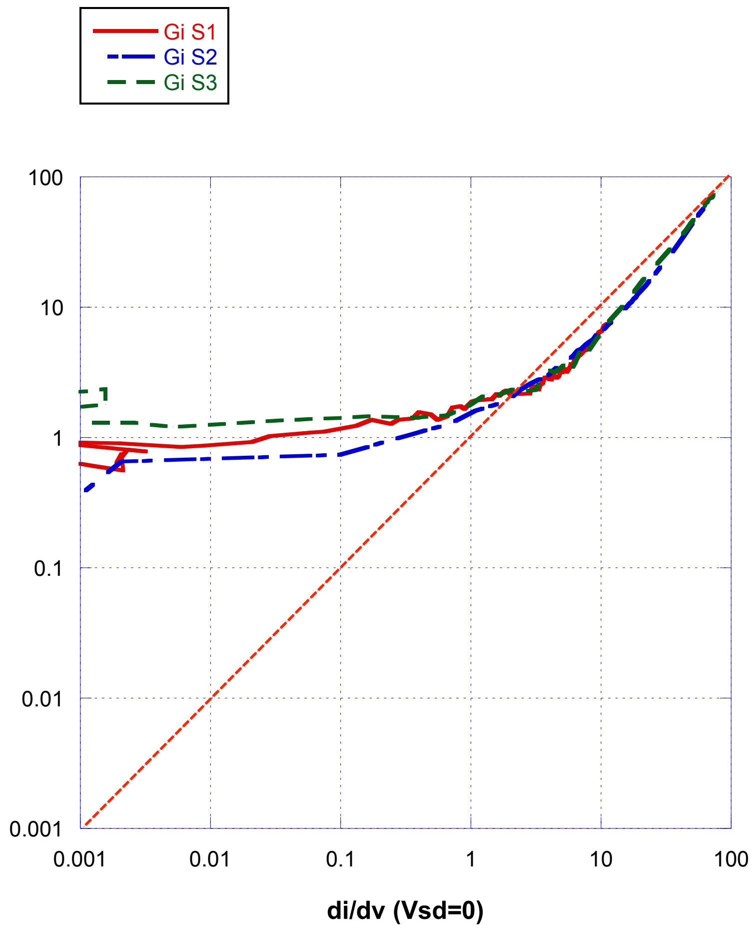
1D LIMIT

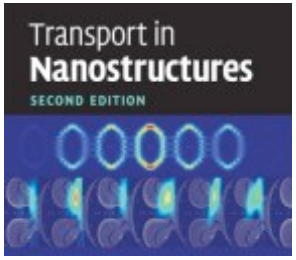
Our Observations:
2. COMPLEX Rise/Fall Times



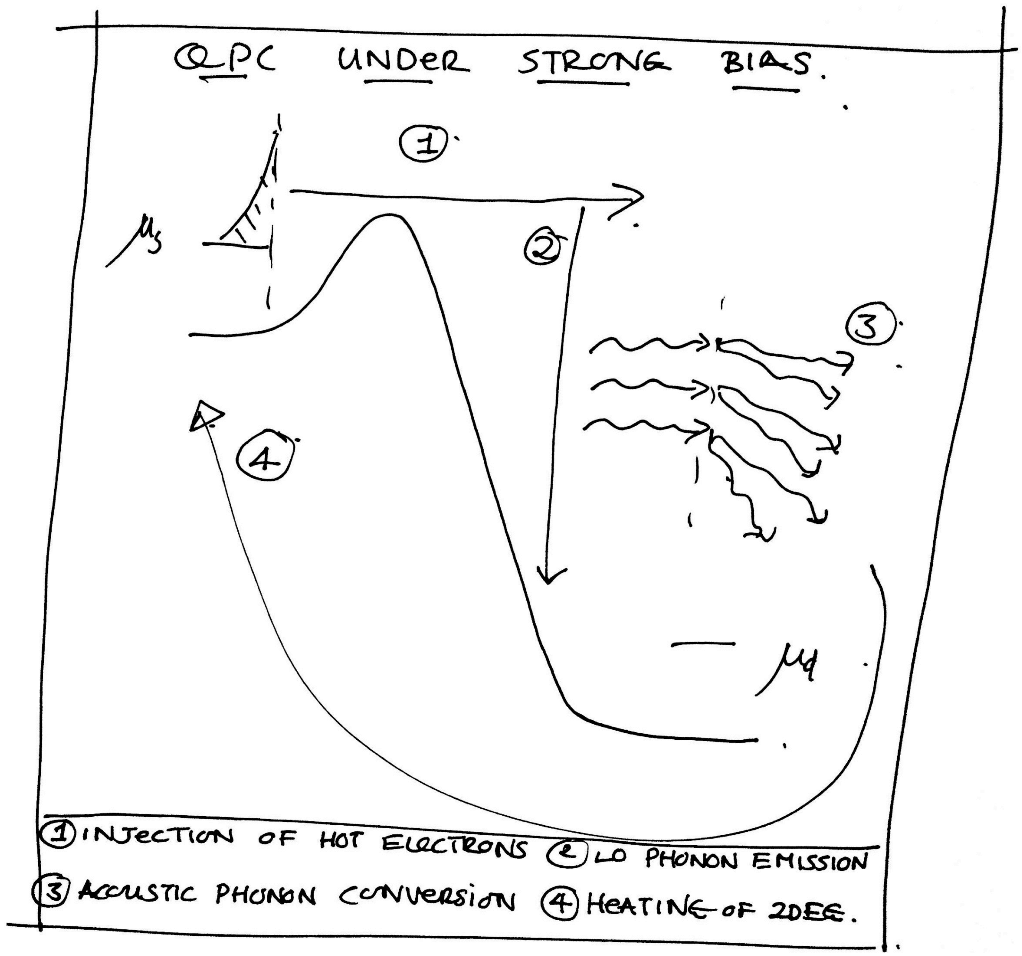


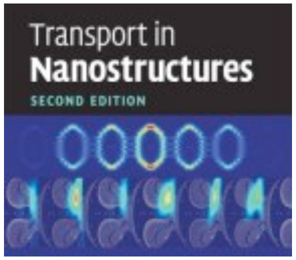
Our Observations:
3. Conductance PINNING at $2e^2/h$!





THEORETICAL Model: PHONON-Induced Subband Mixing



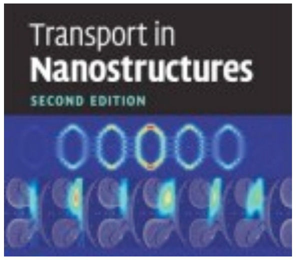


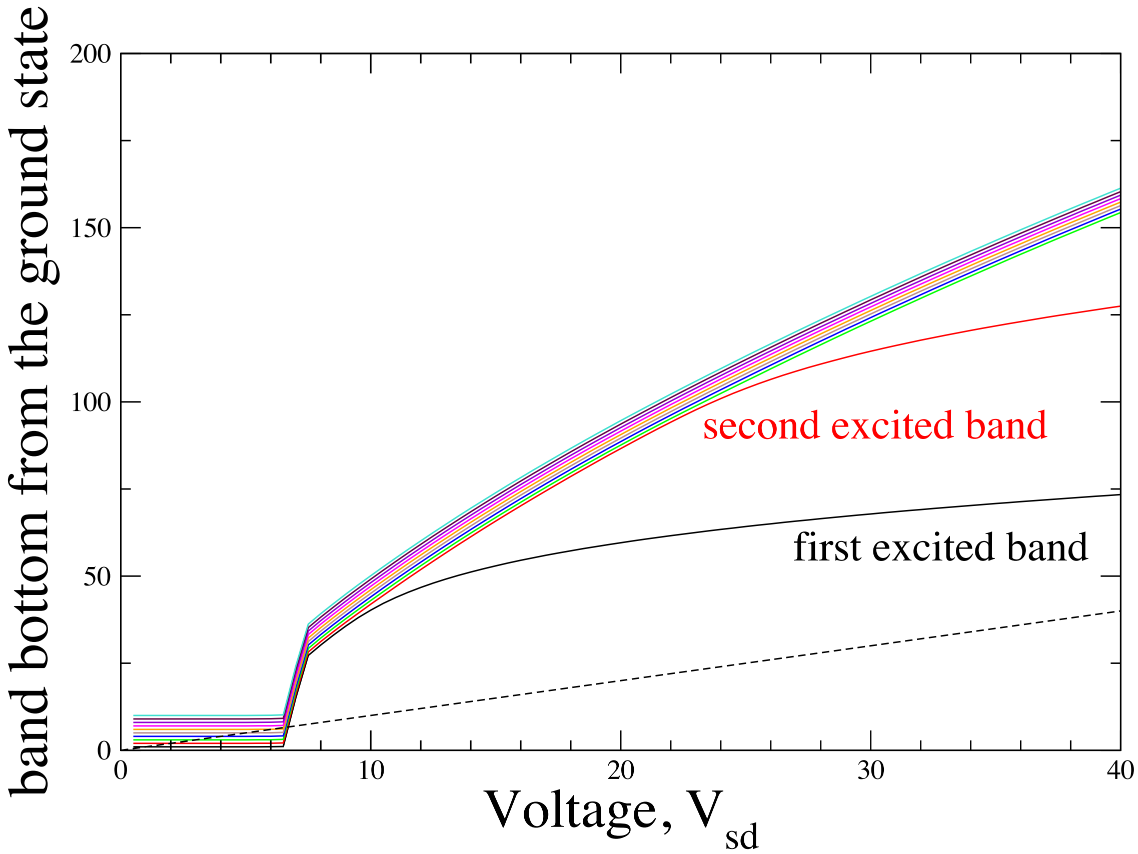
THEORETICAL Model: PHONON-Induced Subband Mixing

$$H = \sum_{n=0}^{\infty} \sum_{k\sigma} \left(\epsilon_n + \frac{\hbar^2 k^2}{2m^*} \right) c^{\dagger}_{nk\sigma} c_{nk\sigma}$$
$$- \frac{1}{2} g \sum_{nn'mm'}{}' \sum_{kk'q} \sum_{\sigma\sigma'} c^{\dagger}_{m,k-q\sigma} c^{\dagger}_{m',k'+q,\sigma'} c_{n'k'\sigma'} c_{nk\sigma},$$

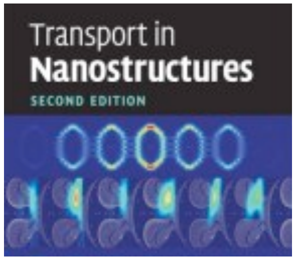
where the effective coupling constant g is a complicated function of the phonon environment.

Mixing Results in MODIFICATION of Subband Structure





Mixing Results in MODIFICATION of Subband Structure



where we suppressed $(k = 0, \sigma)$ indices in c_n. Given the α-th eigenvector $|\alpha\rangle$ and eigenvalue E_α, we evaluate g_{eff} as above and complete the self-consistent procedure via Eqs. (12,13). Numerically I have taken $M = 50$ and $\Delta = 1$ and the coupling $g_0 = 2\Delta$ in FIG 2. As shown, the gap between the new lowest and the next lowest band bottoms is substantially larger than the original subband spacing Δ as V_{sd} grows. And for $V_{\text{sd}} > 6.5$, the first subband spacing remains larger than the bias V_{sd} and only the lowest subband contributes to the current. In such regime the differential conductance is quantized at $2e^2/h$.

The huge enhancement of the first subband gap is due to the bonding effect between subbands. The subband coupling has been introduced by excited phonons created in the nonequilibrium transport process. The subband spacing is transverse wave-vector and its coherent superposition in real-space means narrow transverse wave-packet as depicted in FIG. 2(b). The width of the wave-packet becomes much narrower than the confinement and its corresponding level spacing becomes much greater than the original subband spacing.

In Other Words ... Conductance Quantization is RESTORED at High Bias!!!