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Shot noise in ballistic and disordered grapheneShot noise in ballistic and disordered graphene

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Shot noise in ballistic and disordered graphene

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Graphene Week
August 2008, Trieste

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Outline

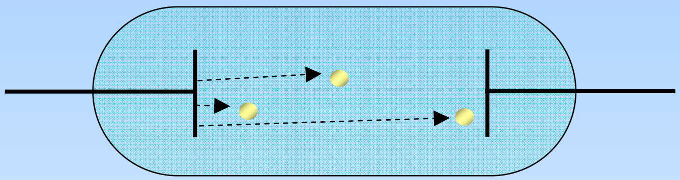
- ***Introduction to shot noise***
- ***Theoretical background***
- ***Experimental techniques***
  - *Noise measurement techniques*
- ***Experimental results***
  - *Shot noise in graphene sheets*
  - *Shot noise in graphene nanoribbons*
- ***Summary***

Shot noise in electronic system

Classical shot noise:
Poissonian process

$$S_P = 2q\langle I \rangle$$

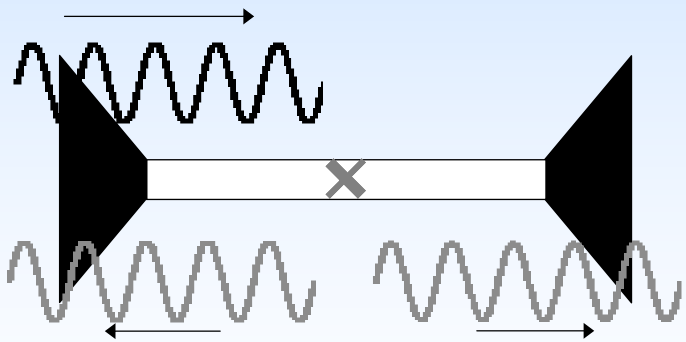
uncorrelated emission events



Schottky, (1918)

Quantum shot noise:
binominal process

$$S = \frac{q^3|V|}{\pi\hbar} T(1-T) = 2q\langle I \rangle (1-T)$$



Khlus (1987), Lesovik (1989)

Fano factor

$$S = \frac{e^3 |V|}{\pi \hbar} \sum_n T_n (1 - T_n)$$

- Sum over quantum partition noise of the eigenchannels

$$S_P = 2e < I > \qquad G = \frac{e^2}{\pi \hbar} \sum_n T_n$$

$$= \frac{e^3 |V|}{\pi \hbar} \sum_n T_n$$

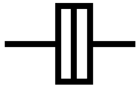
$$F = S / S_P = \frac{\sum_n T_n (1 - T_n)}{\sum_n T_n}$$

- At finite temperature:

$$S = \frac{e^2}{\pi\hbar} \left[2k_B T \sum_n T_n^2 + eV \coth\left(\frac{eV}{2k_B T} \right) \sum_n T_n (1 - T_n) \right],$$

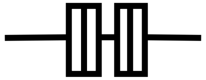
A few examples

Tunnel junction (TJ)



$$F = 1 \quad (T \to 0)$$

2 TJs in series



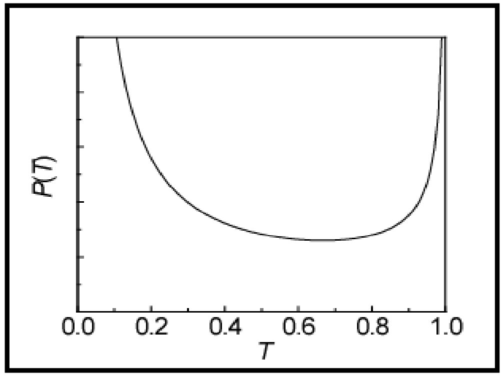
$$\frac{R_1^2 + R_2^2}{(R_1 + R_2)^2}$$

1D diffusive conductor

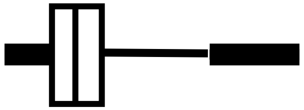
$$F = \frac{1}{3}$$

1D diffusive conductor

$$P(T) = \frac{1}{2L} \frac{1}{T\sqrt{1-T}}$$

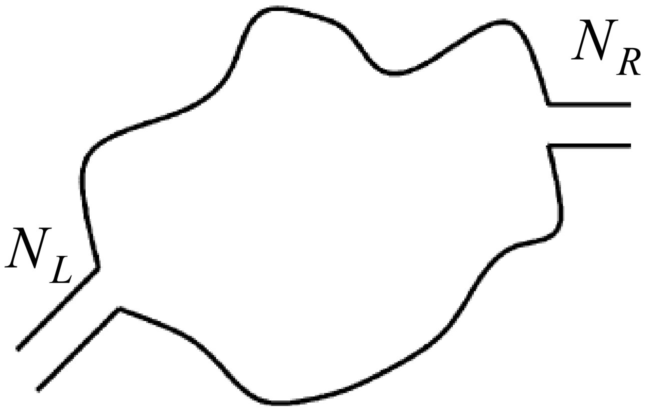


TJ plus 1D diffusive conductor

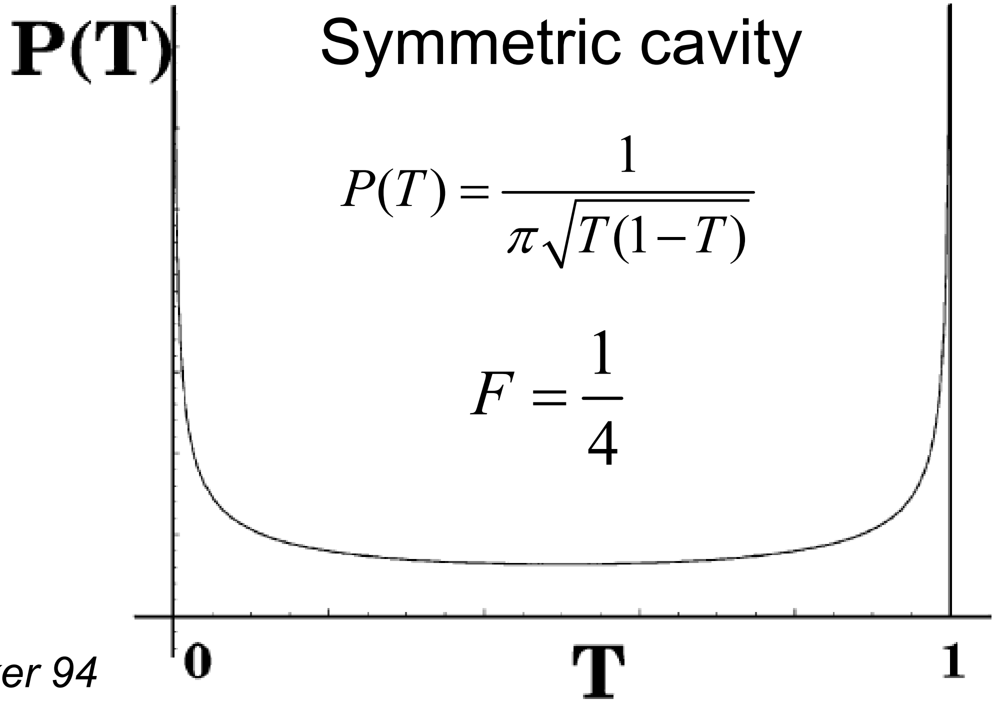


$$F = \frac{1}{3}\left(1 - \frac{3T-2}{(1+TL/l_{el})^3}\right)$$

Chaotic cavity



Baranger and Mello 94
Jalabert, Pichard, and Beenakker 94



$$F = \frac{N_L N_R}{(N_L + N_R)^2}$$

Goes to zero in very asymmetric cavities

$$F = \frac{1}{4}\exp\left(-\frac{t_E}{t_D}\right)$$

Quantum vs. classical

t_E - Ehrenfest time
t_D - dwell time

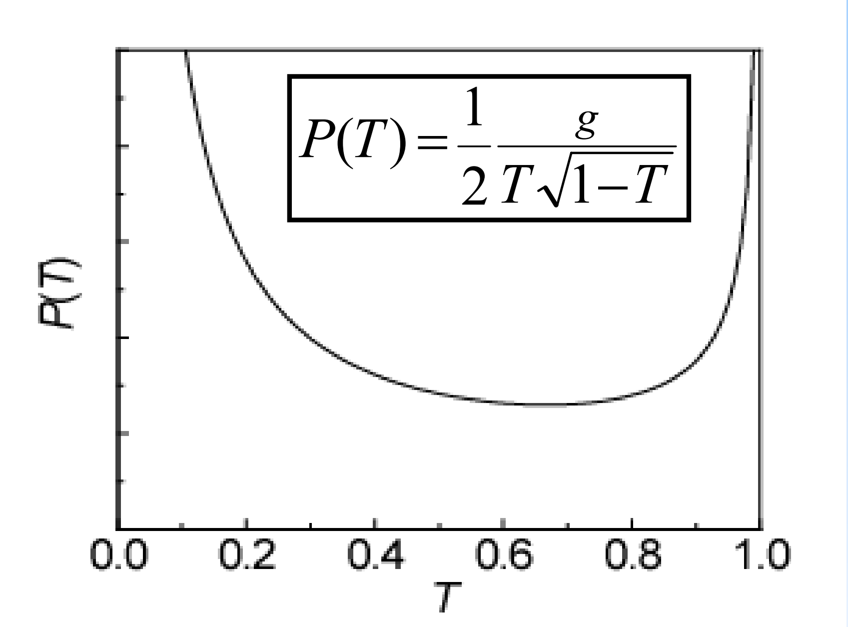
Agam, Aleiner, and Larkin 2000

Distribution of eigenvalues in ballistic graphene

$$T_n = \frac{1}{\cosh^2\left[(n+\alpha)\pi\frac{L}{W}\right]}$$

$$\frac{W}{L} \to \infty$$

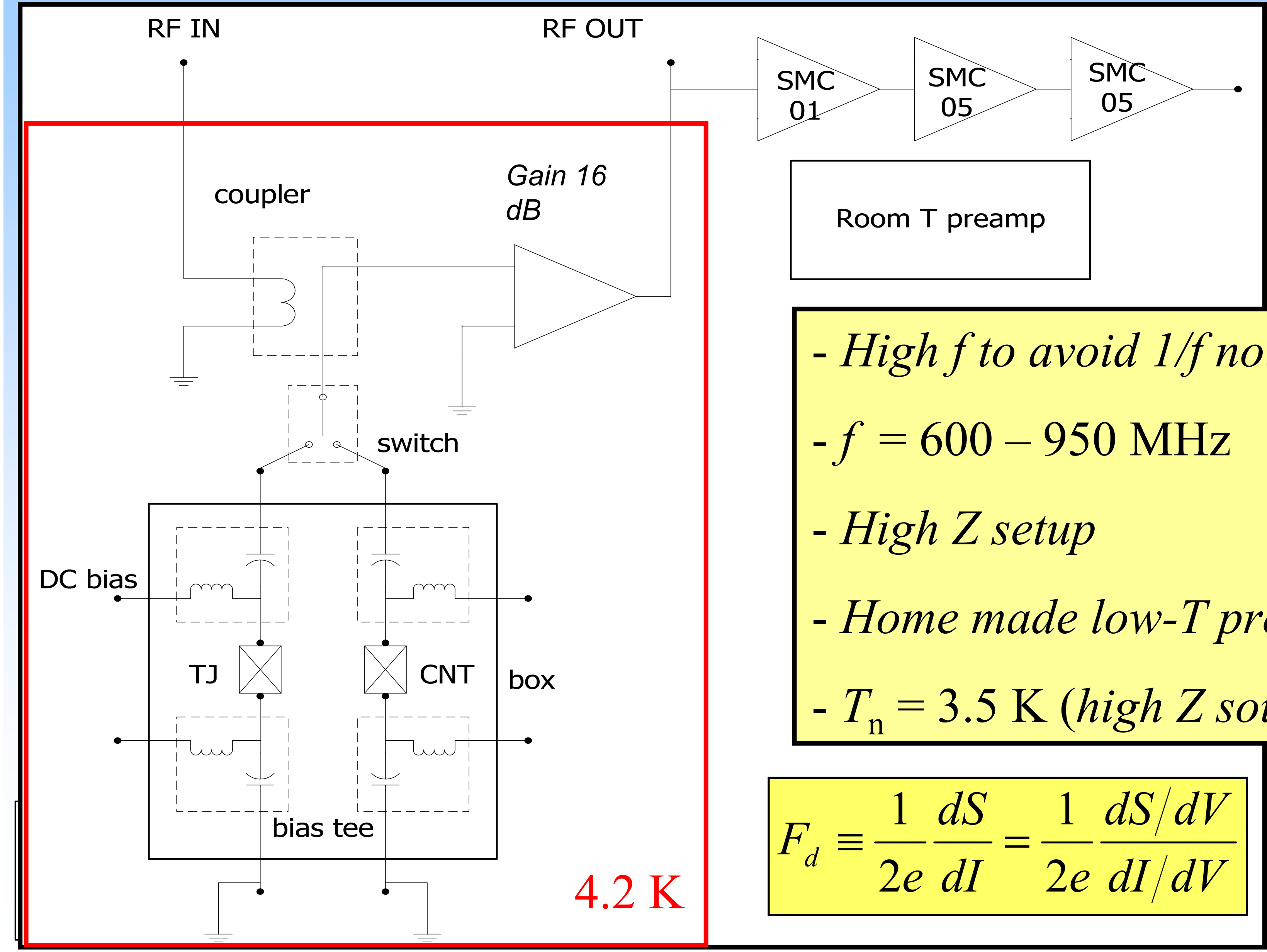
$$F = \frac{\sum_n T_n(1-T_n)}{\sum_n T_n} = \frac{1}{3}$$



J. Tworzydło, B. Trauzettel, M. Titov, A. Rycerz, and C. W. Beenakker, Phys. Rev. Lett. **96**, 246802 (2006).

M.I. Katsnelson, Eur. Phys. J. B **51**, 157 (2006).

Schematics of measurement setup

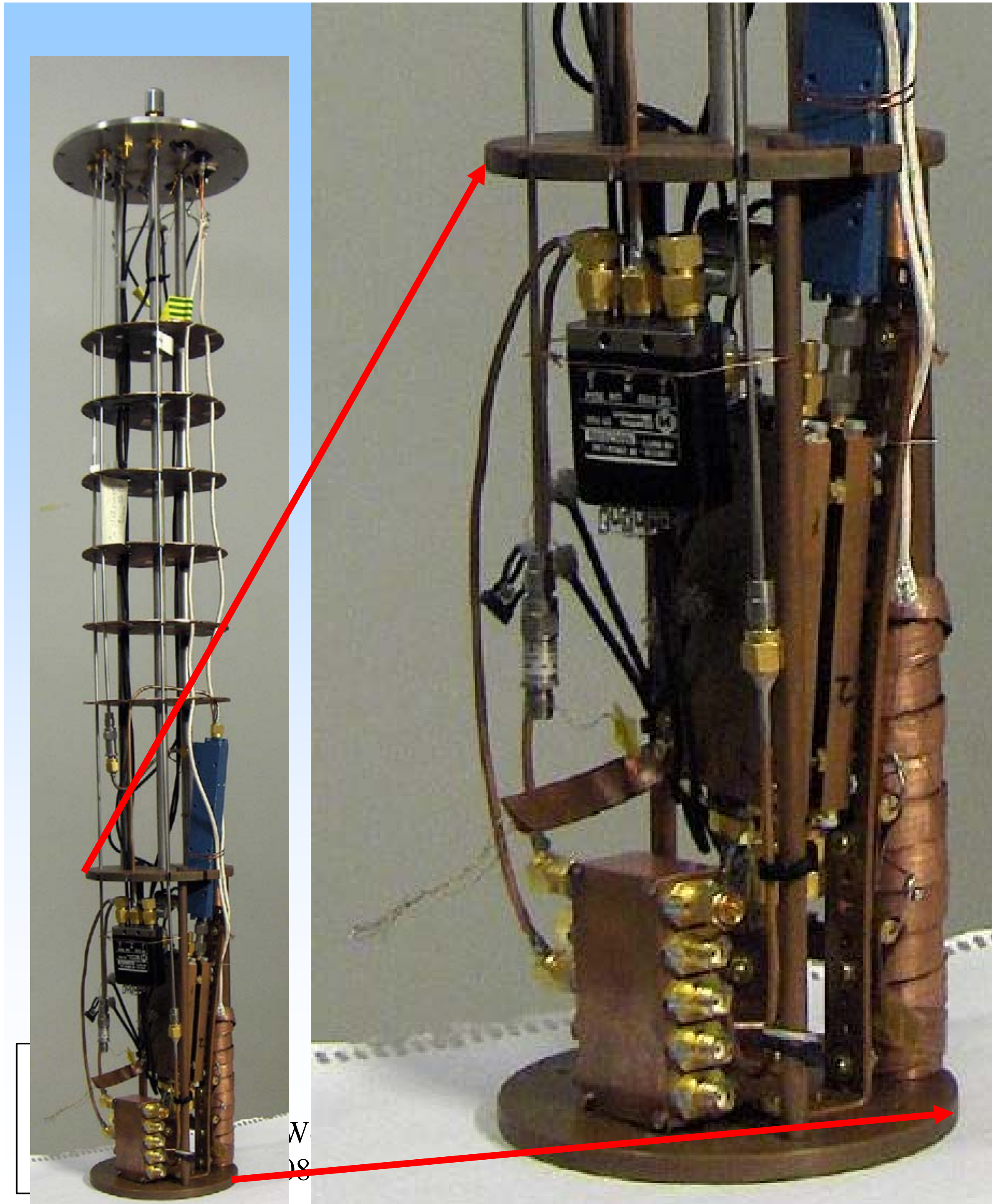


- *High f to avoid 1/f noise*
- f = 600 – 950 MHz
- *High Z setup*
- *Home made low-T preamplifier*
- T_n = 3.5 K (*high Z source*: 14K)

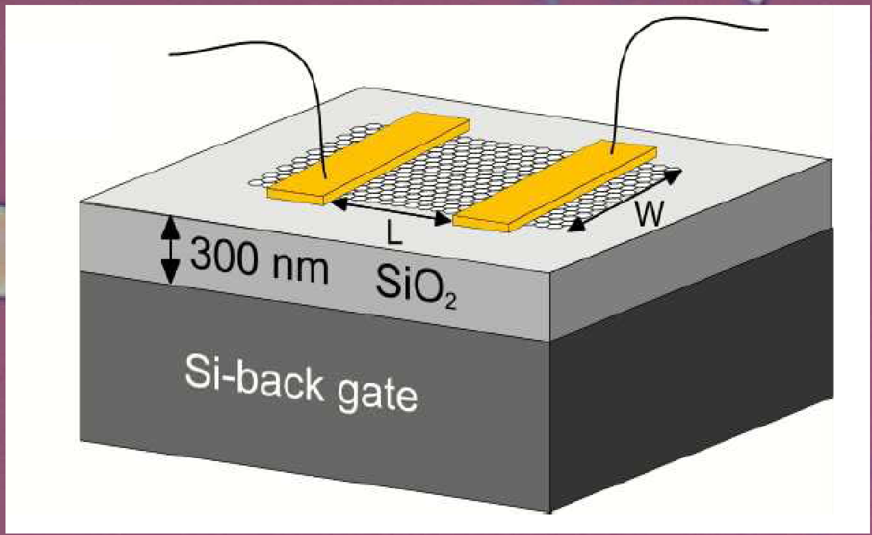
$$F_d \equiv \frac{1}{2e}\frac{dS}{dI} = \frac{1}{2e}\frac{dS/dV}{dI/dV}$$

$$\widetilde{F} = \frac{1}{I}\int_0^I F_d\, dI$$

Measurement setup



Shot noise in graphene



$W/L \sim 10$
$L = 200$ nm

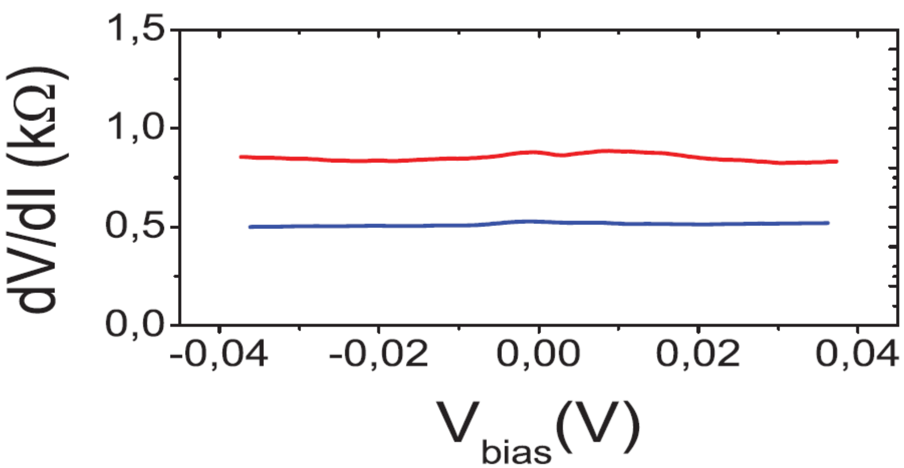
Sample with W/L=24

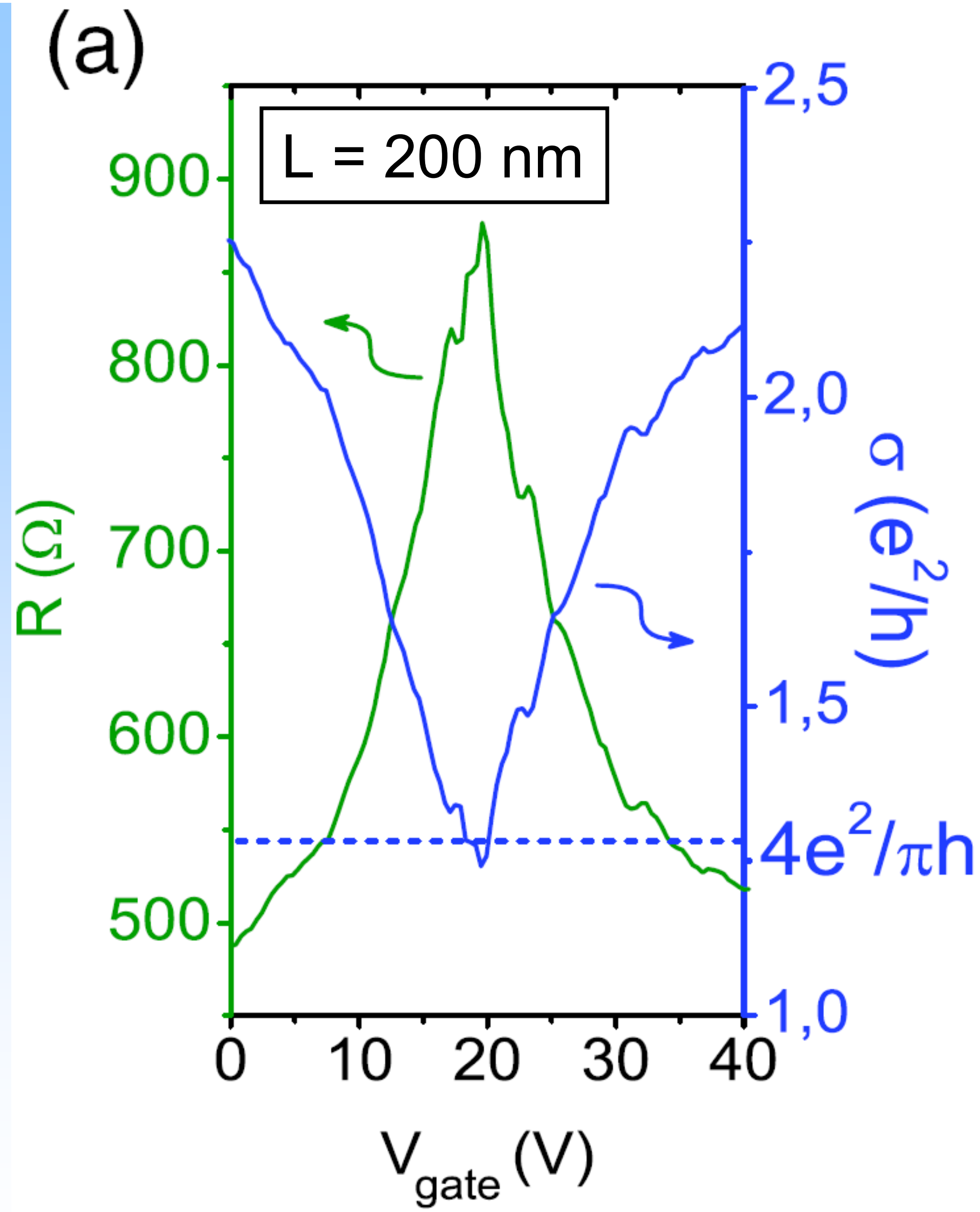
SAMPLE:

- Single layer
- *W/L* = 4.8 / 0.20 ~ 24,
- Ti/Au contacts (10/40 nm)

minimum conductivity: $\frac{4e^2}{\pi h}$

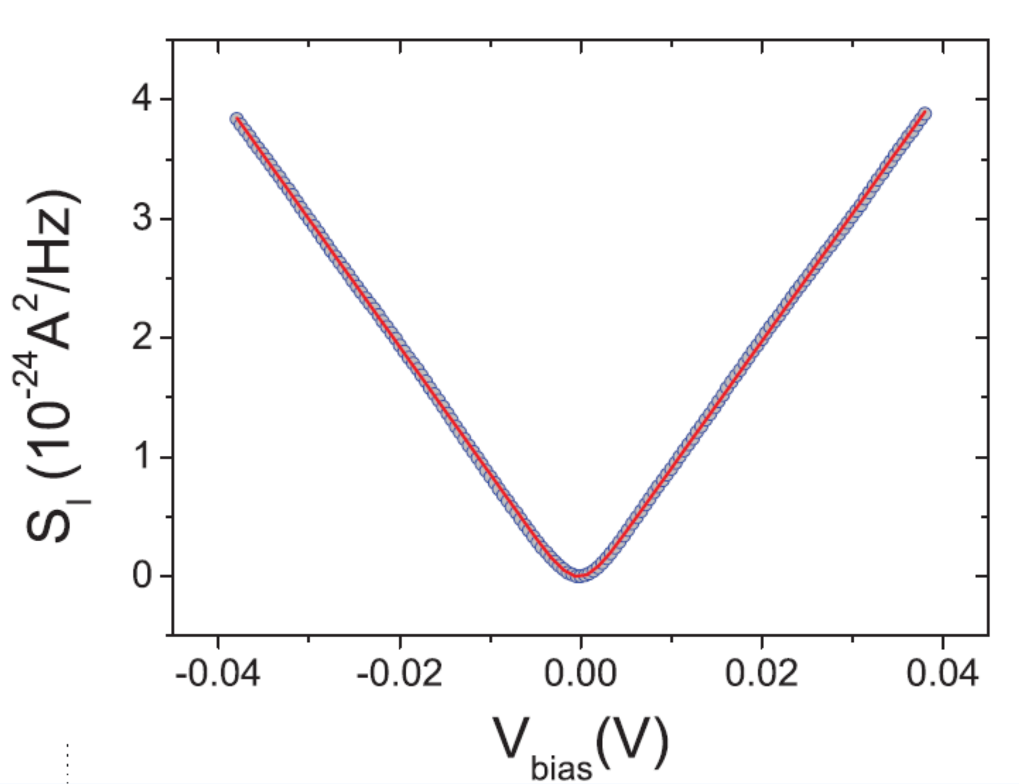
Seen also by:
F. Miao *et al.*, Science **317**, 1530 (2007).





p-doping with gate shift of 20 – 200 V
(uppermost breakthrough at 139 V)

Current noise vs. bias at Dirac point

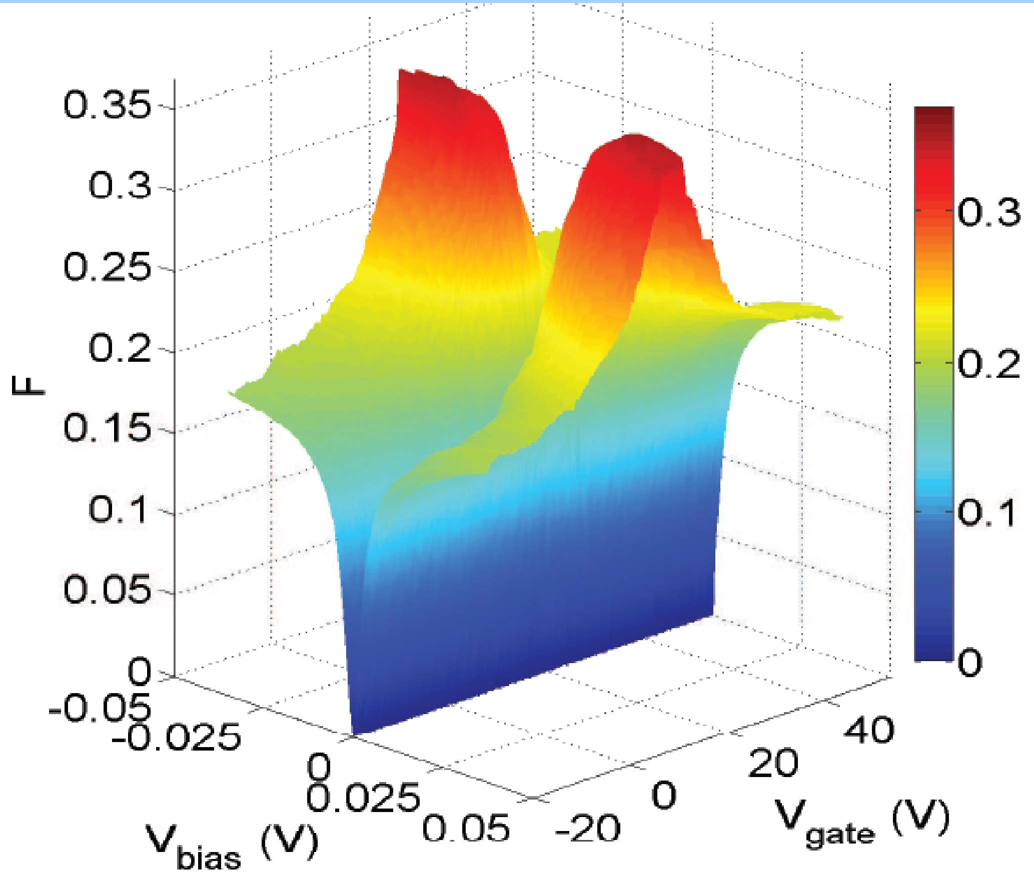


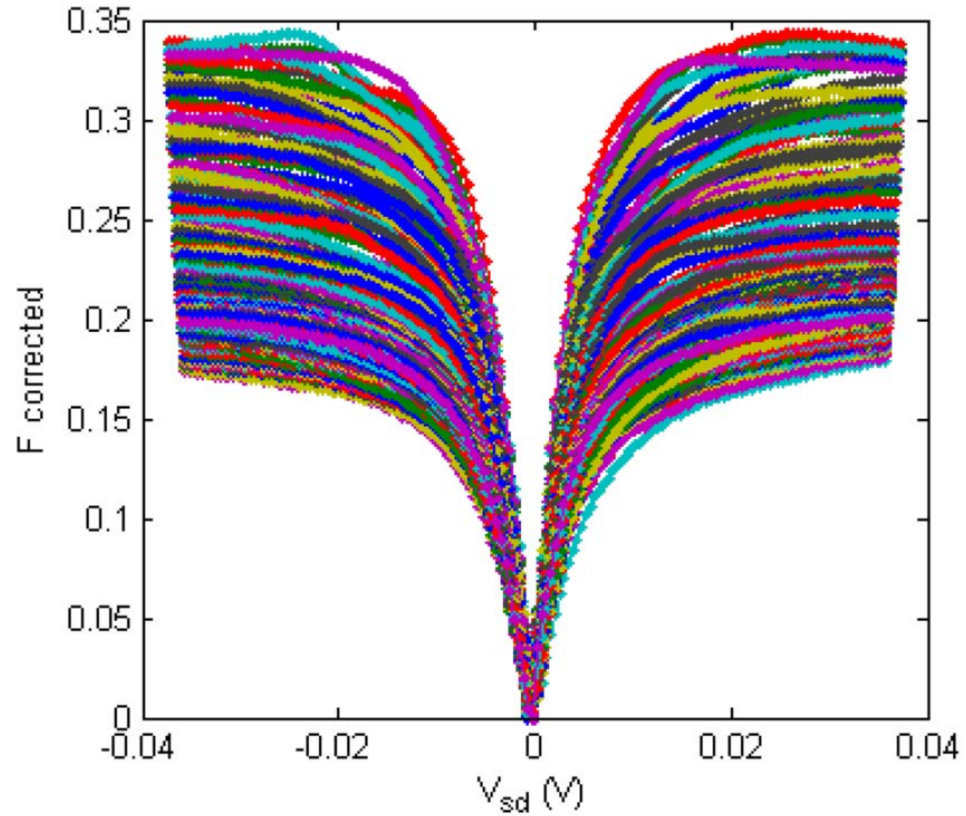
$$S(V,T) - S(0,T) = \frac{4k_BT}{R} F\left(\frac{eV}{2k_BT}\coth\left(\frac{eV}{2k_BT}\right) - 1\right)$$

- T fixed, F only parameter

Fit yields: $F = 0.318$

Fano factor: gate and bias dependence

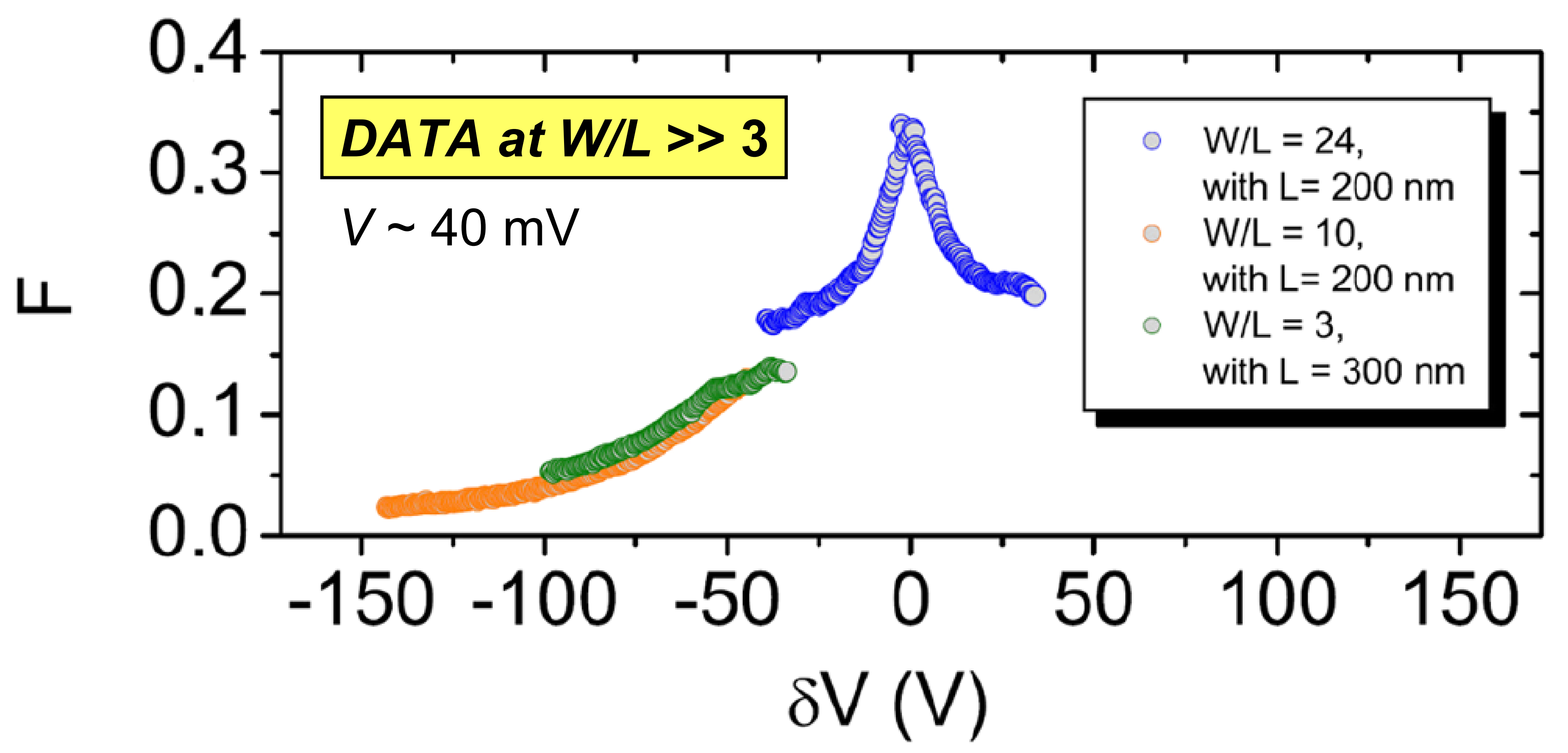




$$F = \widetilde{F} = \frac{1}{I}\int_0^I F_d\,dI$$

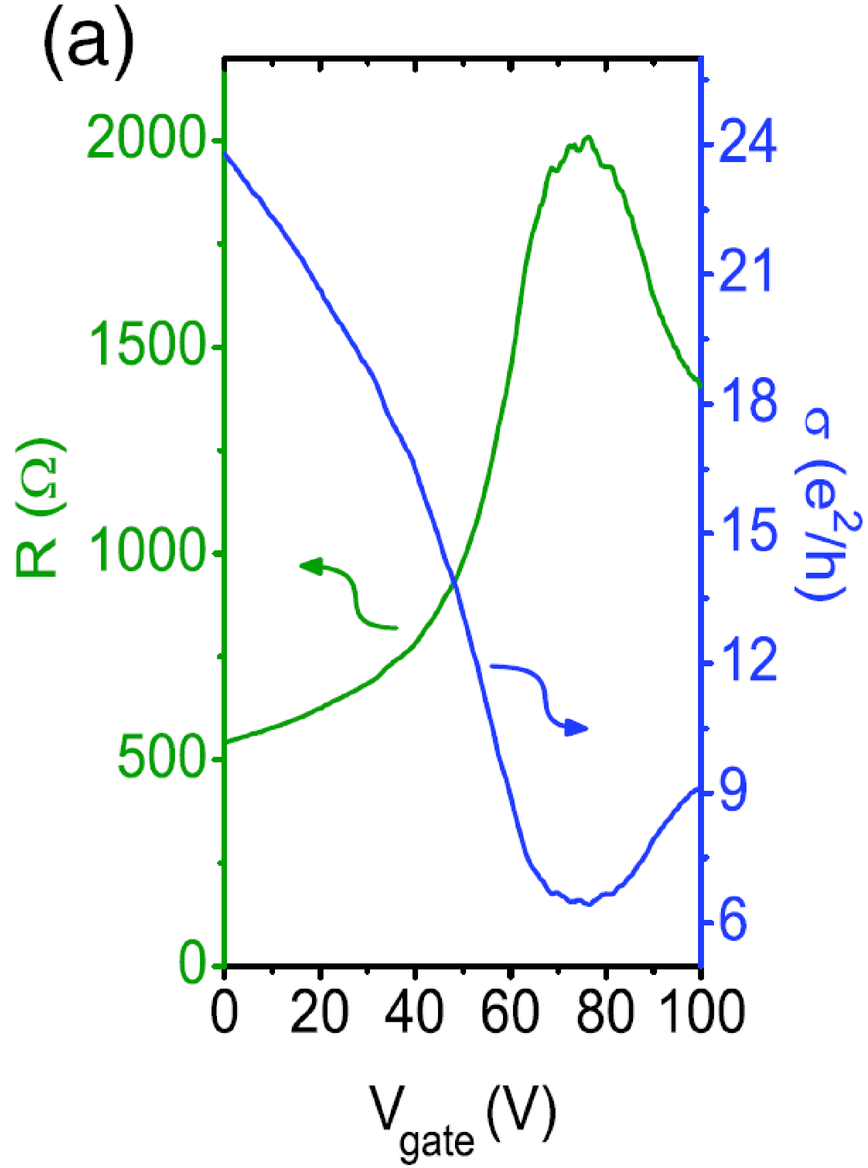
in agreement with J. Tworzydło et al., Phys. Rev. Lett. ***96****, 246802 (2006).*

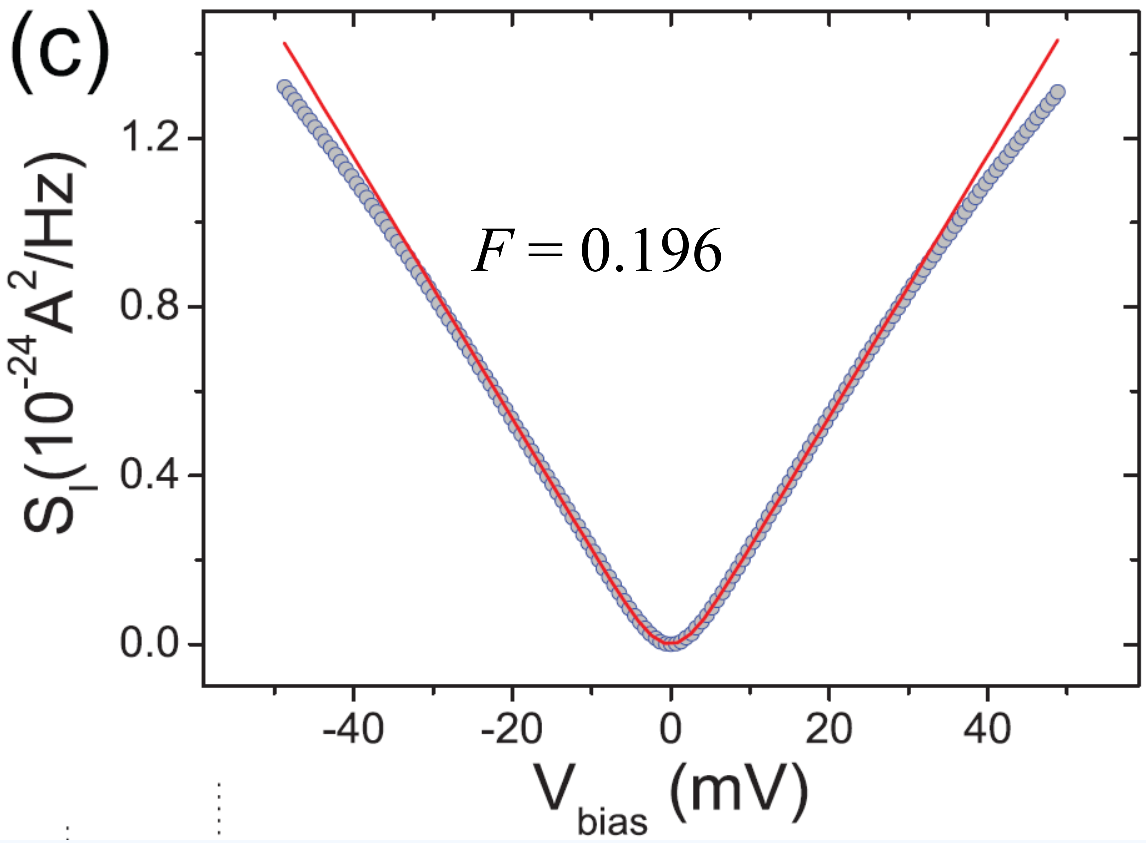
Summary of Fano factor



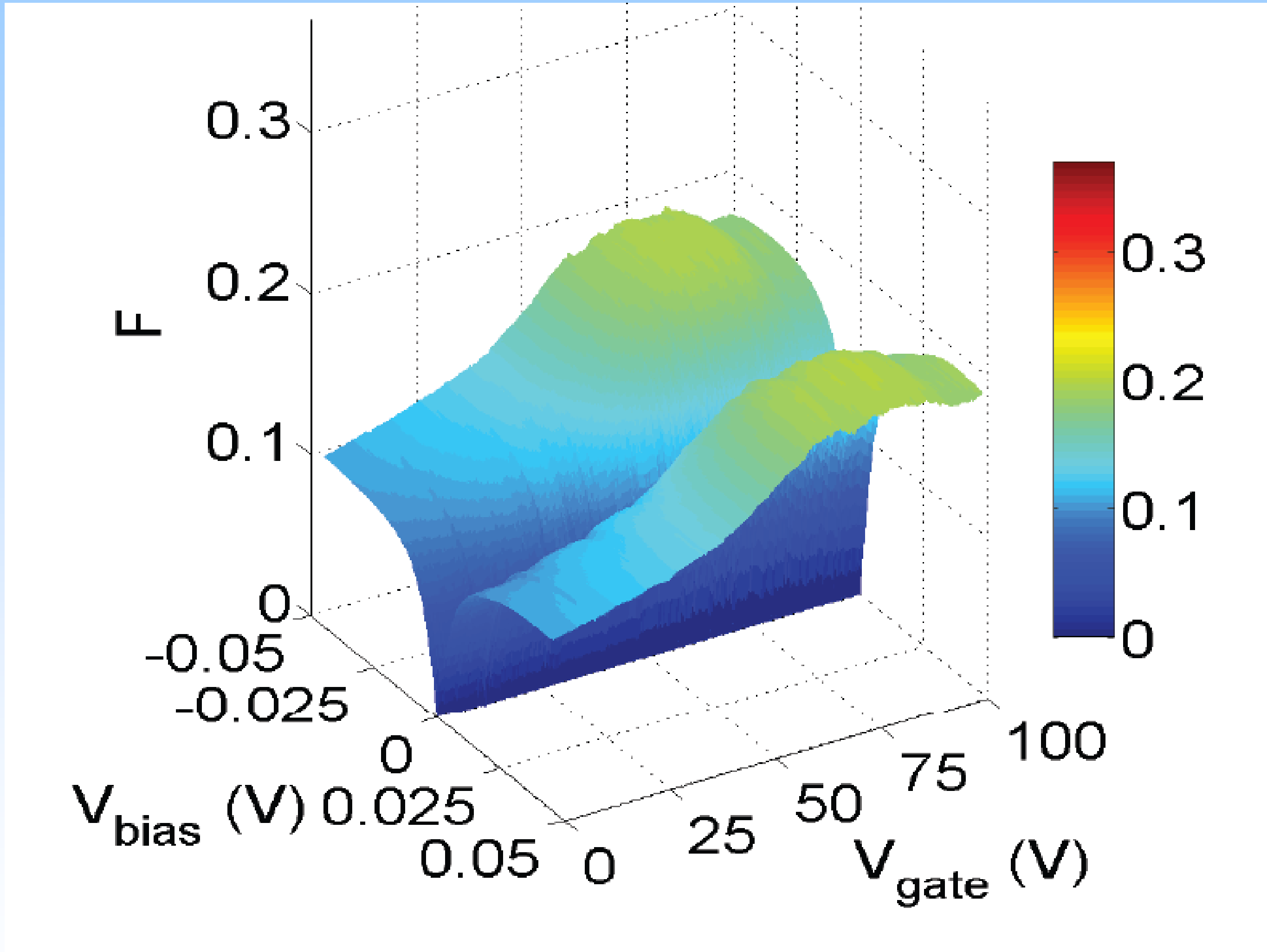
– ***F* = 0.338 at the Dirac point (with *W/L* >> 3)**
– **nearly ballistic at large carrier concentration**

Sample with W/L = 2 (L = 0.5 μm)





Fano factor: sample with W/L = 2

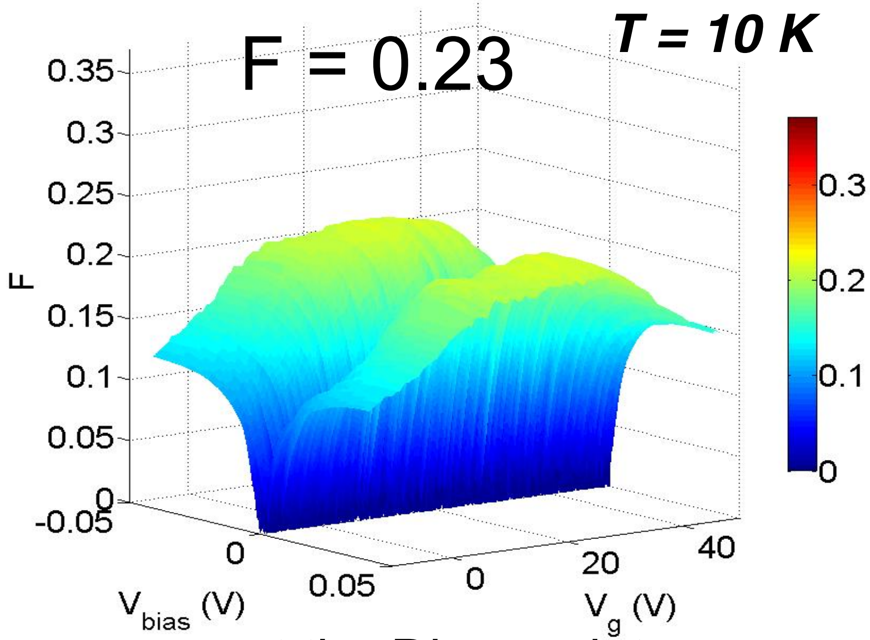


– ***F* = 0.19 at the Dirac point**
– **Agreement with metallic armchair edge**

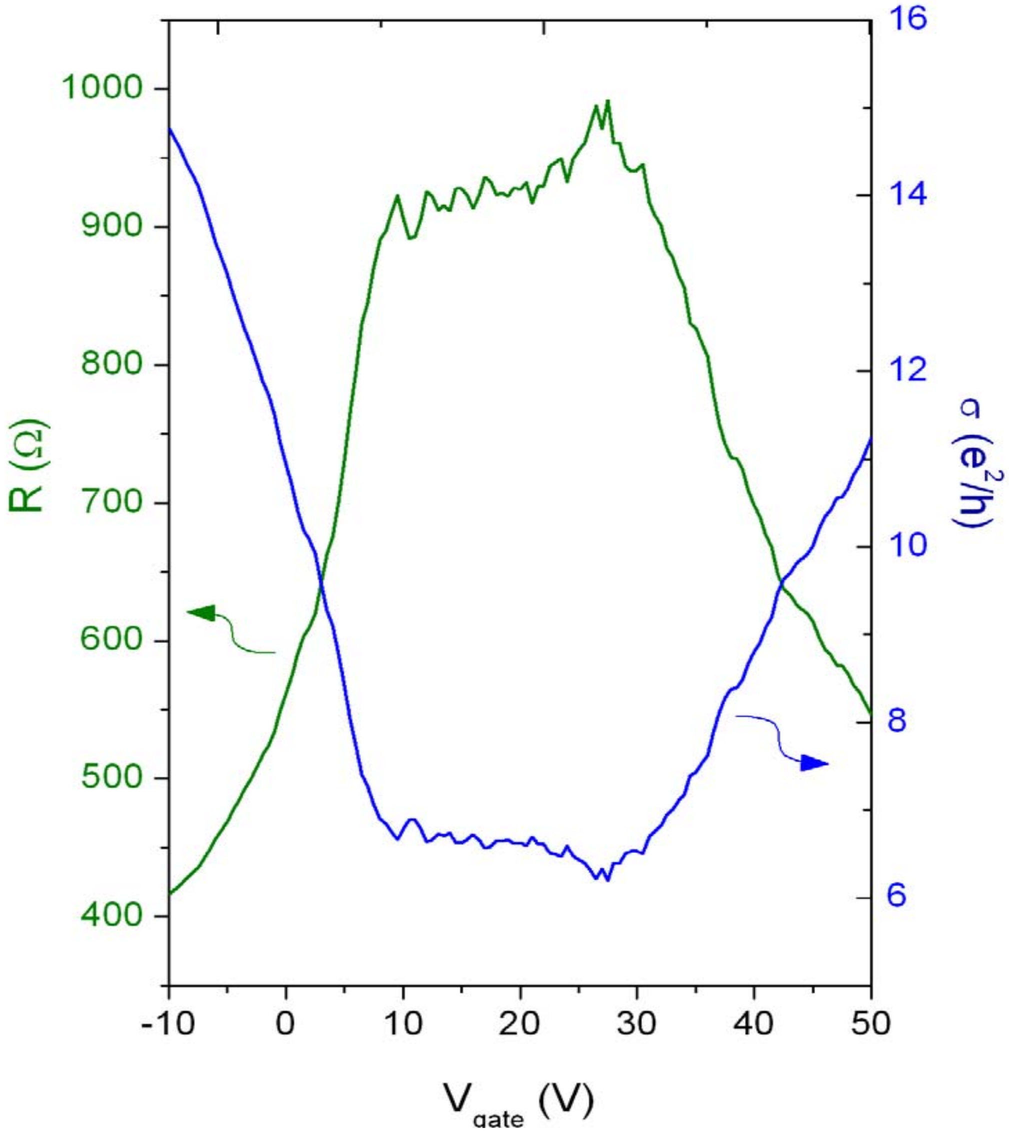
Disorder?

- L = 950 nm
- W/L = 4.2
- $\sigma_{min} \sim 6\ G_0$

1D disorder:
F = 0.25 like
chaotic cavity



max at the Dirac point

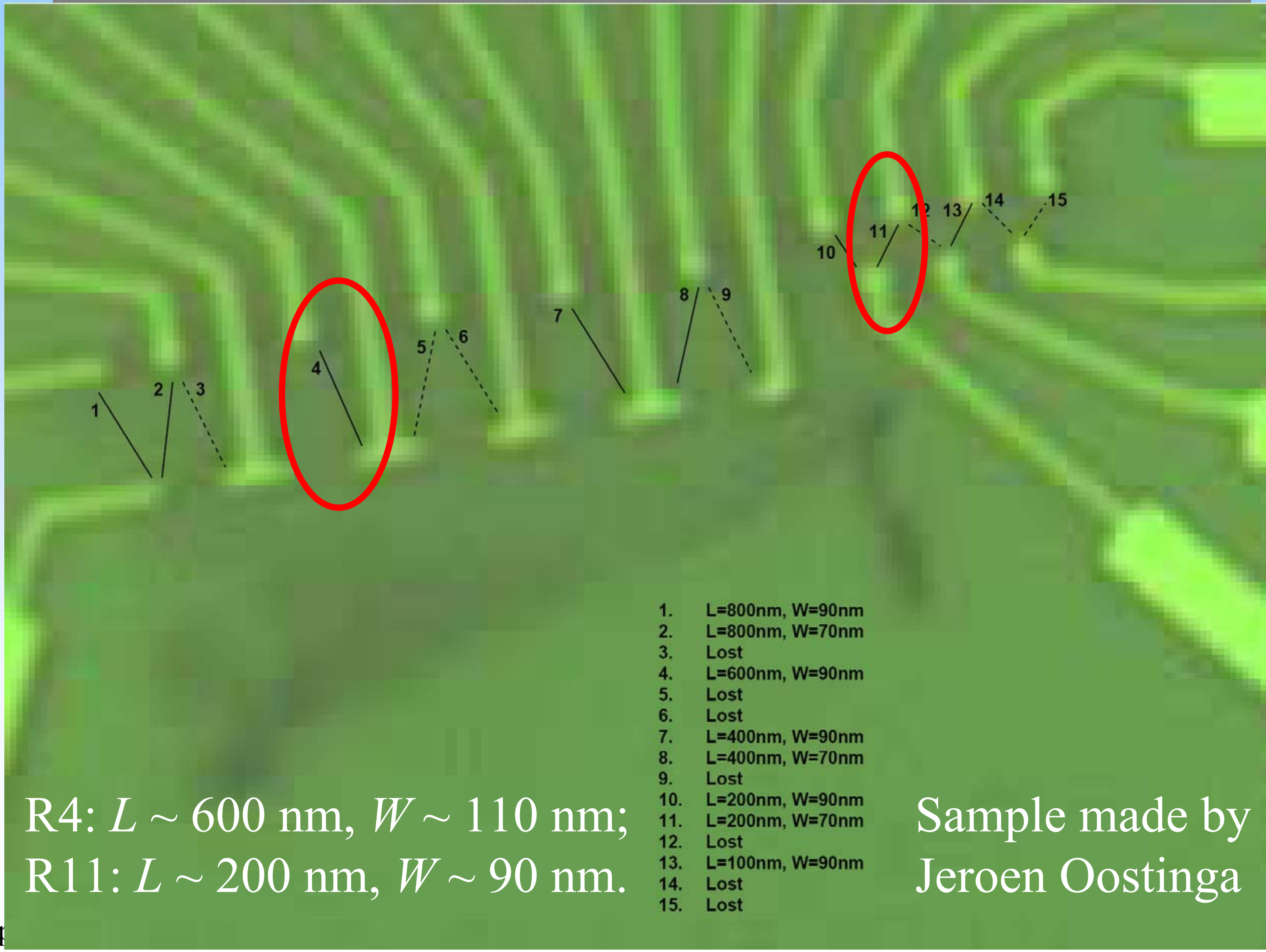


P. San-Jose, E. Prada, and D. Golubev, Phys. Rev. B ***76****, 195445 (2007).*

M. Titov, EPL ***79,*** *17004 (2007); arXiv:cond-mat/0611029v1.*

C.H. Lewenkopf, E.R. Mucciolo, A.H. Castro Neto Phys. Rev. B ***77****, 081410R (2008).*

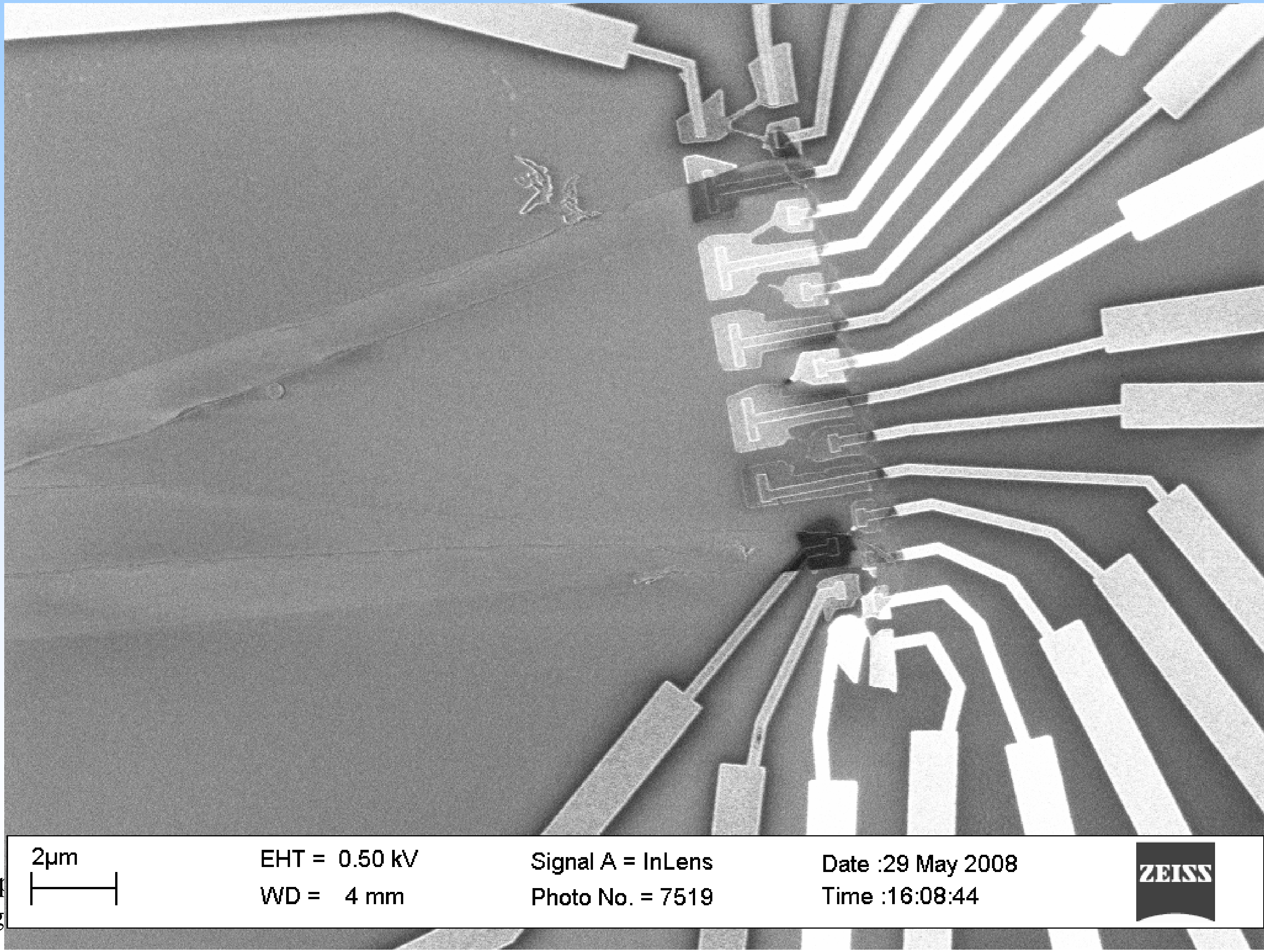
Ribbons



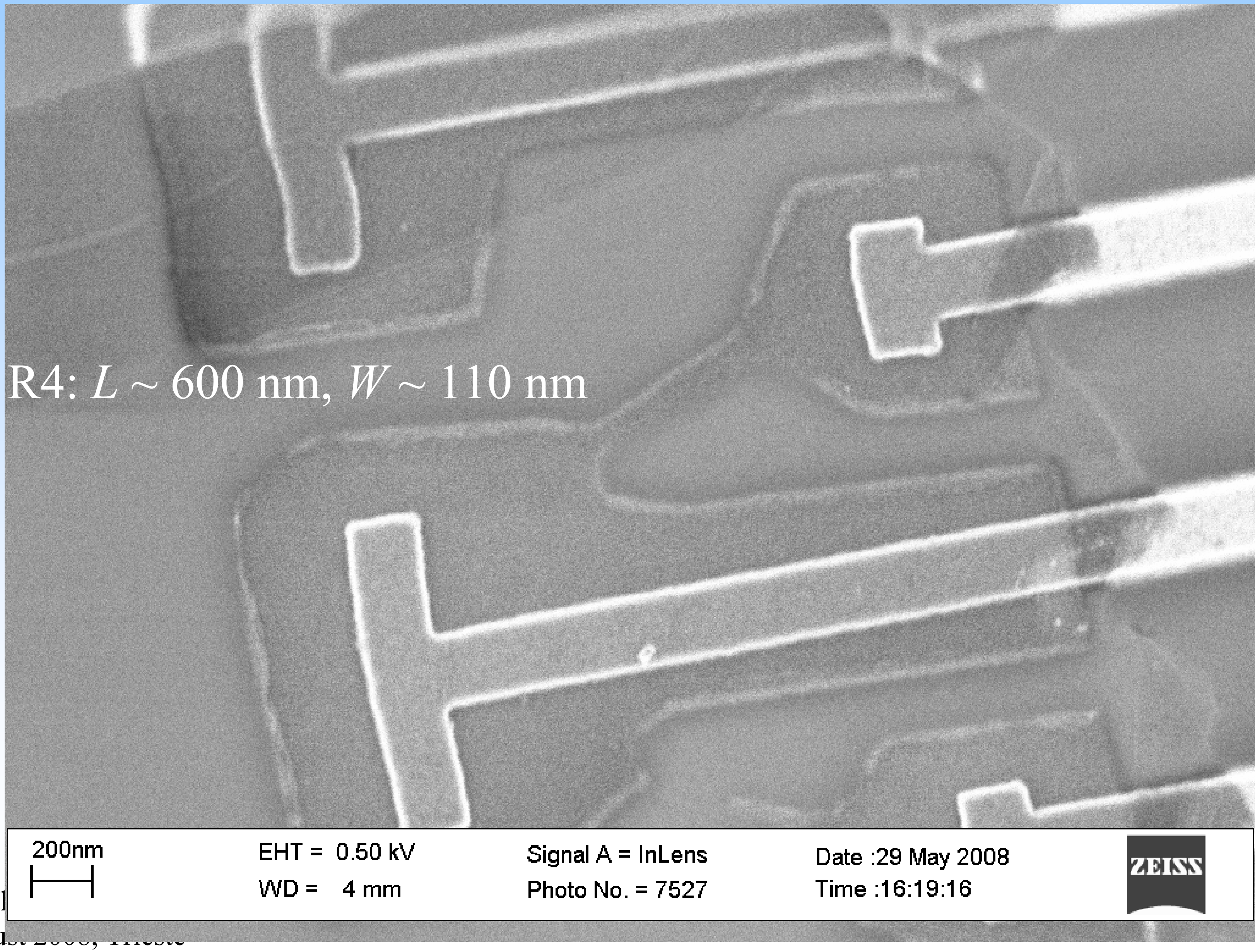
R4: $L \sim 600$ nm, $W \sim 110$ nm;
R11: $L \sim 200$ nm, $W \sim 90$ nm.

Sample made by Jeroen Oostinga

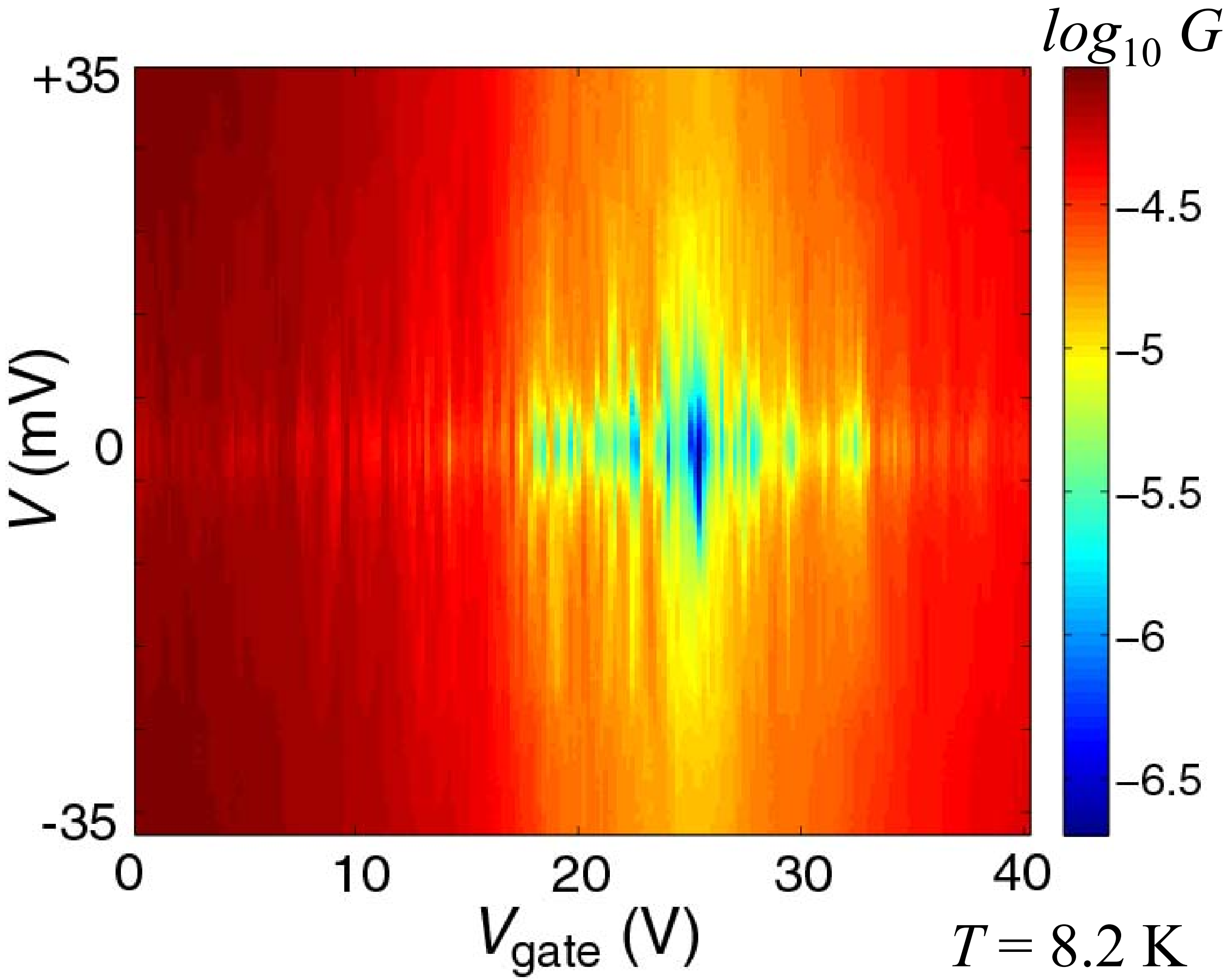
Ribbons


2µm
EHT = 0.50 kV
WD = 4 mm
Signal A = InLens
Photo No. = 7519
Date :29 May 2008
Time :16:08:44
ZEISS

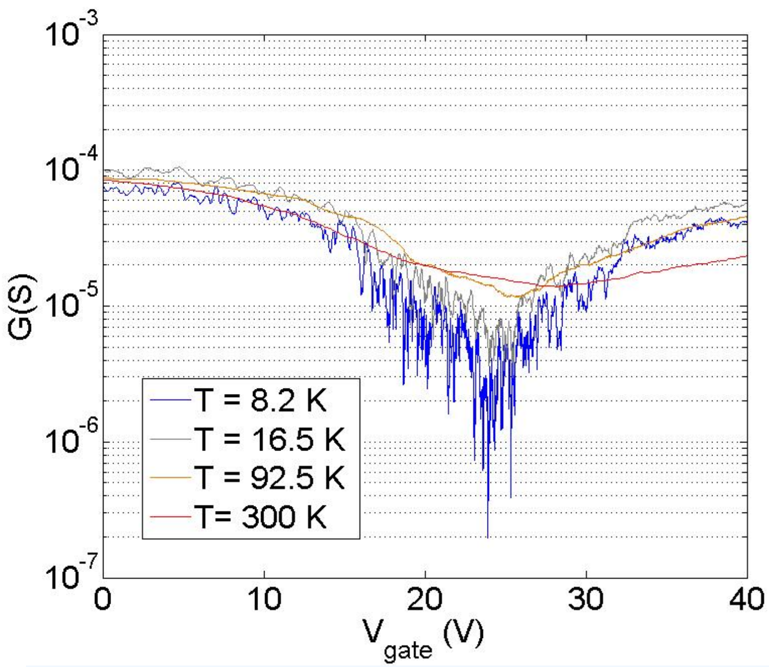
Ribbons: R4 (*L* ~ 600 nm, *W* ~ 110 nm)



Ribbon R4 (*L* ~ 600 nm, *W* ~ 110 nm)

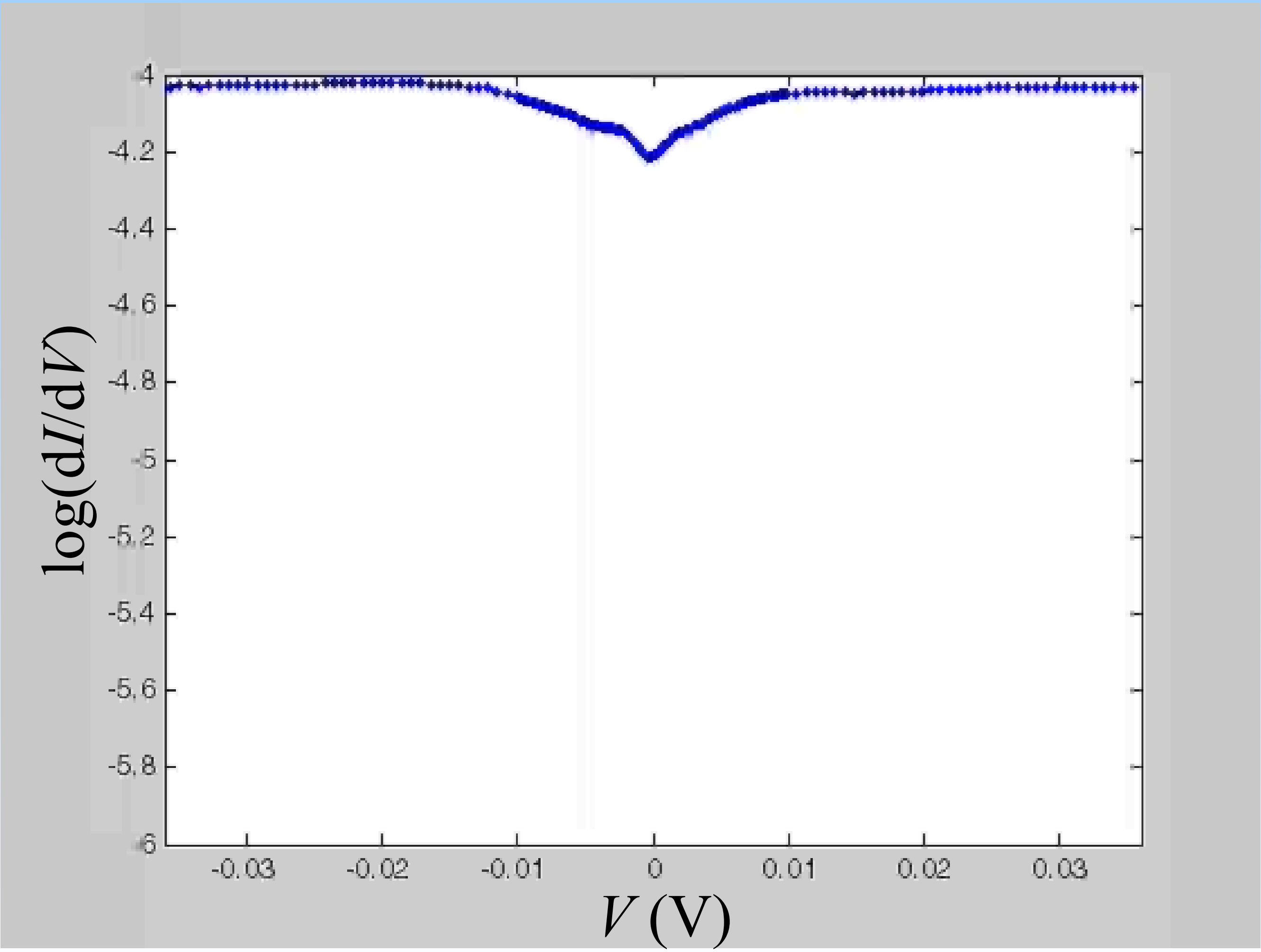


$T = 8.2$ K



No gate periodicity!

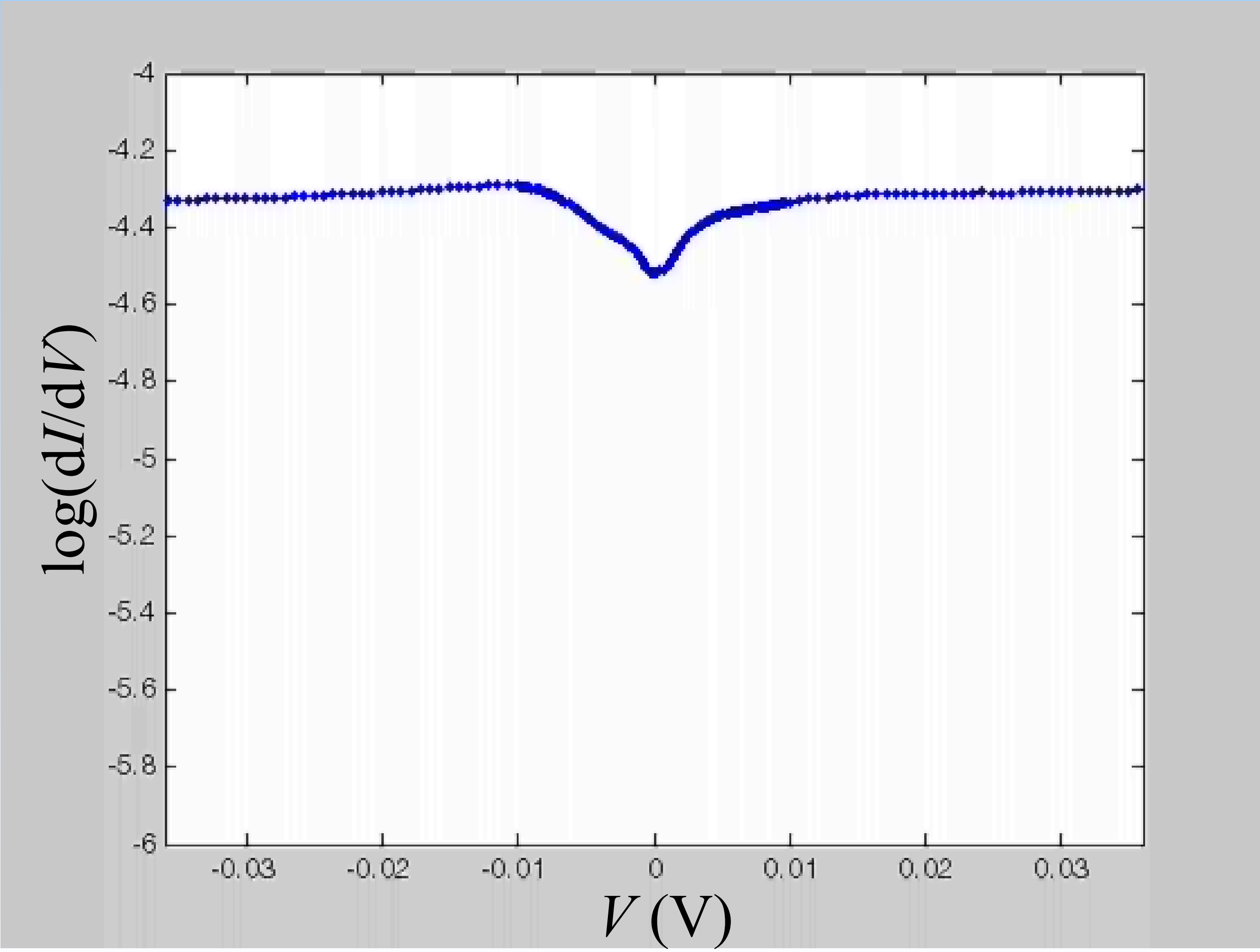
Ribbon R4 (*L* ~ 600 nm, *W* ~ 110 nm)



- Not simple zero bias anomaly
  Conductance peaks at zero bias!?

Graphene Week
August 2008, Trieste

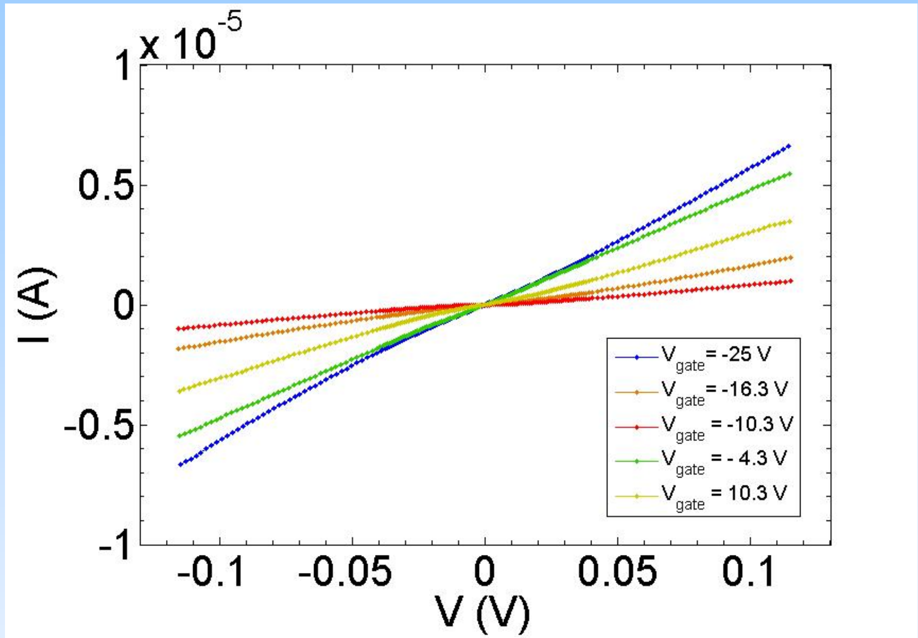
Ribbon R4 (*L* ~ 600 nm, *W* ~ 110 nm)

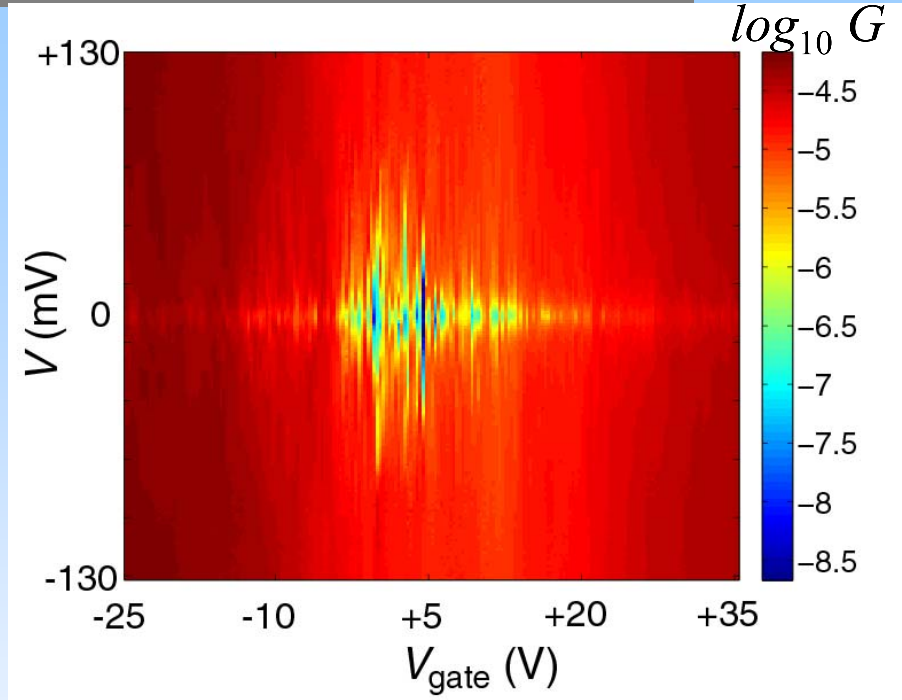


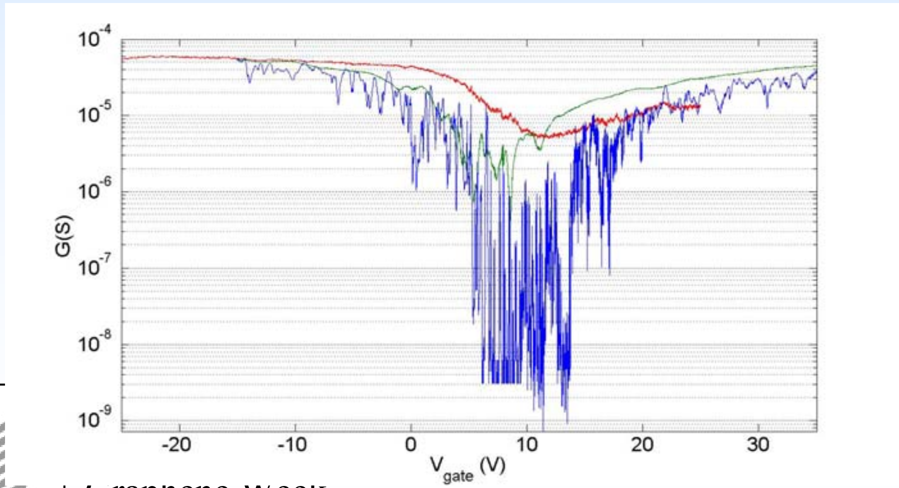
- Not simple zero bias anomaly
  Conductance peaks at zero bias!?

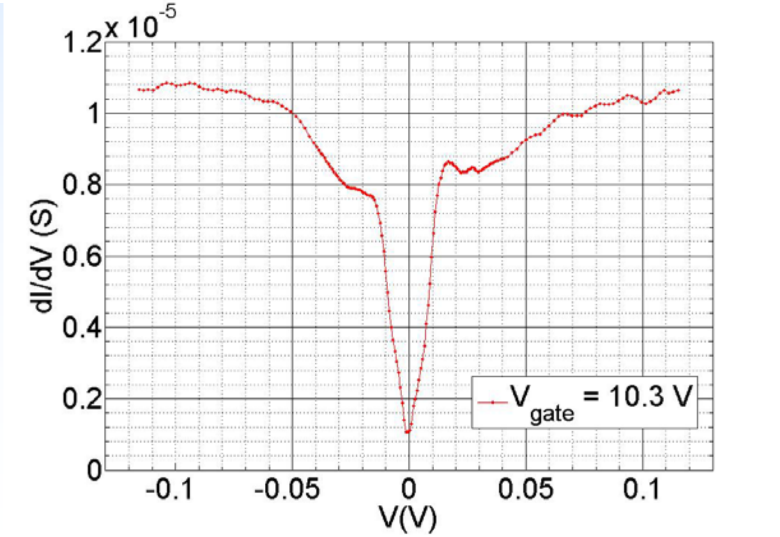
Graphene Week
August 2008, Trieste

Ribbon R11 (*L* ~ 200 nm, *W* ~ 90 nm)

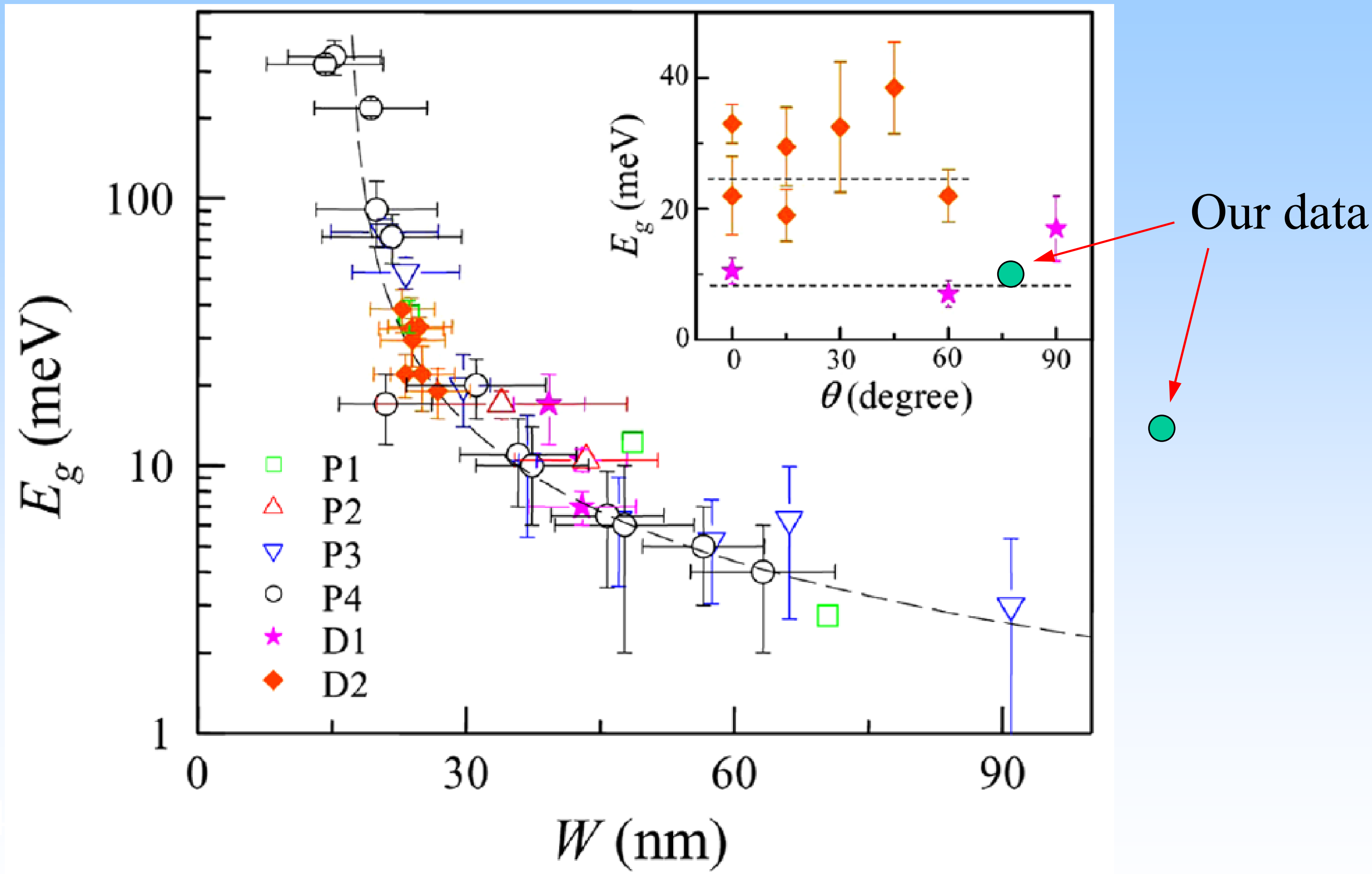








Comparison of conductance gap

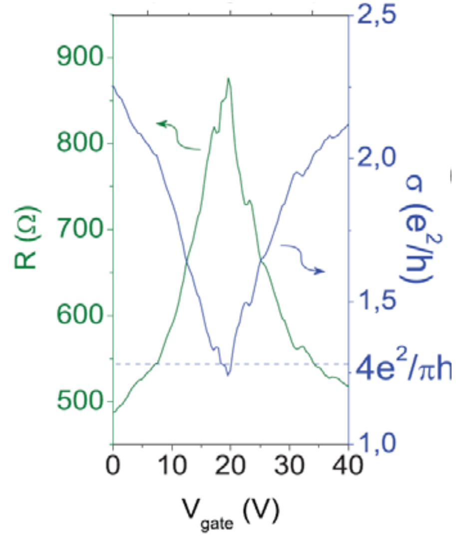


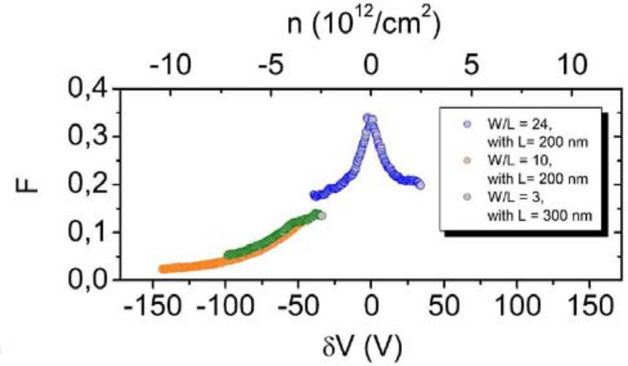
M. Y. Han, B. Özyilmaz, Y. Zhang, and P. Kim
*PRL **98**, 206805 (2007).*

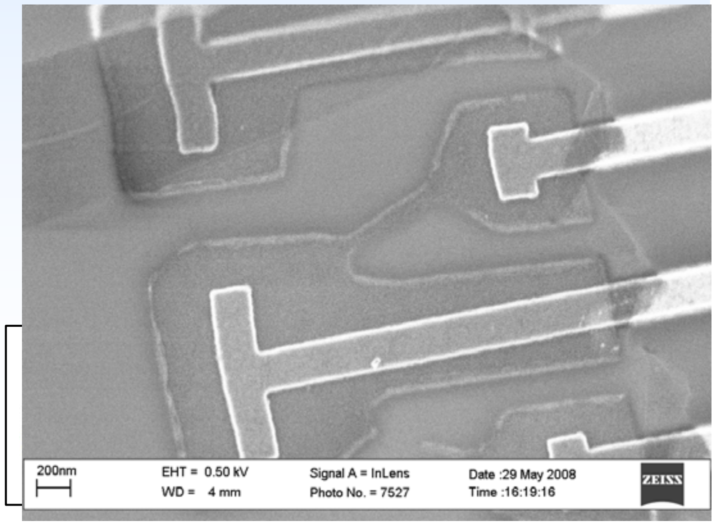
Summary

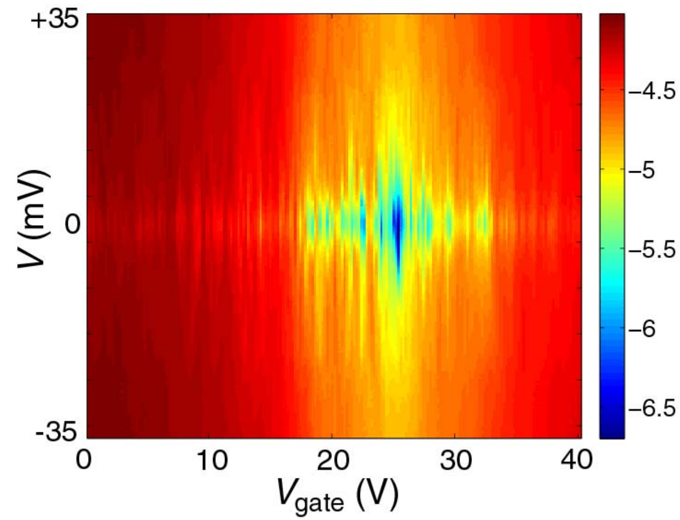
R. Danneau, et al., Phys. Rev. Lett. **100**, 196802 (2008) + unpublished.

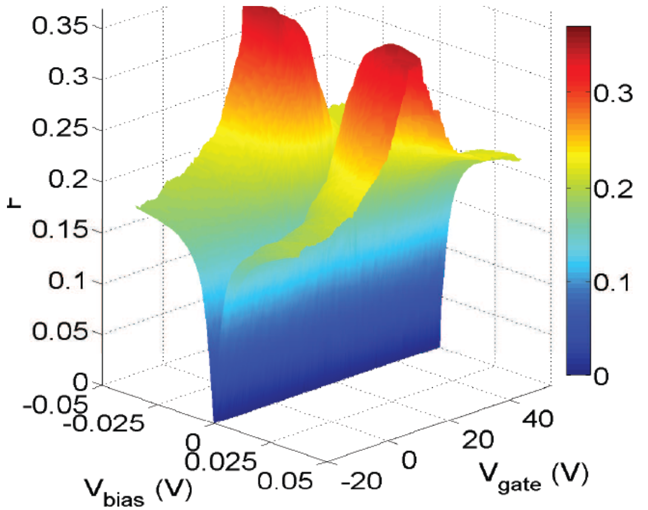
- F_{max} = 0.338 for samples with $W/L >> 3$
  - close to predicted universal value $F_{max} = 1/3$
- Ballistic far from Dirac point: $F_{min} = 0.02$,
  no oscillation found as a function of gate
- F_{max} = 0.19 for a sample with $W/L = 2$
- Disorder effects in longer samples: F_{max} = 0.23
- F small for ribbons with large "gap"
- Unknown correlations in nanoribbons?











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