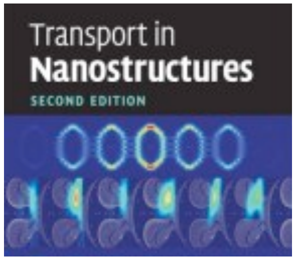
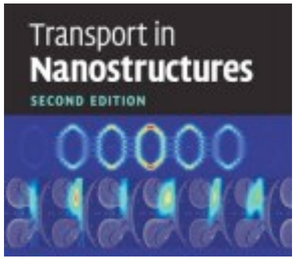


GENERAL ASPECTS OF MESOSCOPIC TRANSPORT: II

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



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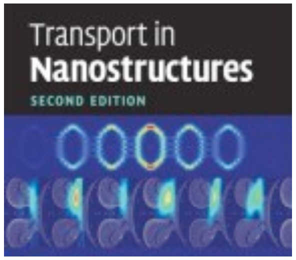
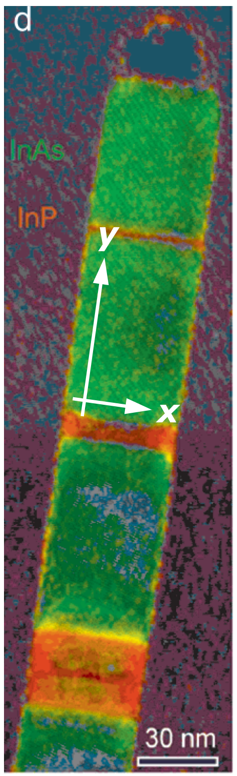
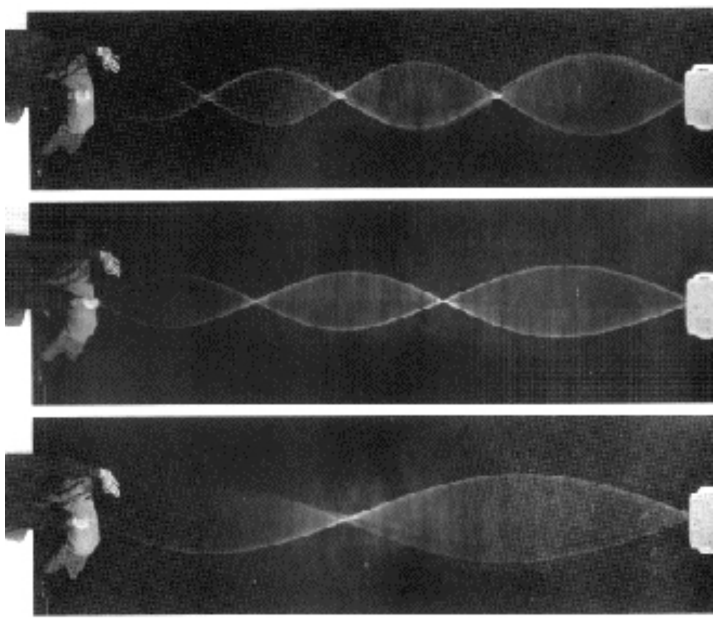


Lateral **CONFINEMENT** in 1-D Wires **QUANTIZES** Motion into **SUBBANDS**



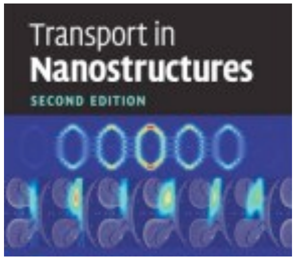


1. ASSUME HARMONIC LATERAL CONFINEMENT

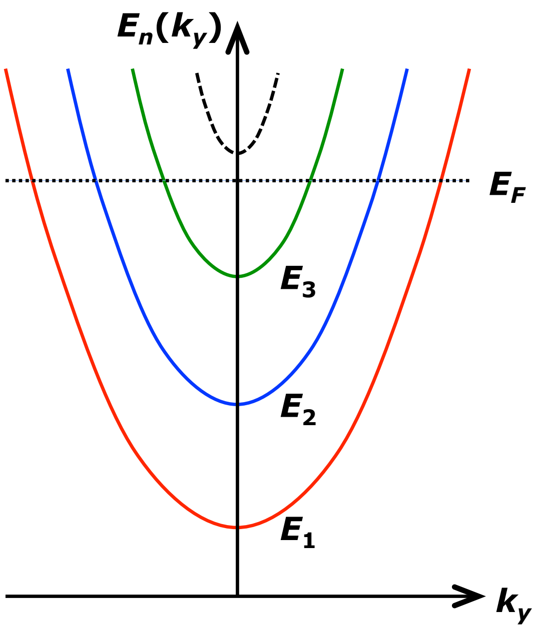
2. INTEGER n IS THE 1-D SUBBAND INDEX

$$E_n(k_y) = \left[\overset{2.}{n} + \frac{1}{2} \right] \hbar\omega_o^{\;1.} + \frac{\hbar^2 k_y^2}{2m}\;{}_{3.}$$

3. FREE MOTION ALONG THE LENGTH OF THE WIRE



FILLING 1-D Subbands (at LOW Temperatures)

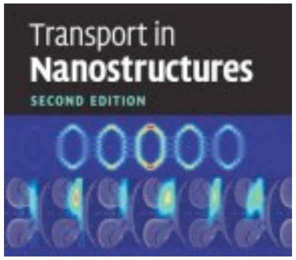


$$E_n(k_y) = \left[n + \frac{1}{2}\right]\hbar\omega_o + \frac{\hbar^2 k_y^2}{2m}, \quad n = 0,1,2,\ldots$$

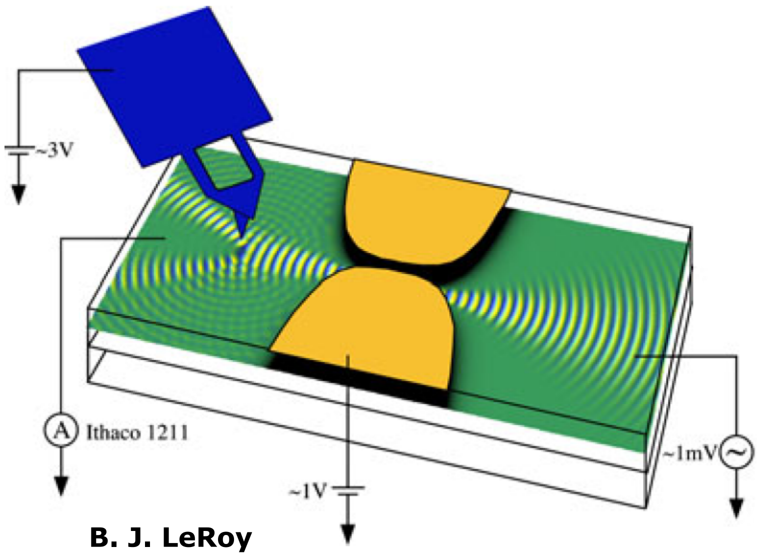
$$g_{1D}(E) = \left[\frac{2m^*}{\pi^2\hbar^2}\right]^{1/2} \sum_{E_n \le E} \frac{1}{\sqrt{E - E_n}}\Theta(E - E_n)$$

$$N = \mathrm{Int}\left[\frac{1}{2} + \frac{E_F}{\hbar\omega_o}\right] \approx \frac{E_F}{\hbar\omega_o} = \frac{k_F W}{4} = \frac{\pi W}{2\lambda_F}$$

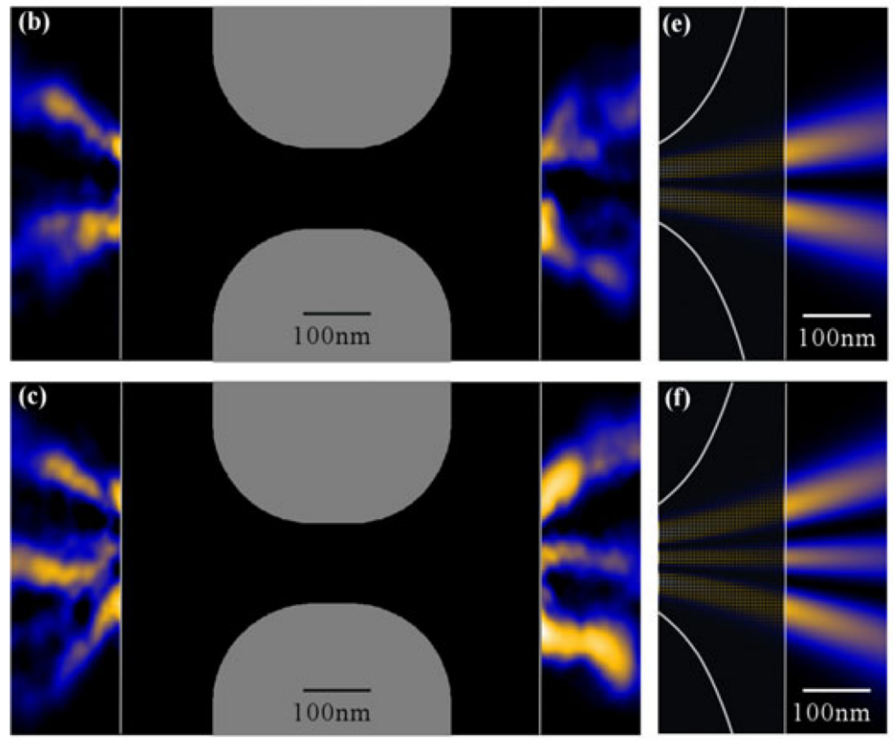
***N*: NUMBER OF OCCUPIED SUBBANDS**



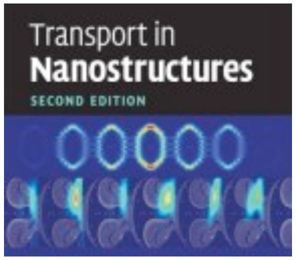
FILLING 1-D Subbands (at LOW Temperatures)



B. J. LeRoy
J. Phys.: Cond. Matt. 15, R1835 (2003)



Observation With Scanning Probe



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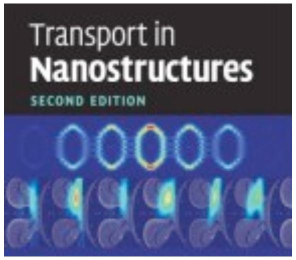
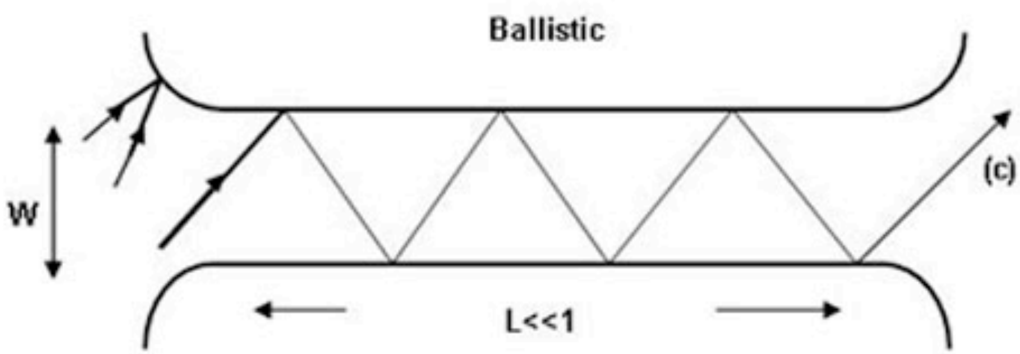


BALLISTIC Model for 1-D Conductance (V_{sd} = 0)

SOURCE RESERVOIR

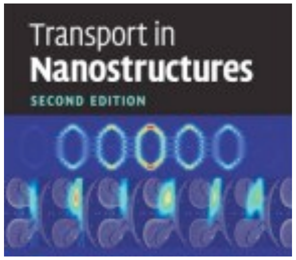


DRAIN RESERVOIR

1. EACH RESERVOIR IS CHARACTERIZED BY A UNIQUE CHEMICAL POTENTIAL (FERMI ENERGY)

2. EACH RESERVOIR INJECTS CARRIERS WITH ENERGIES UP TO THIS CHEMICAL POTENTIAL

3. SINCE TRANSPORT IN THE WIRE IS BALLISTIC ALL ENERGY RELAXATION MUST TAKE PLACE IN THE RESERVOIRS



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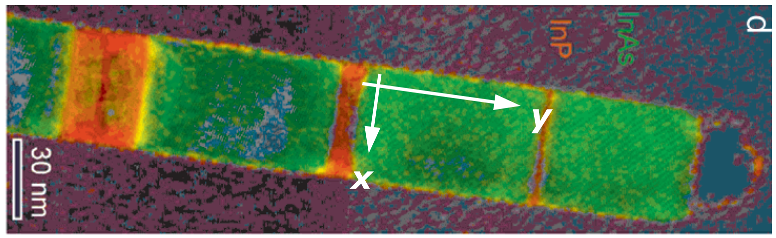
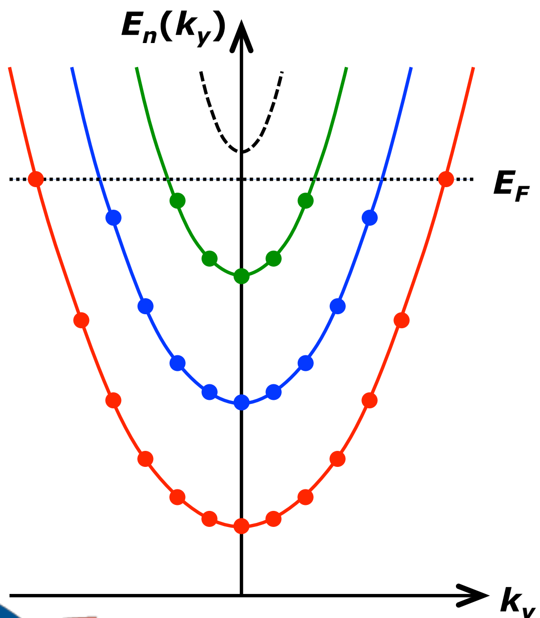
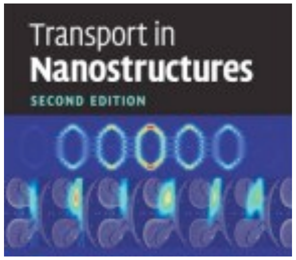




1. CARRIERS INJECTED FROM SOURCE HAVE POSITIVE k_y WHILE THOSE INJECTED FROM DRAIN HAVE NEGATIVE k_y

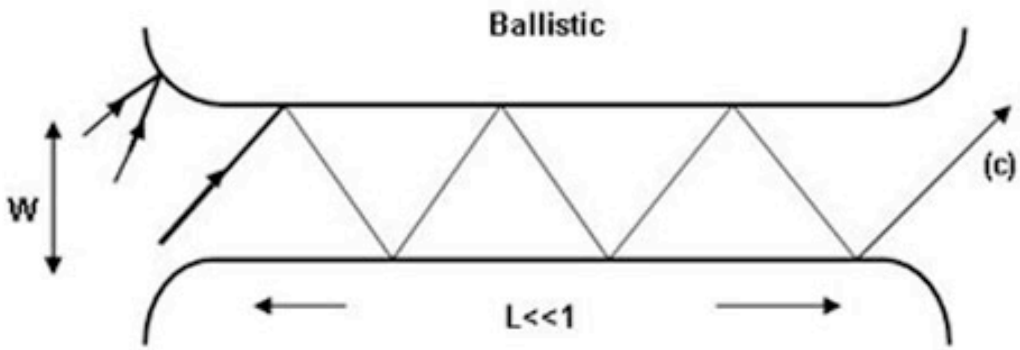
2. CARRIERS INJECTED FROM A PARTICULAR RESERVOIR PRESERVE THEIR MOMENTUM DUE TO THEIR BALLISTIC MOTION

3. WITH NO APPLIED SOURCE-DRAIN VOLTAGE THE NET CURRENT IS ZERO DUE TO CANCELLATION OF CARRIER MOMENTA



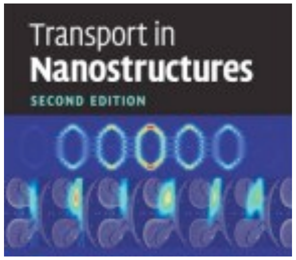
BALLISTIC Model for 1-D Conductance (V_{sd} > 0)

SOURCE RESERVOIR

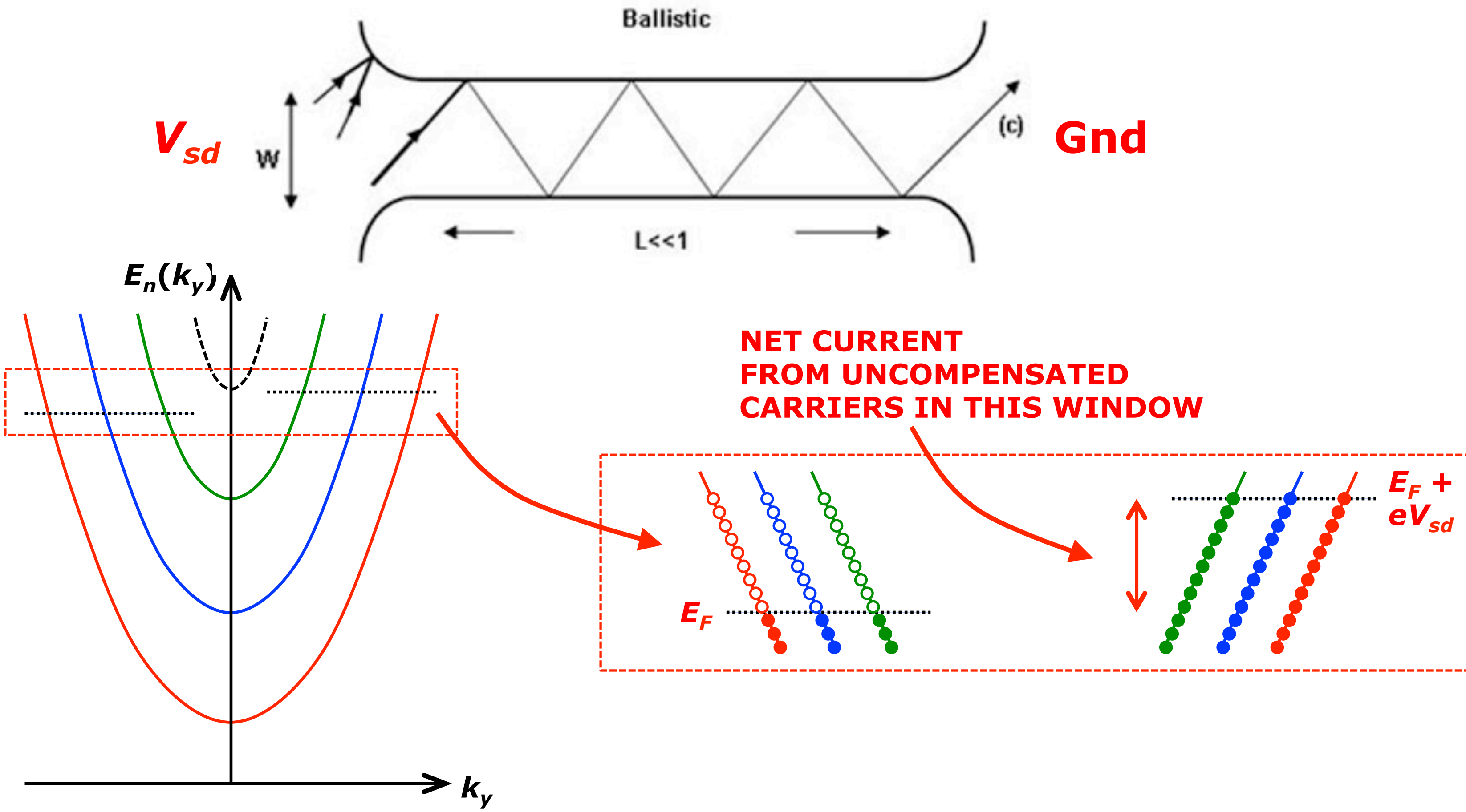


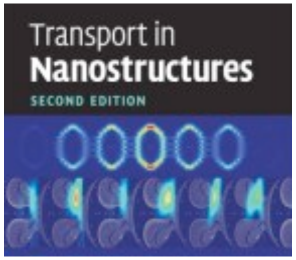
DRAIN RESERVOIR

1. WITH SOURCE-DRAIN VOLTAGE APPLIED RESERVOIRS HAVE DISTINCT ELECTRO-CHEMICAL POTENTIALS
2. NET CURRENT ARISES DUE TO THE DIFFERENT CARRIER FLUXES INJECTED FROM THE TWO RESERVOIRS
3. CURRENT CAN BE CALCULATED BY TREATING THE CONDUCTANCE AS A TRANSMISSION PROBLEM



BALLISTIC Model for 1-D Conductance ($V_{sd} > 0$)





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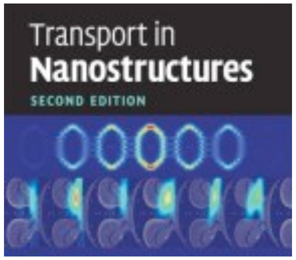
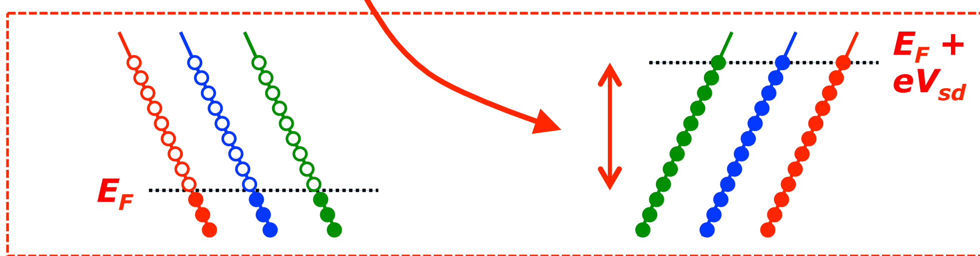


Computing the 1-D Conductance

NET CURRENT
FROM UNCOMPENSATED
CARRIERS IN THIS WINDOW

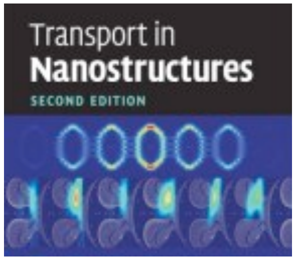


Excess charge per unit length PER OCCUPIED SUBBAND:

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

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

ONLY STATES WITH POSITIVE MOMENTUM CONSIDERED



Computing the 1-D Conductance

CURRENT carried by the excess charge in EACH subband:

$$I_{pc} = \delta Q \times v_g$$

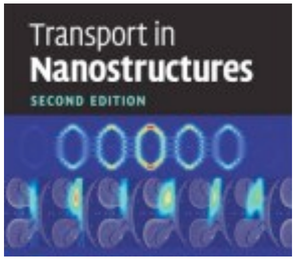
Since the GROUP VELOCITY:

$$v_g = \frac{1}{\hbar}\frac{dE}{dk} = 2\sqrt{\frac{E}{2m^*}}$$

We obtain the CURRENT:

NOTE THE CANCELLATION OF ENERGY TERMS!

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



Computing the 1-D Conductance

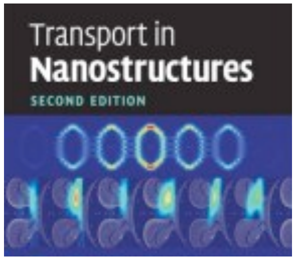
We note that the current is INDEPENDENT of subband index - this is the concept of EQUIPARTITION of current

The TOTAL current is therefore simply obtained by multiplying by the NUMBER of occupied subbands (*N*):

$$I = NI_{pc} = N\frac{2e^2}{h}V_{sd}$$

We finally obtain the QUANTIZED conductance:

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



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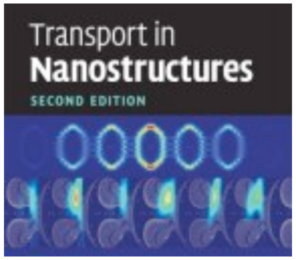
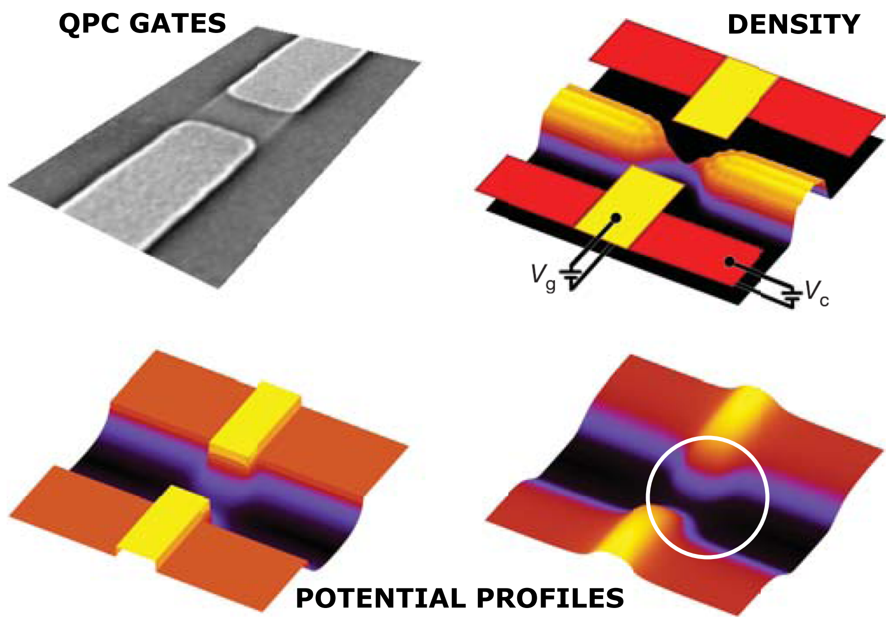
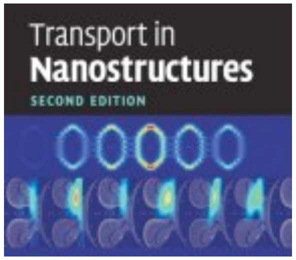


Archetypal 1-D Conductor: QUANTUM POINT CONTACT (QPC)

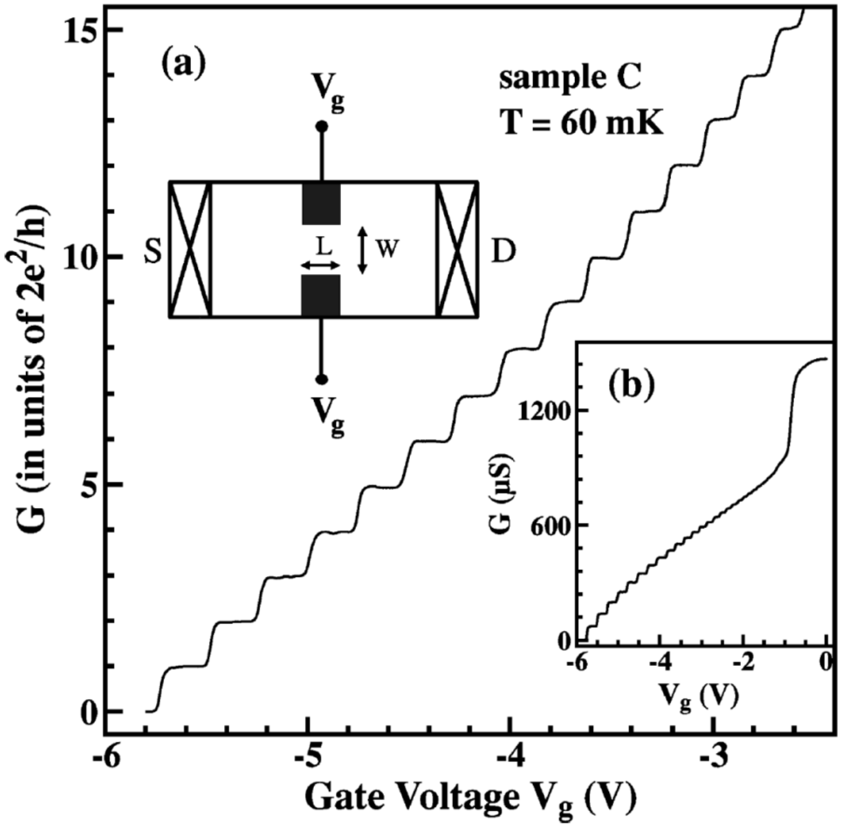


T. Rejec & Y. Meir, Nature 442, 900 (2006)

1. DEVICE CONSISTS OF A PAIR OF SPLIT METAL GATES FORMED ON THE SURFACE OF A HIGH-MOBILITY HETEROJUNCTION
2. APPLICATION OF NEGATIVE VOLTAGE TO THE GATES DEPLETES 2DEG UNDERNEATH AND FORMS A QPC IN THE GAP BETWEEN THEM
3. QPC WIDTH – AND SO NUMBER OF OCCUPIED SUBBANDS – CAN BE TUNED IN SITU VIA THE GATE VOLTAGE
4. NOTE THE PRESENCE OF THE SADDLE BARRIER AT THE CENTER OF THE QPC



QUANTIZED Conductance Of QPCs

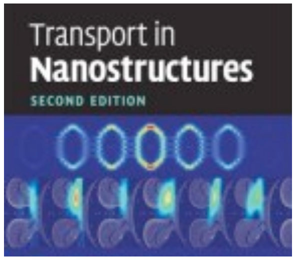


K. J. Thomas et al.
Phys. Rev. B 58, 4846 (1998)

1. CONDUCTANCE DECREASES IN INTEGER UNITS OF $2e^2/h$ AS THE GATE VOLTAGE IS MADE MORE NEGATIVE!

2. EACH STEP-LIKE DECREASE SIGNIFIES A DECREASE IN THE NUMBER OF OCCUPIED SUBBANDS BY ONE AS THE WIDTH DECREASES

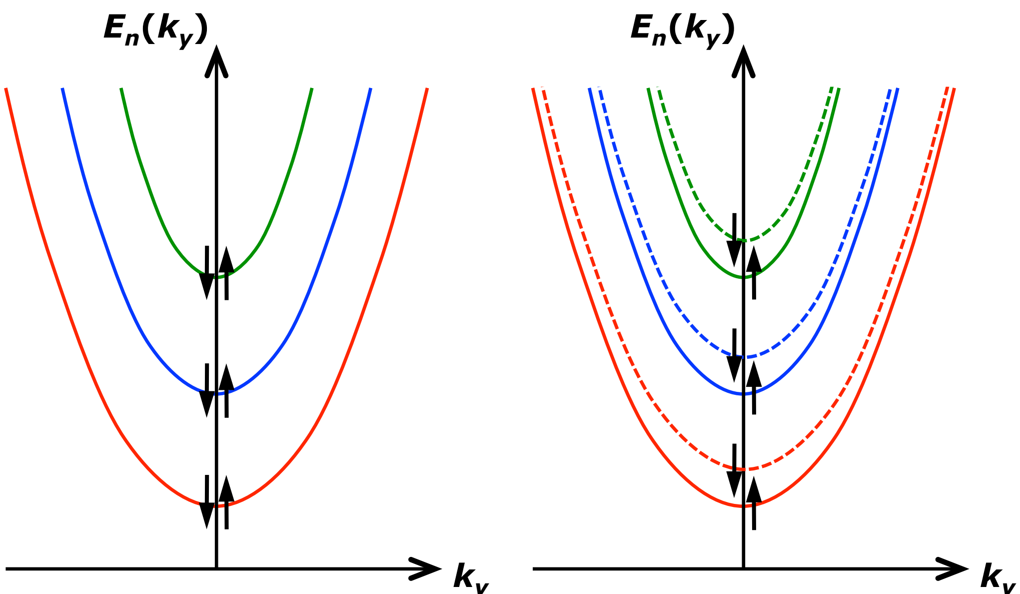
$$N = \frac{\pi W}{2\lambda_F} \qquad G = N\frac{2e^2}{h}$$

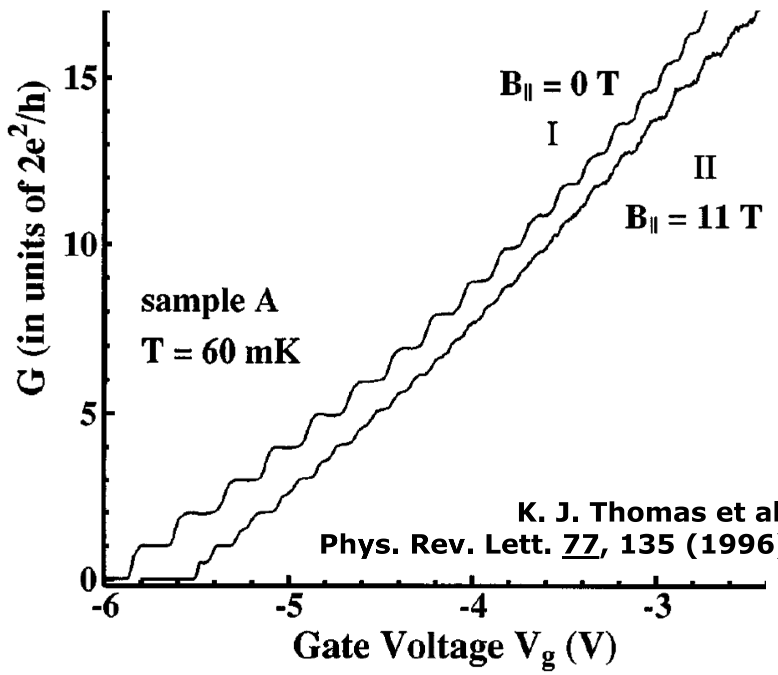


SPIN SPLITTING of 1-D Conductance Quantization

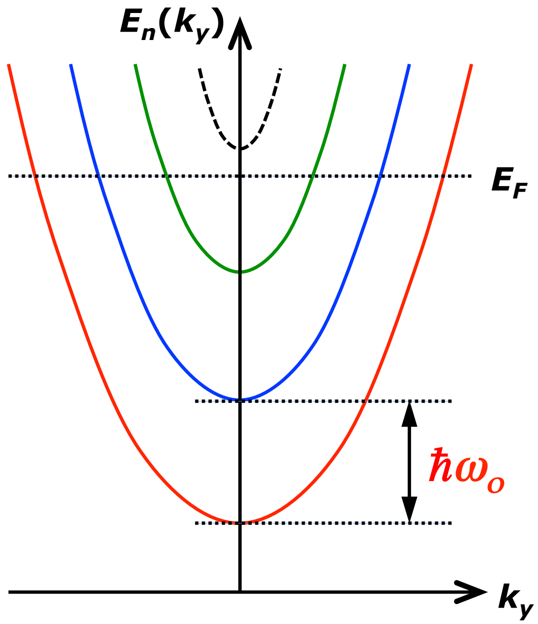
$$G = N\frac{2e^2}{h}$$

PRE-FACTOR OF TWO FROM PRESUMED SPIN DEGENERACY

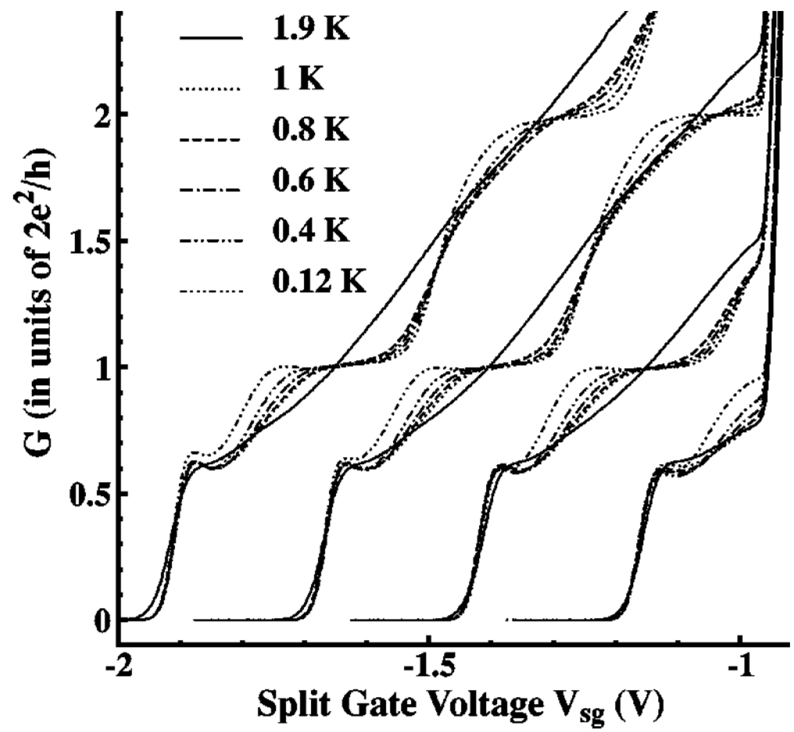




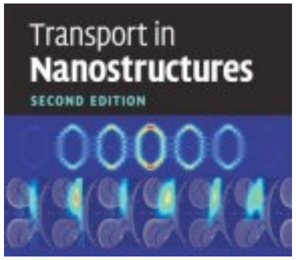
THERMAL Averaging of Conductance Quantization



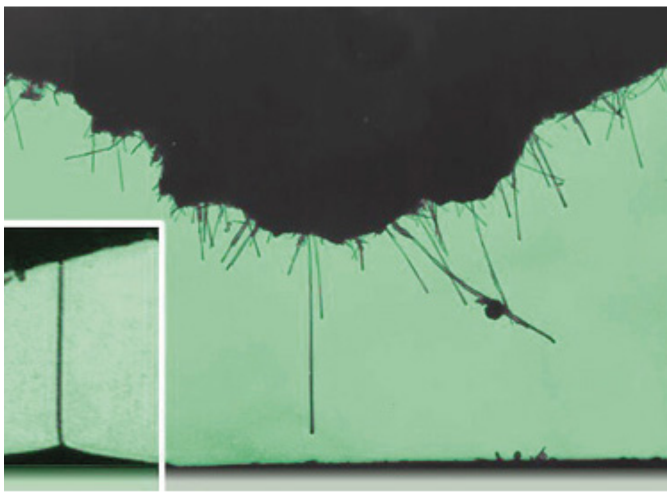
K. J. Thomas *et al.*, Phys. Rev. B 61, R13365 (2000)



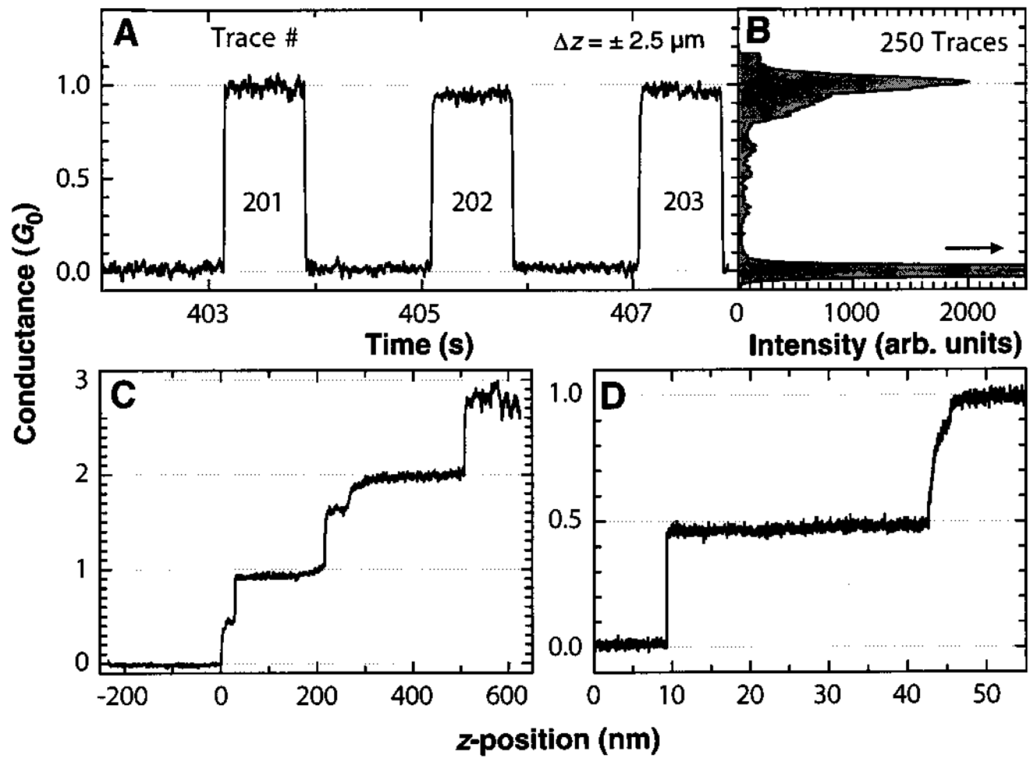
QUENCHED Once $k_BT > \hbar\omega_o$



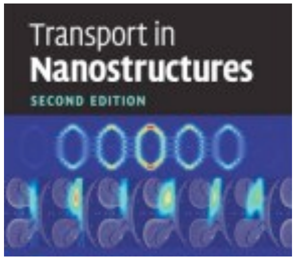
OTHER Observations: CARBON NANOTUBES



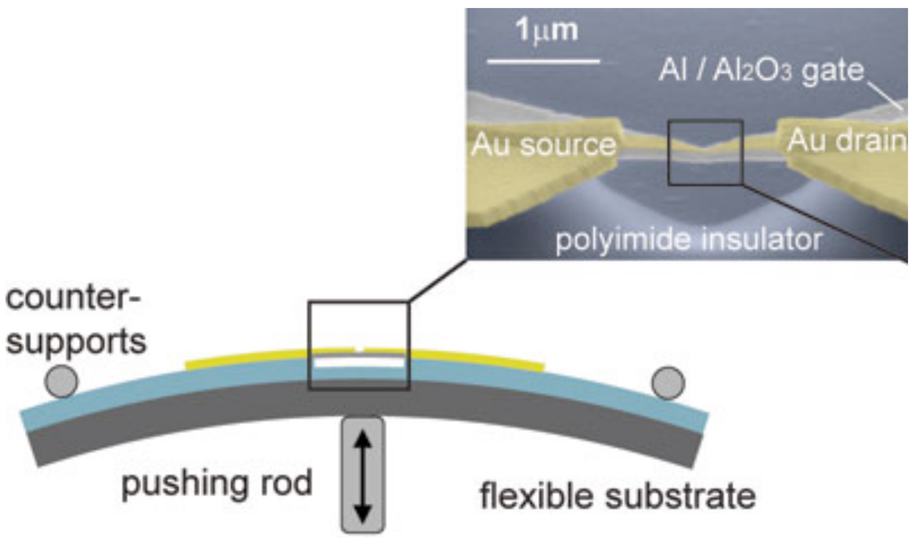
S. Frank et al., Science <u>280</u>, 1744 (1998)

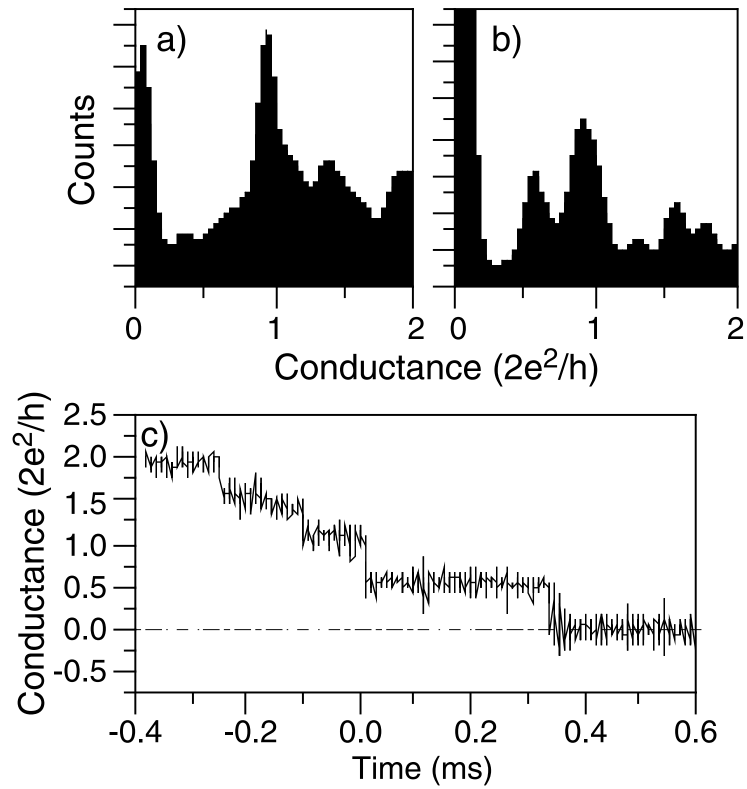


Quantization at ROOM Temperature!

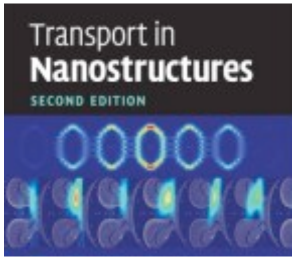


OTHER Observations: Mechanical BREAK JUNCTIONS





ADDITIONAL Plateaus Observed!



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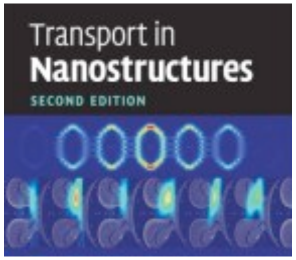
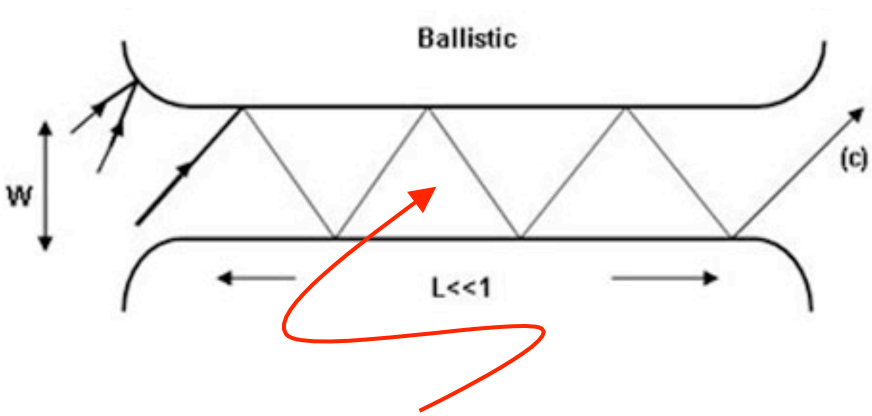


HOLD ON a Minute! WHERE is the Resistance?!



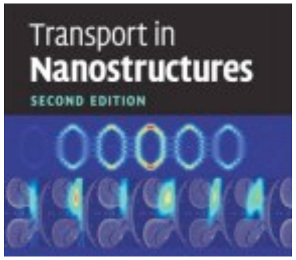
NO DISSIPATION IN HERE … SO NO RESISTANCE???

1. SINCE THERE IS NO SCATTERING WITHIN BALLISTIC WIRES WE MIGHT EXPECT THE CONDUCTANCE TO BE INFINITE?

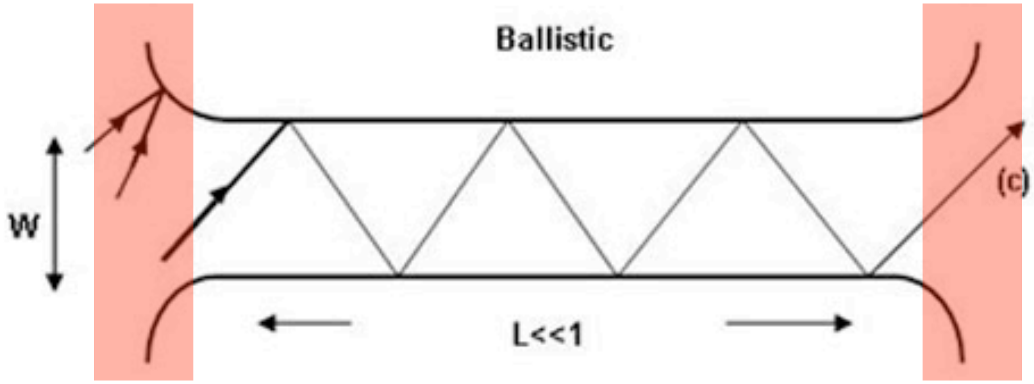
2. INSTEAD HOWEVER WE KNOW THAT IT TAKES FINITE QUANTIZED VALUES

3. FOR A SINGLE-SUBBAND QPC THE RESISTANCE IS AROUND 13 kOHMS – NOT AN INSIGNIFICANT AMOUNT!

4. WHERE DOES THIS RESISTANCE COME FROM



Quantized Conductance is a CONTACT RESISTANCE!

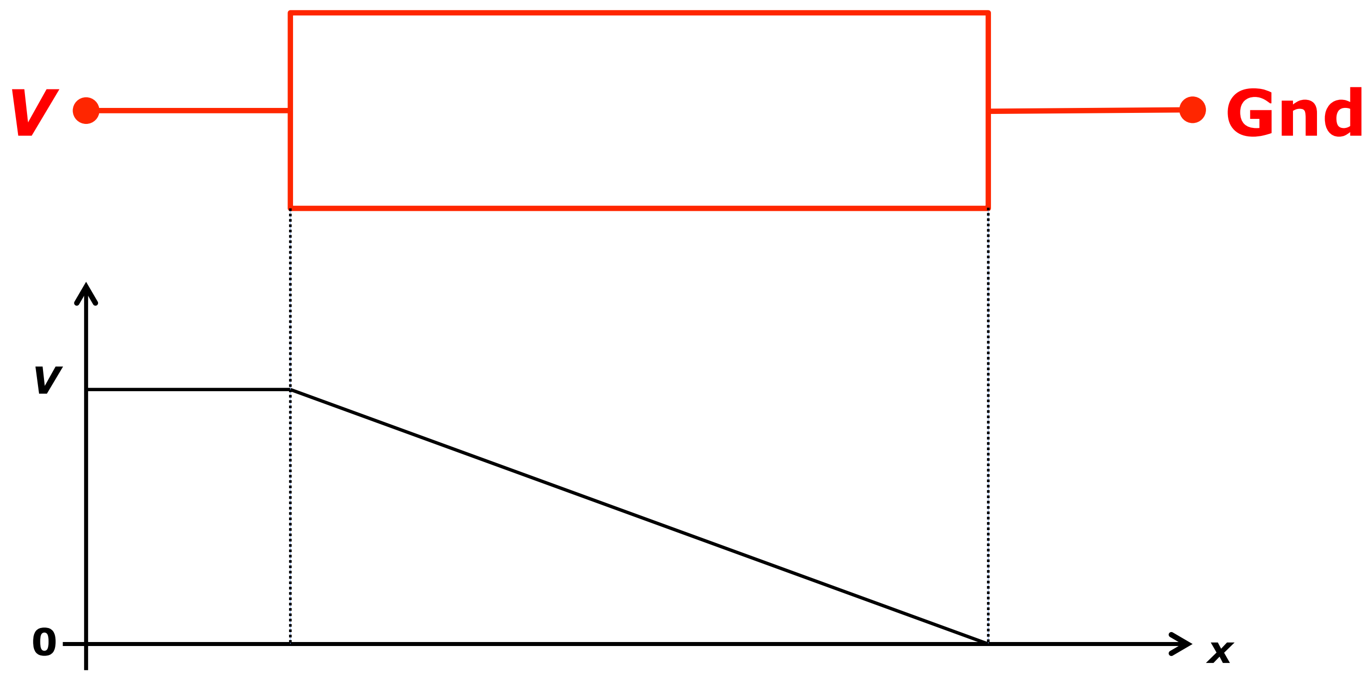


1. RESERVOIRS THAT SOURCE AND SINK CARRIERS TO CONDUCTOR MAY BE VIEWED AS SUPPORTING AN INFINITE NUMBER OF SUBBANDS

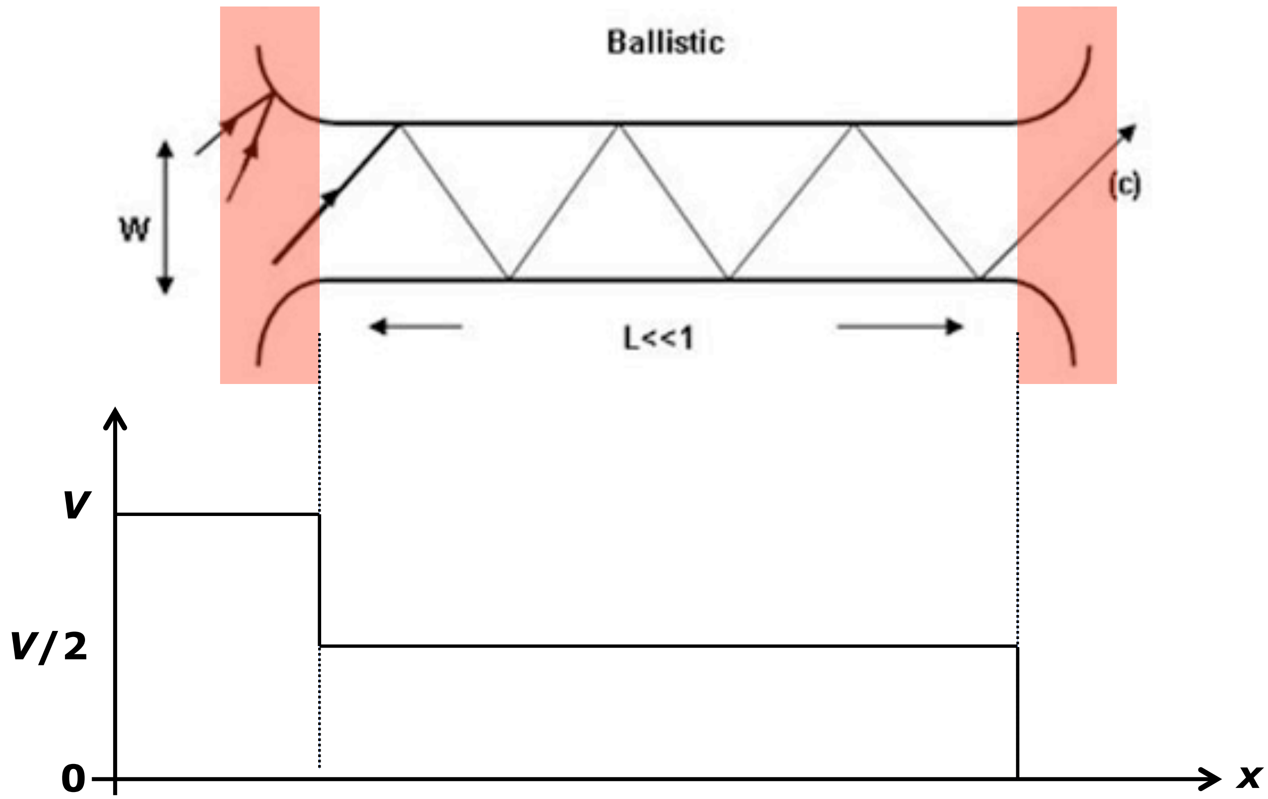
2. WHEN CURRENT FLOWS FROM THE RESERVOIRS TO THE CONDUCTOR IT MUST THEREFORE BE REDISTRIBUTED INTO A MUCH SMALLER NUMBER OF SUBBANDS

3. THIS MODE MISMATCH IS THE SOURCE OF THE QUANTIZED RESISTANCE

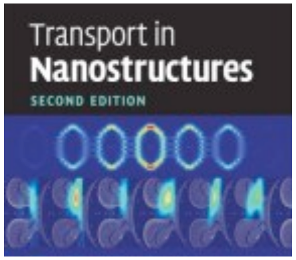
VOLTAGE-DROP in a MACROSCOPIC Conductor



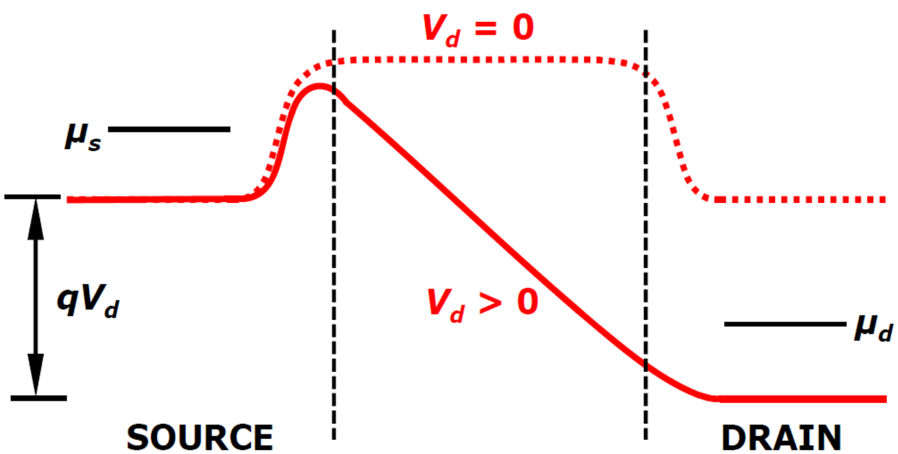
VOLTAGE-DROP in a BALLISTIC Conductor



VOLTAGE DROPPED AT ENDS!!!



VOLTAGE-DROP in a BALLISTIC Conductor



1. ON THE PREVIOUS SLIDE WE MADE AN AD-HOC <u>ASSUMPTION</u> THAT THE "CONTACT RESISTANCE" IS THE SAME AT BOTH ENDS OF THE QPC
2. THIS SEEMS TO BE <u>SATISFIED</u> IN GENERAL
3. THE EXCEPTION ARISES WHEN THE QPC IS VERY CLOSE TO PINCH-OFF
4. IN THIS SITUATION THE VOLTAGE IS TYPICALLY DROPPED LARGELY AT THE <u>DRAIN</u> END
5. THIS IS REMINISCENT OF THE SITUATION IN MODERN <u>MOSFETs</u>