Electronic Noise in Nanostructures

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in collaboration with

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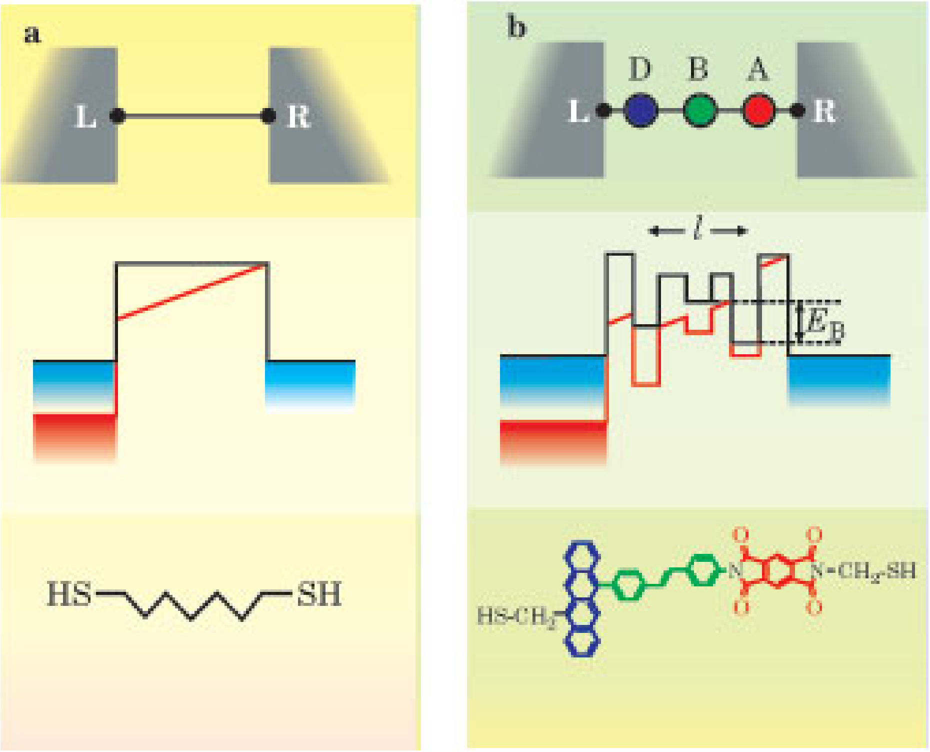
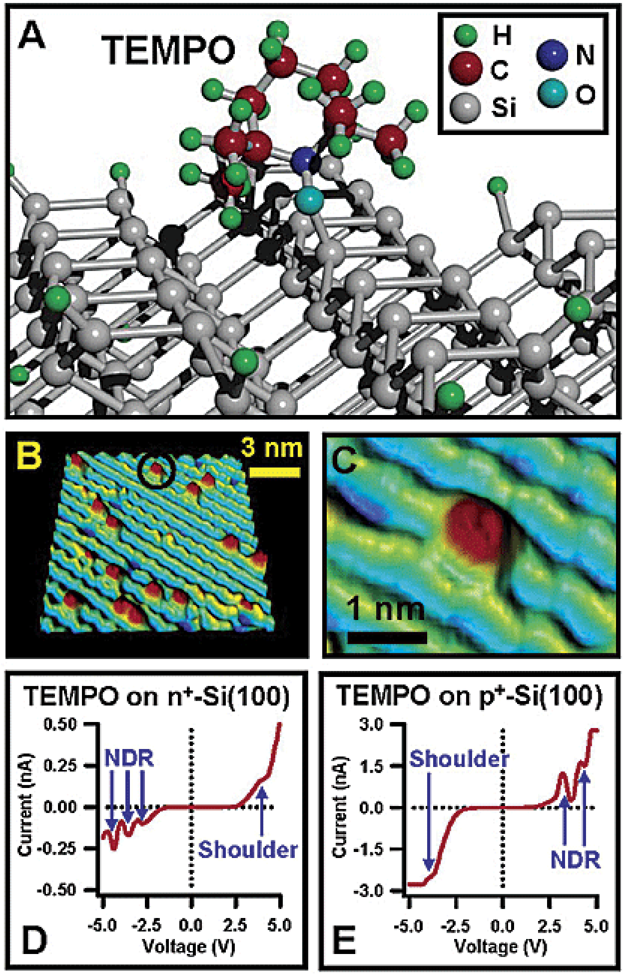
Molecular Electronics

Room Temperature **Negative Differential Resistance through Individual Organic Molecules** on Silicon Surfaces (Guisinger et al., *Nano Letters* **4**, 55 (2004))



Some examples of potential profiles in molecular electronics (Phys. Today, May 2003)

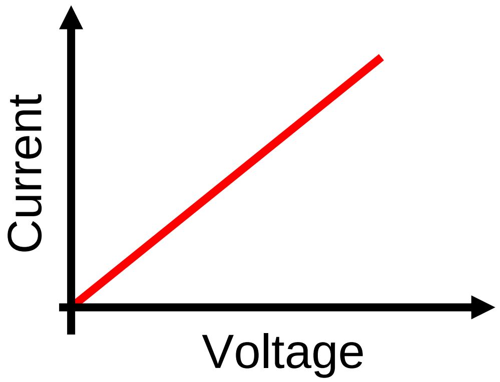


Experimental Data

The Noise is the Signal (Rolf Landauer)

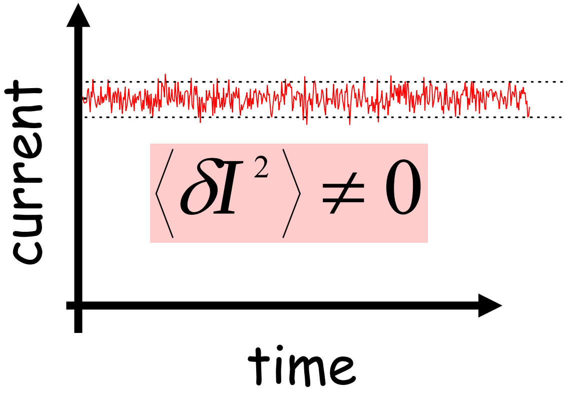
Electronic Noise = Rapid Fluctuations in the Average Value of an Electrical Quantity (voltage, current)

$$\overline{I} = G\overline{V}$$



(Physics Today, May 2003)

$$S_I = F(2qI)$$

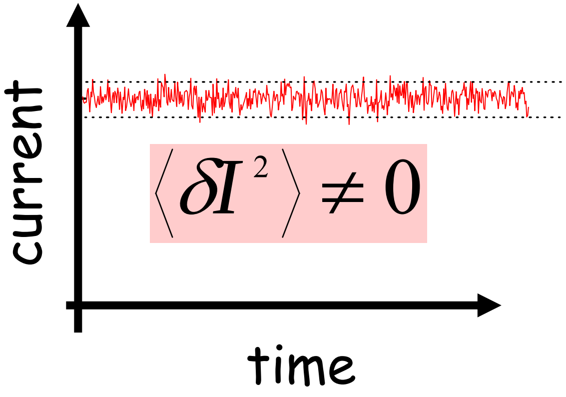


$$\langle \delta I^2 \rangle \neq 0$$

Why Do We Care about Noise?

- It limits the performance of nanodevices
- It sheds "microscopic" light on electron transport

Electronic Noise



$$\langle \delta I^2 \rangle \neq 0$$

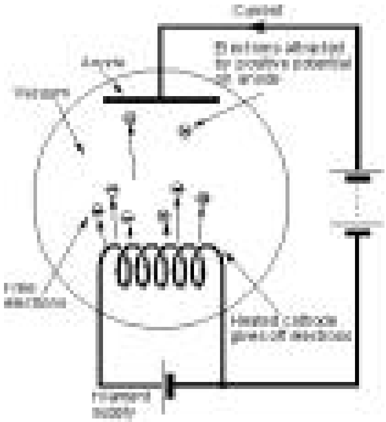
Electronic fluctuations occur because of:

— finite temperature (thermal noise)

— charge discreteness (**shot noise**)

— trapping/detrapping of charge (flicker, 1/f noise)

Shot Noise



- First studied by W. Schottky (1918)
- Electrons emitted at random from hot cathode
- Fluctuation in number of electrons follows

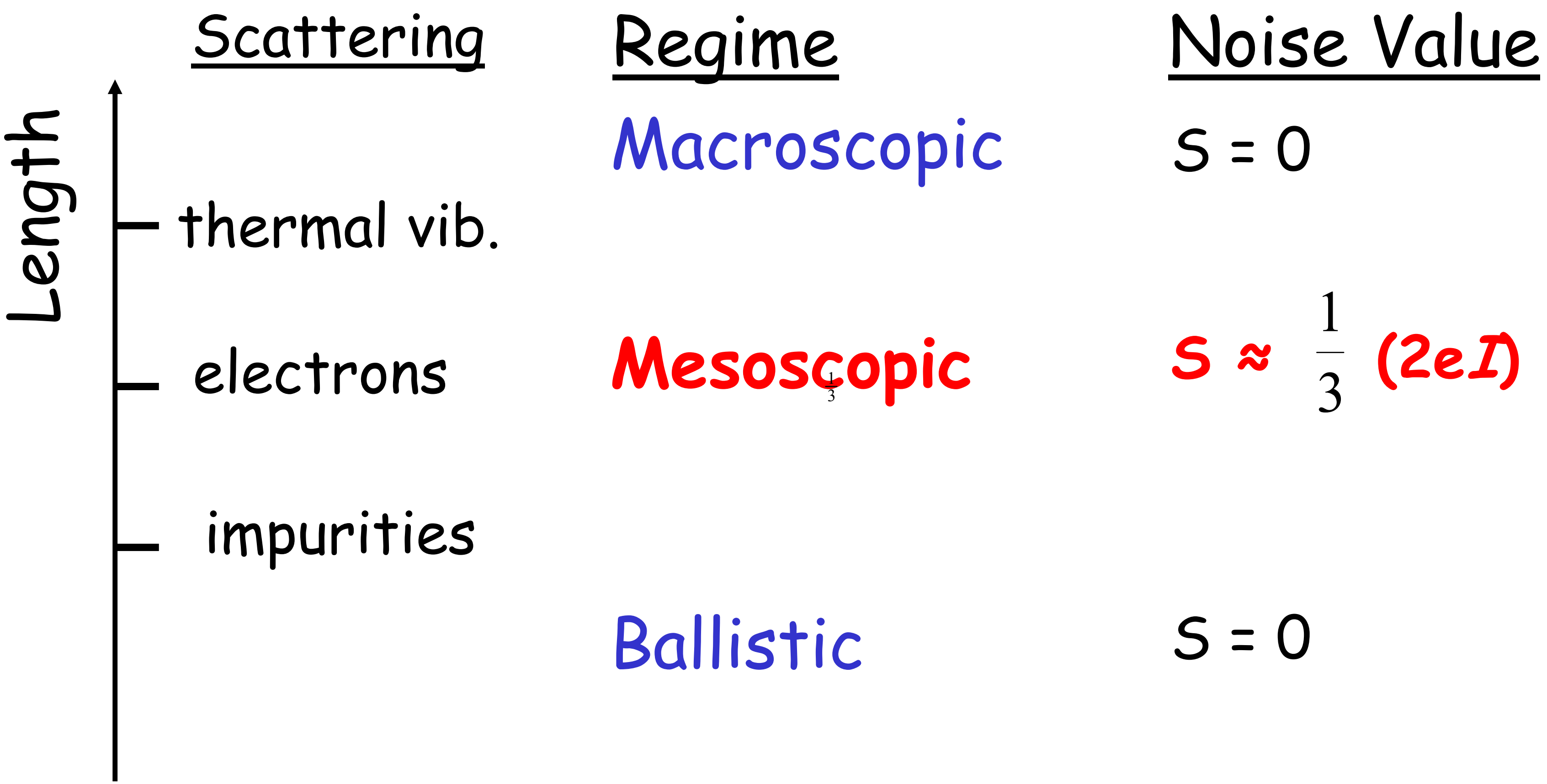
Poisson distribution

$$\overline{\Delta N^2} \equiv \overline{\left(N - \overline{N}\right)^2} \propto \overline{N}$$

-

$$S(f) = \frac{\langle \Delta I(f)^2 \rangle}{\delta f} \equiv$$ **Noise Power Spectral Density** $= 2 \times$ Charge $\times$ Current

Noise in Mesoscopic Metals



Regime	Noise Value
Macroscopic	$S = 0$
Mesoscopic	$S \approx \frac{1}{3}(2eI)$
Ballistic	$S = 0$

Only in a mesoscopic conductor, is noise different from zero

Determination of the Effective Charge from the Shot Noise

High-mobility 2D electron gas at GaAs-GaAlAs interface in a magnetic field

VOLUME 79, NUMBER 13 PHYSICAL REVIEW LETTERS 29 SEPTEMBER 1997

Observation of the $e/3$ Fractionally Charged Laughlin Quasiparticle

L. Saminadayar and D. C. Glattli
Service de Physique de l'État Condensé, CEA/Saclay, F-91191 Gif-sur-Yvette Cedex, France

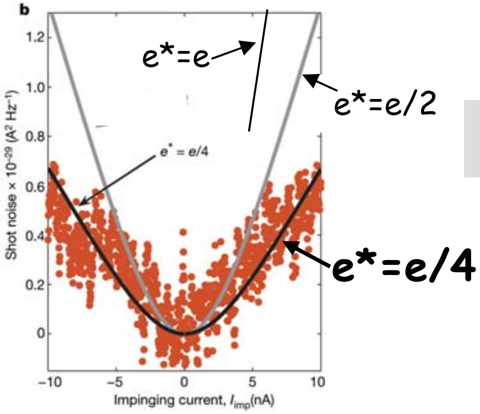
Y. Jin and B. Etienne
Laboratoire de Microstructures et Microélectronique, CNRS, B.P. 107, F-92225 Bagneux Cedex, France

(Received 30 June 1997)

$e^* = 1/3$

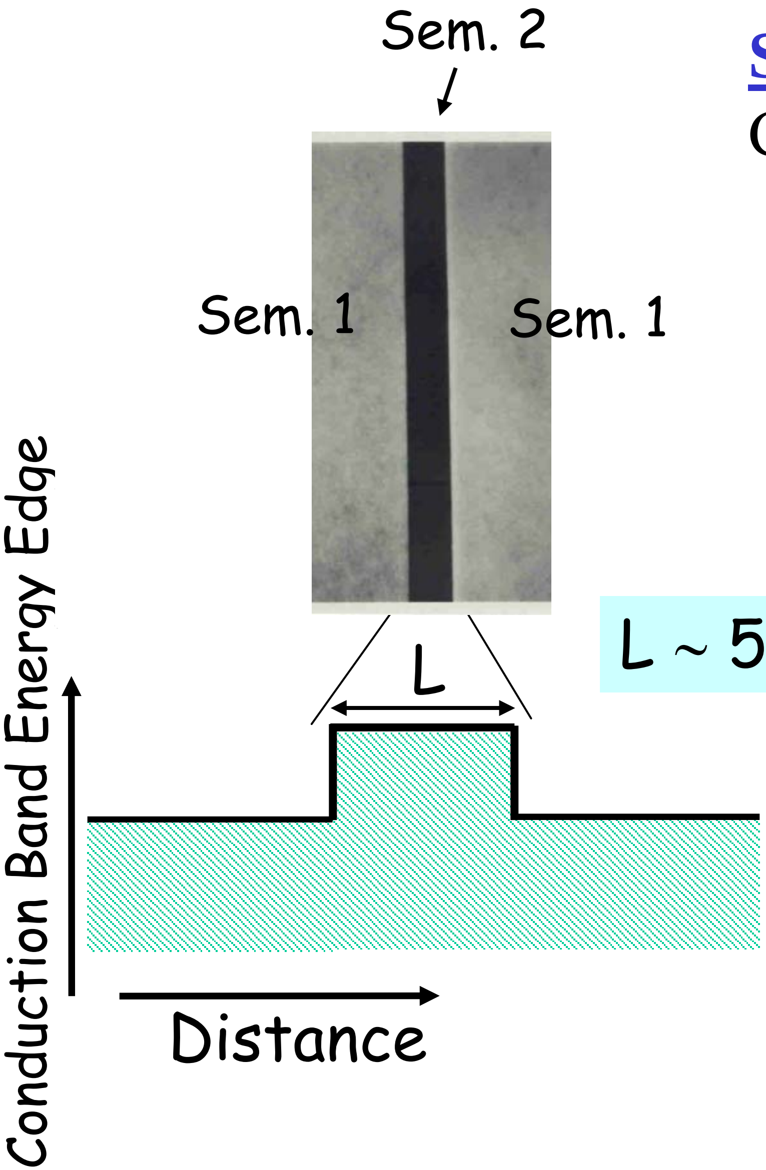
Observation of a quarter of an electron charge at the $\nu = 5/2$ quantum Hall state

M. Dolev[1], M. Heiblum[1], V. Umansky[1], Ady Stern[1] & D. Mahalu[1]



NATURE 452, 829 (2008)

Examples of Shot Noise in Heterostructures

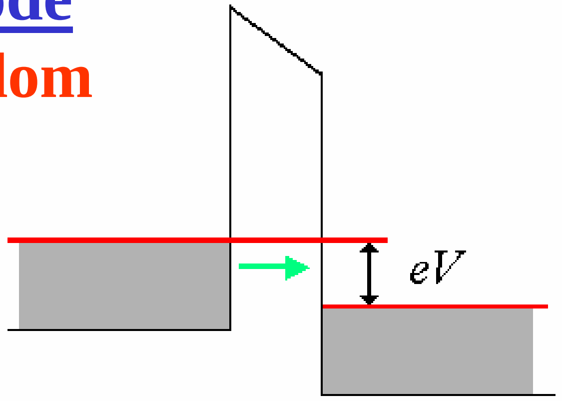


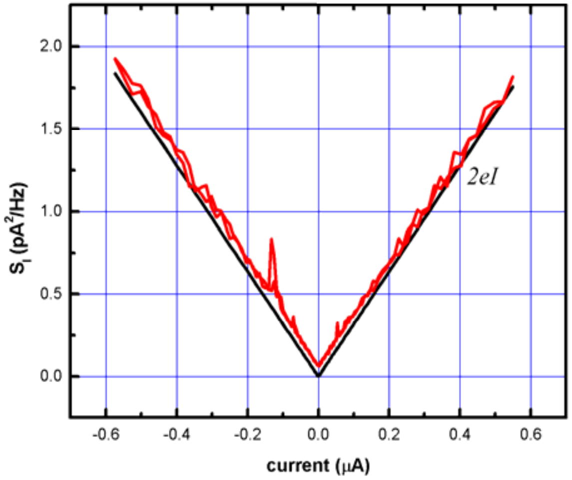
L ~ 5 nm

Single Barrier Diode

Charge flow is **random**

S = 2eI

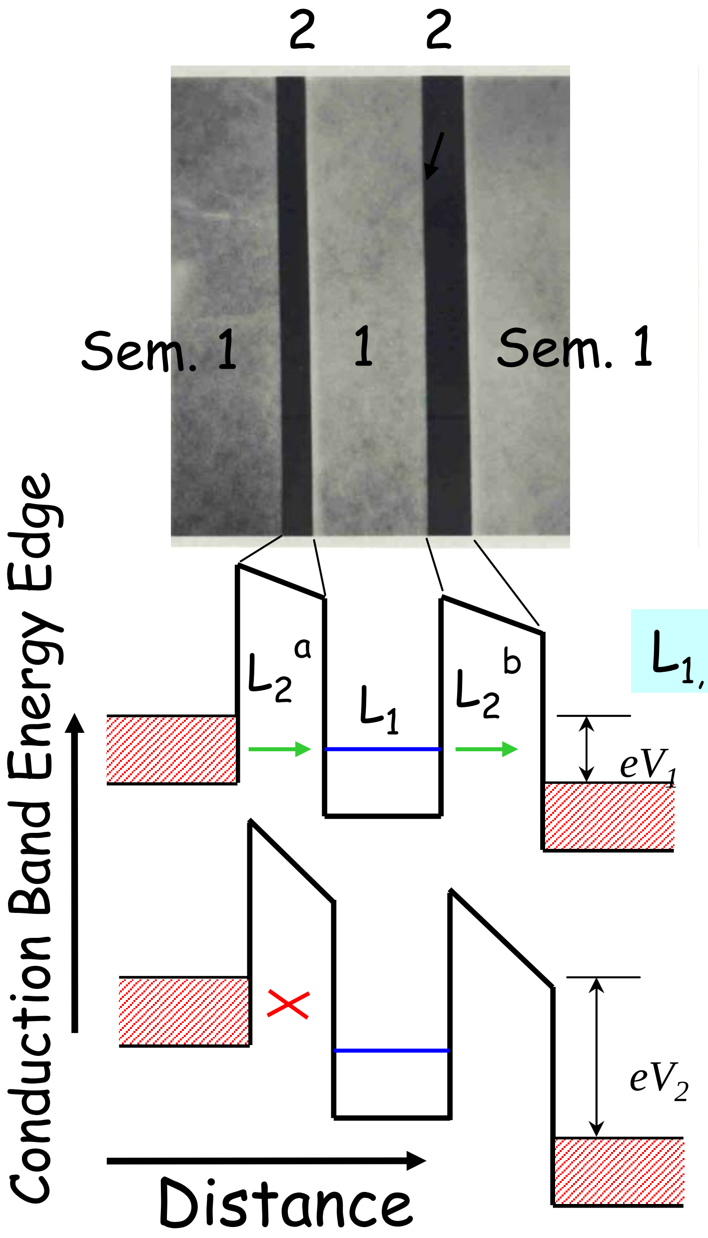


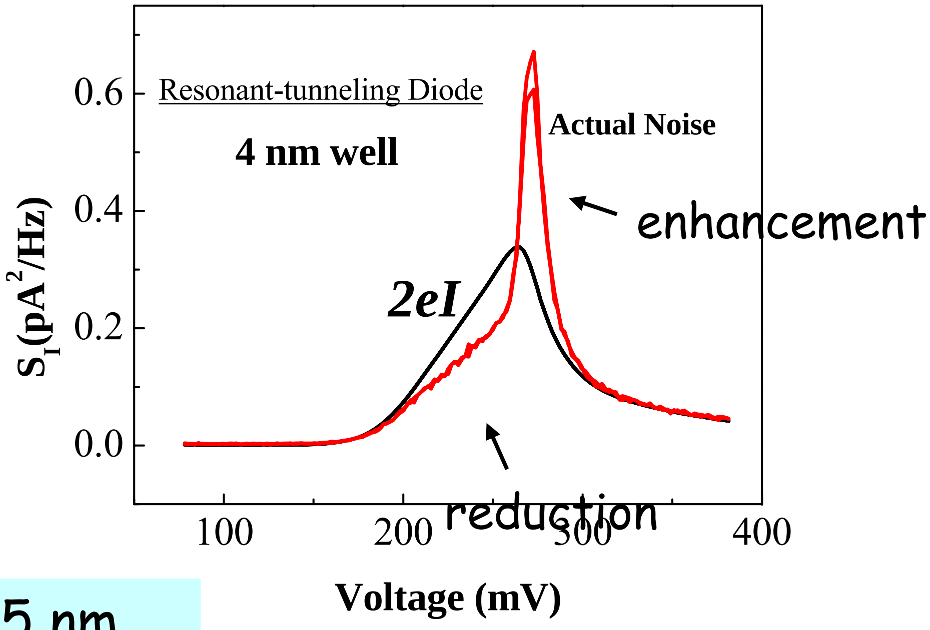


F = 1

$$Fano\ Factor \equiv \frac{S}{2e\bar{I}}$$

Fano Factor in Resonant Tunneling Diodes





$L_{1,2} \sim 5$ nm

Experimentally:

Smallest Fano Factor ≈ 0.7

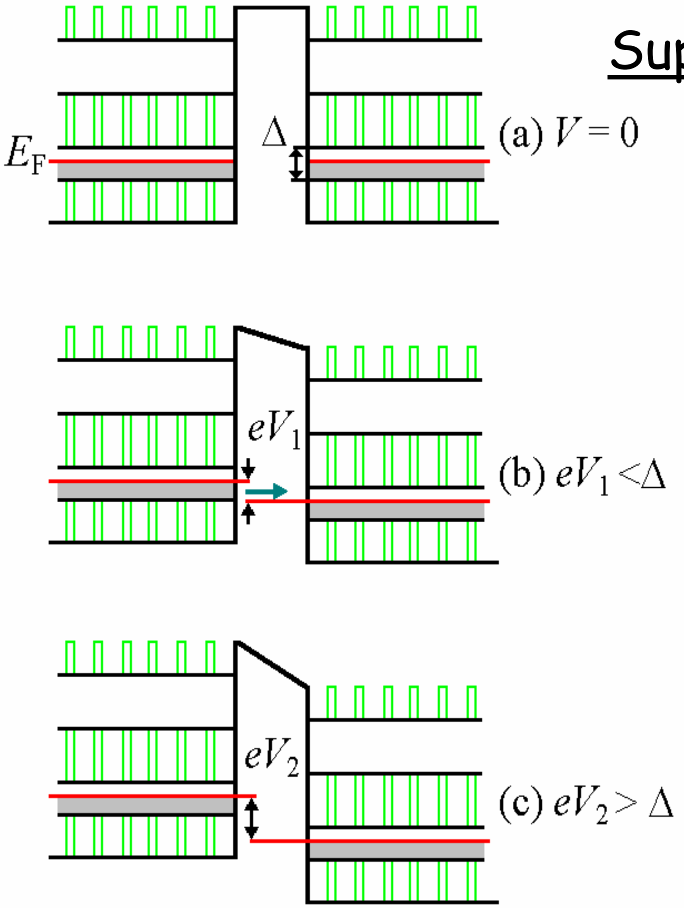
- Fano factor is > **1** in NDC

— correlated electron motion

— negative correlation in PDC region

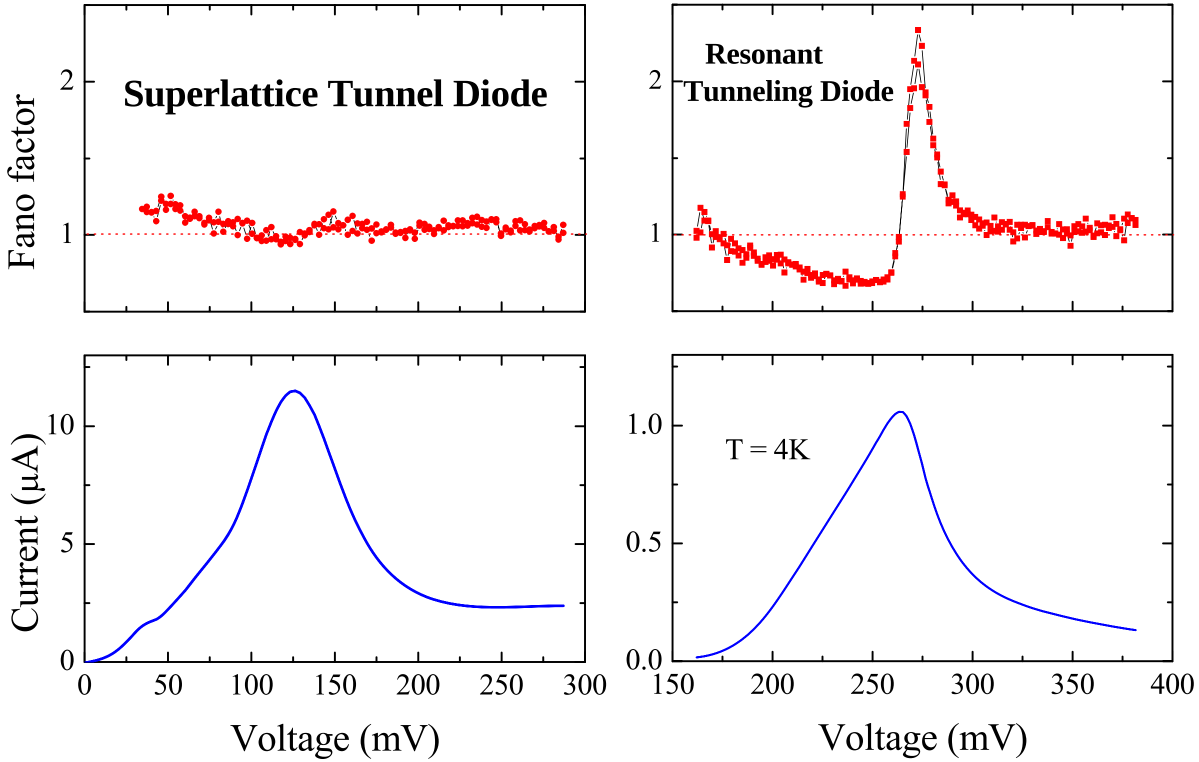
— positive correlation in NDC region

Shot Noise in Superlattice Tunnel Diode



Superlattice tunnel diode Double-barrier diode

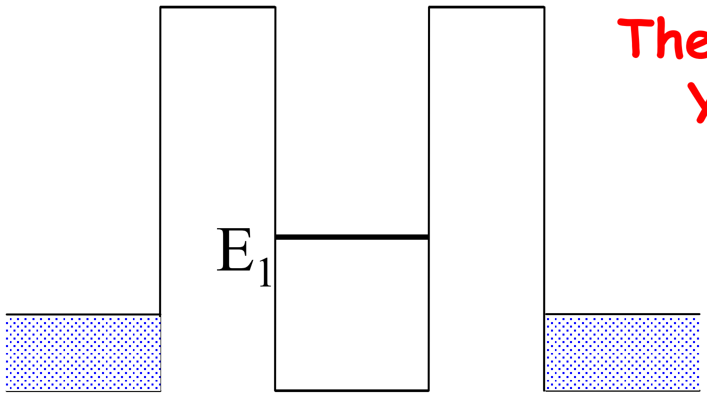
[Song et al., Appl. Phys. Lett. **82**, 1568 (2003)]



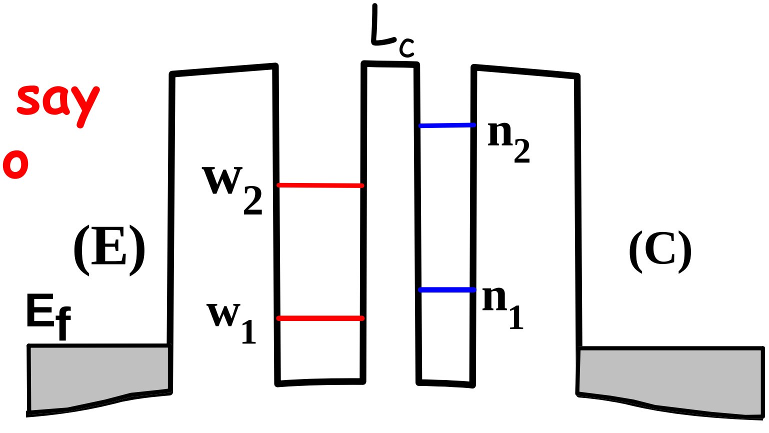
Nanoscale engineering makes it possible to design structures with similar (average) electric behavior but very different noise characteristics

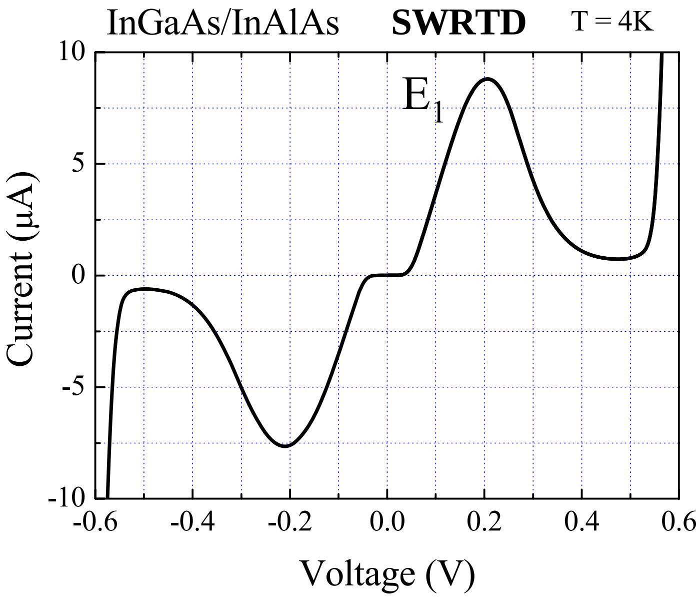
Sequential vs Coherent Tunneling

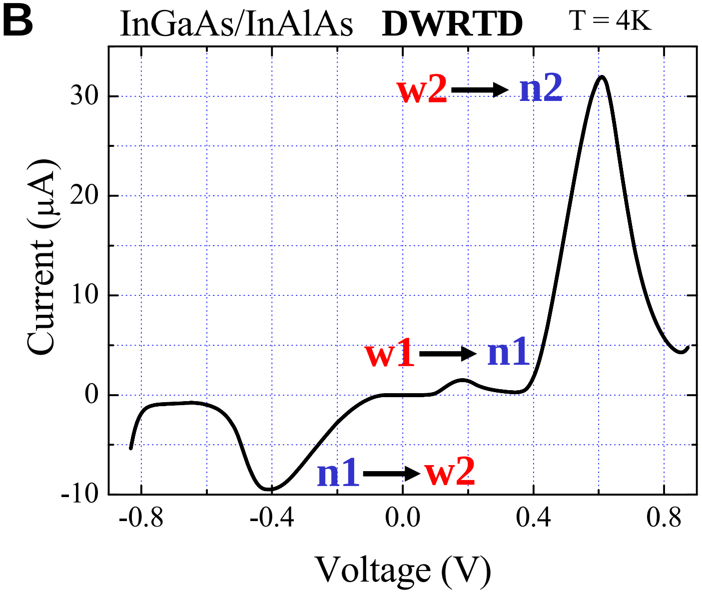
Conductance Cannot Distinguish Between Sequential and Coherent Tunneling. **Can Shot Noise?**



Theories say Yes/No







Shot Noise in N-barrier Systems

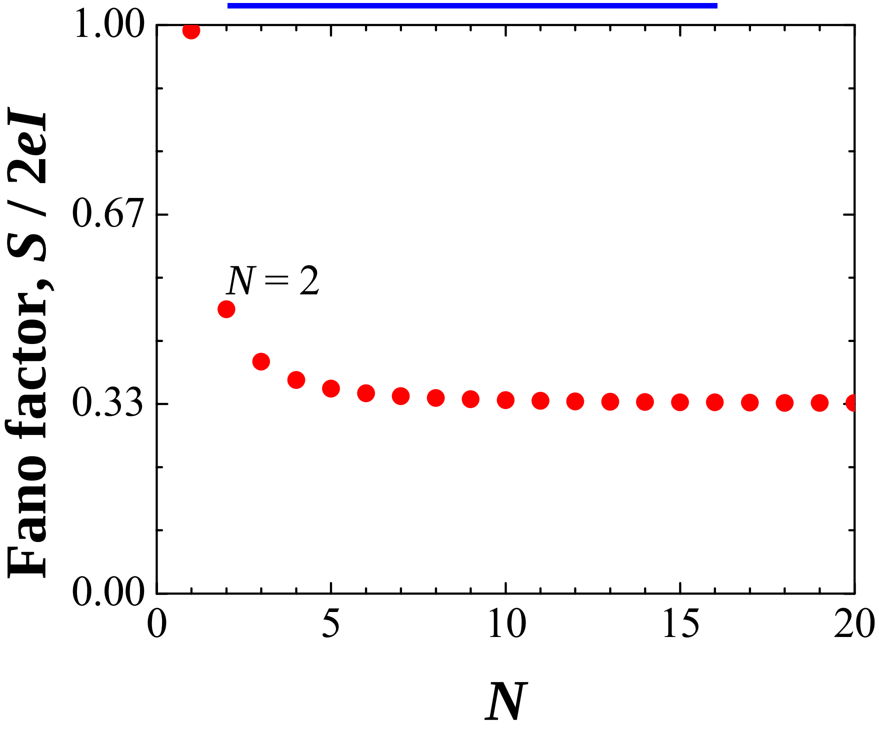
$$S = \frac{1}{3}\left(1+\frac{N(1-\Gamma)^2(2+\Gamma)-\Gamma^3}{\left(\Gamma+N(1-\Gamma)\right)^3}\right)2eI$$

[De Jong and Beenakker,
Phys. Rev. B **51**, 16867 (1995)]

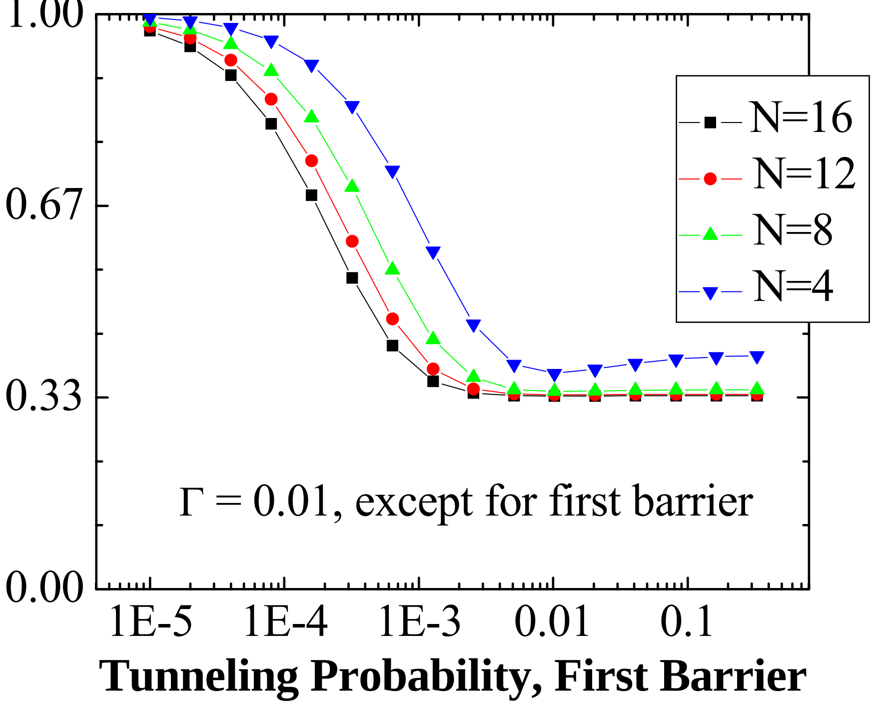
When $N=2$ and $\Gamma \ll 1$, then $S=\frac{1}{2}2eI$

When $N\to\infty$, then $S=\frac{1}{3}2eI$

***N* identical barriers**

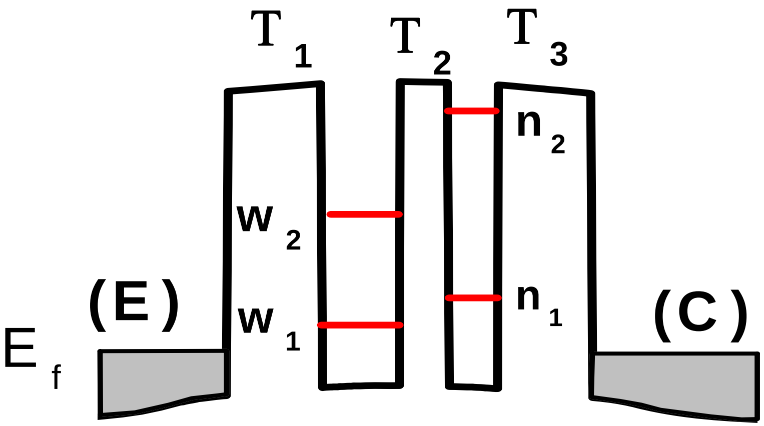


Multiple-barrier Structure



Triple-barrier Resonant-Tunneling Diodes

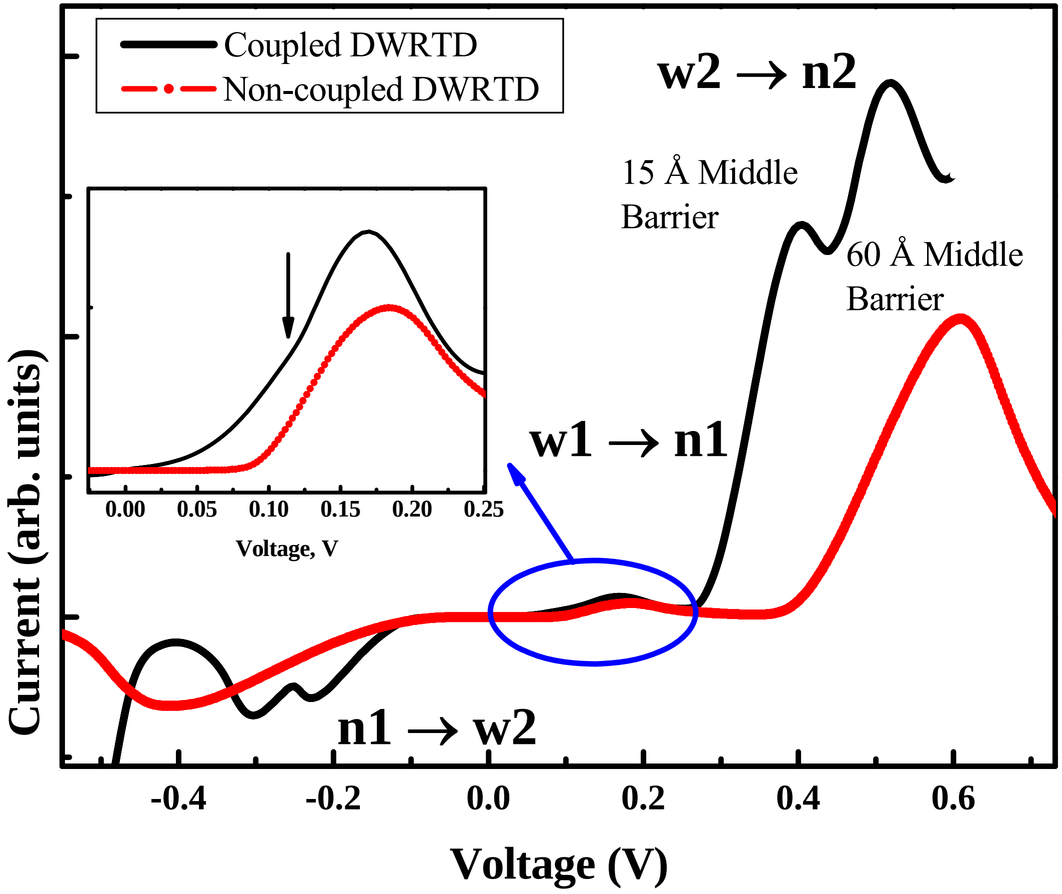
TBRTDs are quite suitable to study the effect of coherence, as interwell coupling can be varied by changing the central barrier thickness.



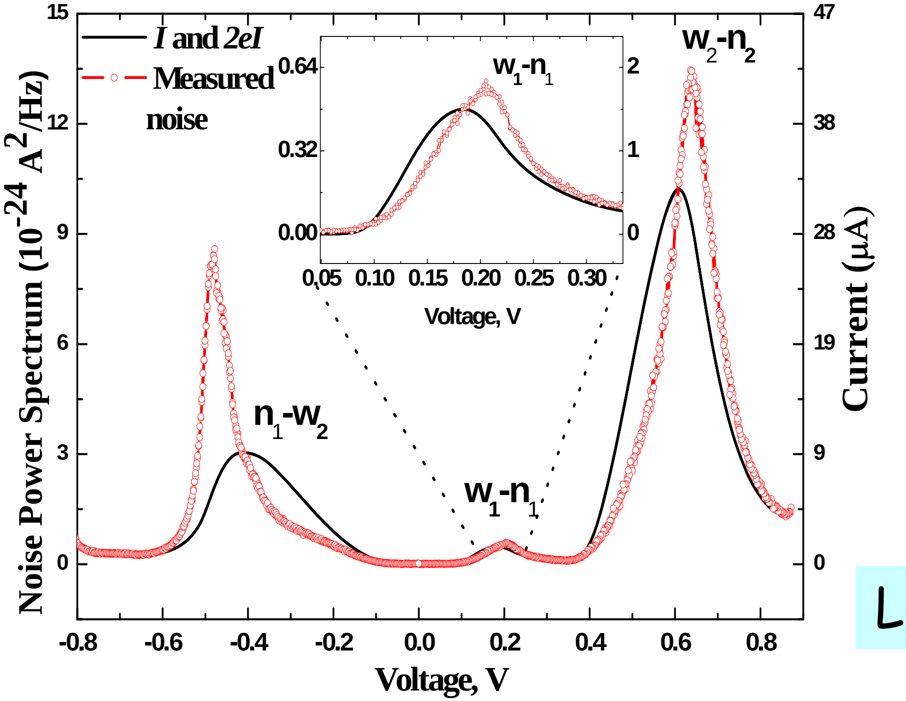
Samples

A) $In_{0.53}Ga_{.0.47}As$ (Well)
$Al_{0.48}In_{0.52}As$ (Barrier)
Middle Barrier 60 Å

B) GaAs (Well)
AlGaAs (Barrier)
Central Barrier
L_c = 6.0 nm, 2.0 nm, 1.5 nm



Noise Characteristics of Non-coupled TBRTD

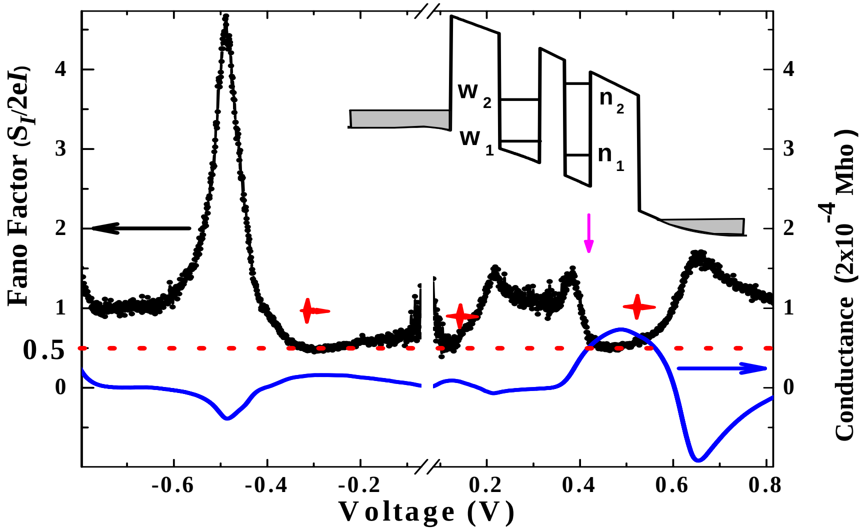


[Newaz et al. , Phys. Rev. B **71**, 195303 (2005)]

Similarities with DBRTDs:

- Poissonian ($S_I=2eI$) at current peak
- Reduced when current rises (PDC region)
- Enhanced in NDC region

L_c = 6.0 nm

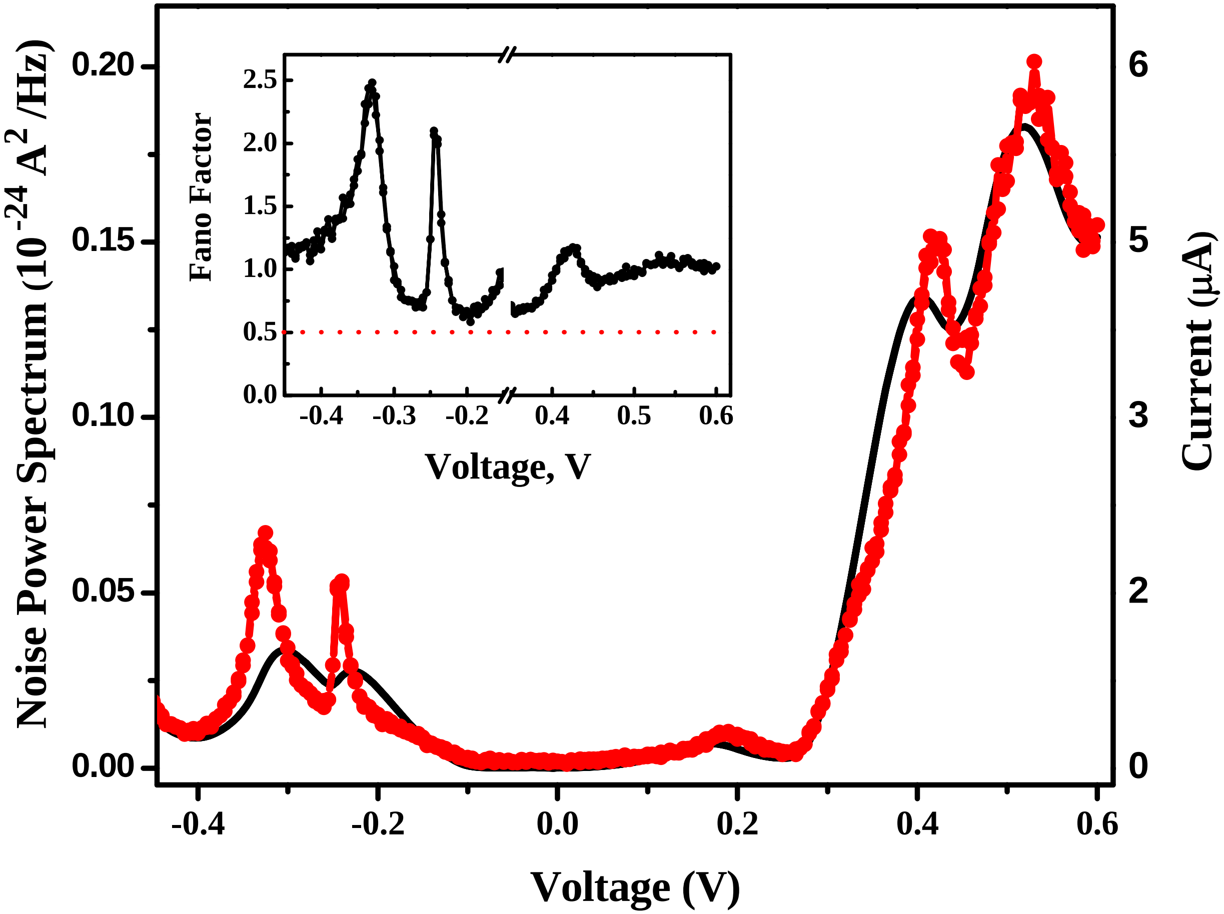


Smallest Fano Factor ≈ 0.5

Differences

- Reduction larger than predicted
- Asymmetric enhancement

Shot Noise in Strongly Coupled DWRTD



Smallest Fano Factor ≈ 0.65

Interwell coupling effectively "eliminates" central barrier (from triple-barrier to double-barrier tunneling)

New Directions

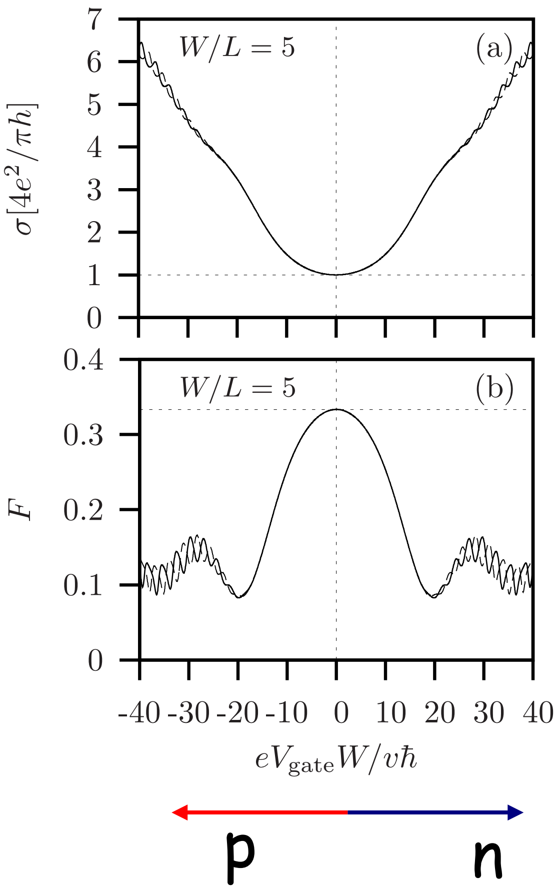
→ Shot Noise in Graphene

Theory

Ballistic: W/L > 4 F = 1/3 to 0.1

W/L ~ 1 F ~ 1 or ~ 0

Diffusive: F ≈ 0.30



(Tworzydlo et al. PRL **96**, 246802 (2006))

Experiment

- Danneau et al., PRL **100**, 196802 (2008)

  W/L = 24 F ≈ 0.34 to 0.20, depending on n

  W/L = 2 F ≈ 0.19

  ballistic transport? but F is too large …

- Di Carlo et al., PRL **100**, 156801 (2008)

  F ~ 0.35 – 0.37, regardless of W/L or n

  diffusive transport? but F is too large …

→ Graphene Nanoribbons

hopping conductance? no noise experiments yet

Main Points

Shot-noise measurements in low-dimensional systems

- yield effective charge in interacting electron phenomena (e.g., FQHE)
- elucidate electron transport mechanisms.

In resonant tunneling devices,
shot noise is reduced or enhanced (relative to Poissonian noise)
depending on nature of electronic correlation.

Shot noise allows to discriminate between different transport
mechanisms that nevertheless produce same I-V characteristics.

Shot noise (possibly) cannot discriminate between
sequential and coherent tunneling.

Shot noise is helping to understand electronic transport
in graphene.

In molecular electronics, shot noise measurements could
help elucidate electron transport – but experiment
is far from trivial.