# Electronic noise measurements as a tool for characterisation of physical processes in semiconductor heterostructures

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## *Abstract:*

Nowadays semiconductor heterostructures and devices become smaller and smaller. Therefore electronic transport properties of small electronic systems are substantially influenced by stochastic processes related to thermal agitation and quantum transitions of electrons and quasiparticles.
The purpose of this presentation is to familiarize our semiconductor community with electronic noise measurements as a method for characterisation of physical processes in semiconductor heterostructures.
"The noise is the signal" (R. Landauer) and - moreover - **there is a signal in the noise**, which is absent in time-avereged value of the physical quantity; especially for nonequilibrium processes like e.g. electron transport through tunneling barrier.


## *Fluctuations (noise):*

spontaneous, random (stochastic) deviations from the time-average of the physical quantity. They manifest a thermal agitation and quantum (discrete) nature of matter (charge, spin, etc...).

## *Power SpectrumDensity (PSD) of fluctuations*

$$\widetilde{X}(\omega)=\int_{-\infty}^{\infty}x(t)e^{-i\omega t}dt$$ Fourier transform of the measured signal $x(t)$, units: V/Hz, A/Hz, etc.

$$x(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\widetilde{X}(\omega)e^{i\omega t}d\omega$$ real signal $x(t)$, units: V, A, etc.

$$W=\int_{-\infty}^{\infty}x^2(t)dt=\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|\widetilde{X}(\omega)\right|^2d\omega$$ total „energy" of the signal $x(t)$; units V²/Hz, A²/Hz,

$$S_{xx}(\omega)=\frac{1}{2\pi}\lim_{T\to\infty}\frac{\left|\widetilde{X}(\omega)\right|^2}{2T}$$ Power Spectrum Density (PSD), units: V²/Hz, A²/Hz, etc or RMS: $\frac{V}{\sqrt{Hz}},\frac{A}{\sqrt{Hz}}$ where $2T$ is the time interval for Fourier transform, where the signal is not equal zero.

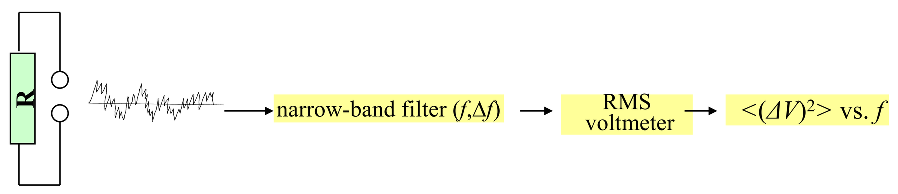
$$P=\left\langle x^2(t)\right\rangle=\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T}x^2(t)dt=\int_{-\infty}^{\infty}\lim_{T\to\infty}\frac{1}{2\pi}\frac{\left|\widetilde{X}(\omega)\right|^2}{2T}d\omega=\int_{-\infty}^{\infty}S_{xx}(\omega)d\omega$$ total „power" of the signal

## *Thermal Noise*

**Origin:** thermal movement of electrons

**PSD:** $S(f)=4kTR$ (V²/Hz), white noise for $f < kT/h$

**Observation**



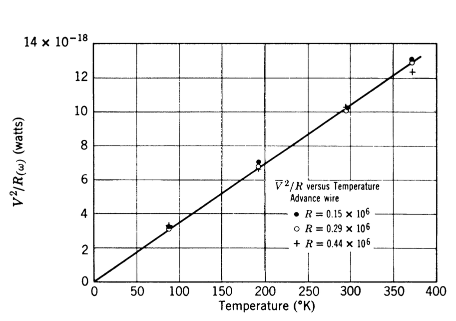




*Fig. 23.3.* Apparent power versus temperature for various resistors, as observed through a band pass filter of width of 1000 cycles at room temperature. The graph permits a direct determination of Boltzmann's constant (after J. B. Johnson).

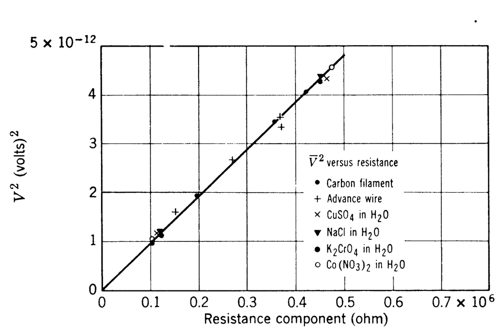



*Fig. 23.2.* Experimental plot of noise mean square voltage versus resistance in various resistors at fixed temperature and band width (after J. B. Johnson).

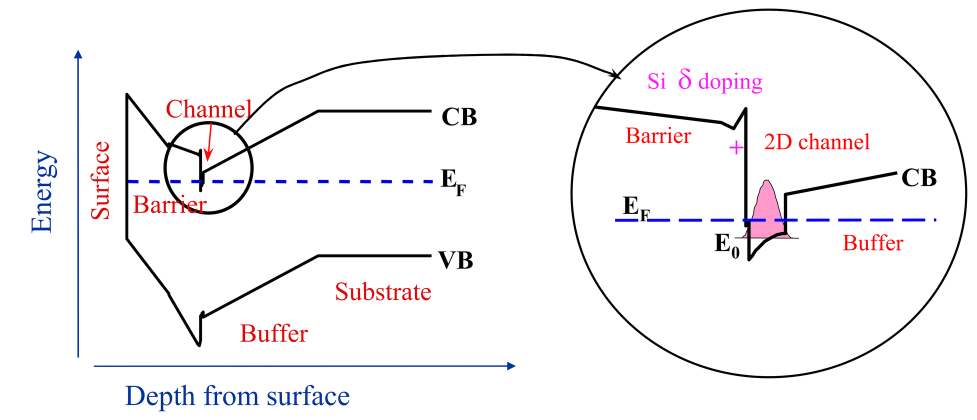
J.B. Johnson *Phys. Rev.* **32**, 97 (1928) taken from G.H. Wannier, *Statistical Physics*, Dover Publications, Inc., New York, 1966

## *Fluctuation - Dissipation Theorem (Nyquist 1928, Callen, Welton 1951)*

$$S_I^{\mathrm{int}}(f)=4k_BT\,\mathrm{Re}\,Z^{-1}(f)$$
$$S_U^{\mathrm{int}}(f)=4k_BT\,\mathrm{Re}\,Z(f)$$

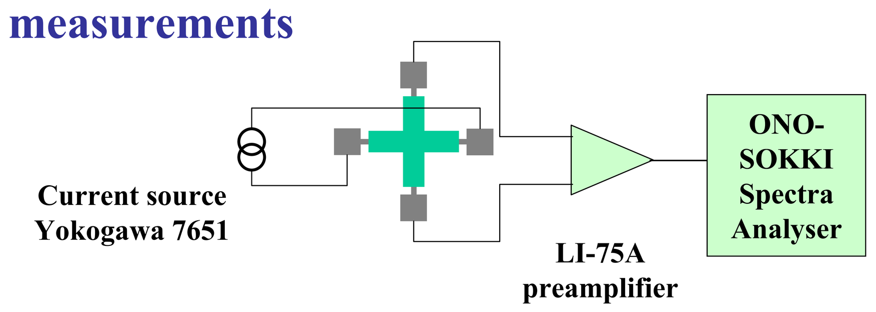
The spectral density of fluctuations in the system in equilibruim and the respose of the physical system to the small external perturbation are governed by the same kinetic processes.
Basing on F-D Theorem one can independently determine (using noise measurements) the kinetic coefficients (e.g. conductivity).

## Generation-Recombination Noise in Hall effect magnetic sensors based on GaAlAs/InGaAs/GaAs pseudomorfic heterostructure with 2DEG




Band diagram of a pseudomorphic AlGaAs/InGaAs/GaAs heterostructure with delta-doping and graded barrier.

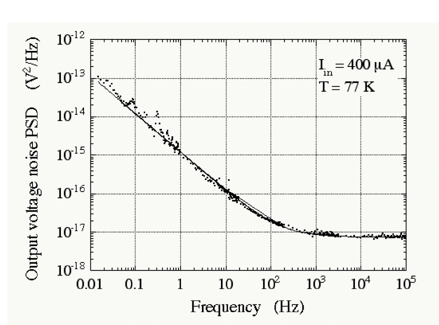
### Noise measurements




The PSD of the voltage noise has been measured on signal contacts of the Hall cross-shaped samples under current polarisation.

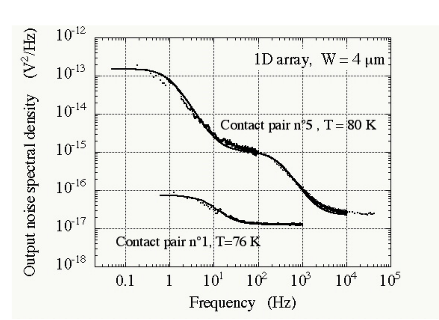
## Low Frequency noise due to continuum of surface states

Low-frequency 1/*f* noise

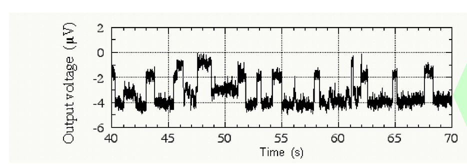



Low temperature voltage noise. Dots are experimental, the full line is calculated as the sum of thermal noise $4kTR$ plus 1/f noise. The bias current $I_{in}$ amounts to 400 µA.

Random Telegraph Signal

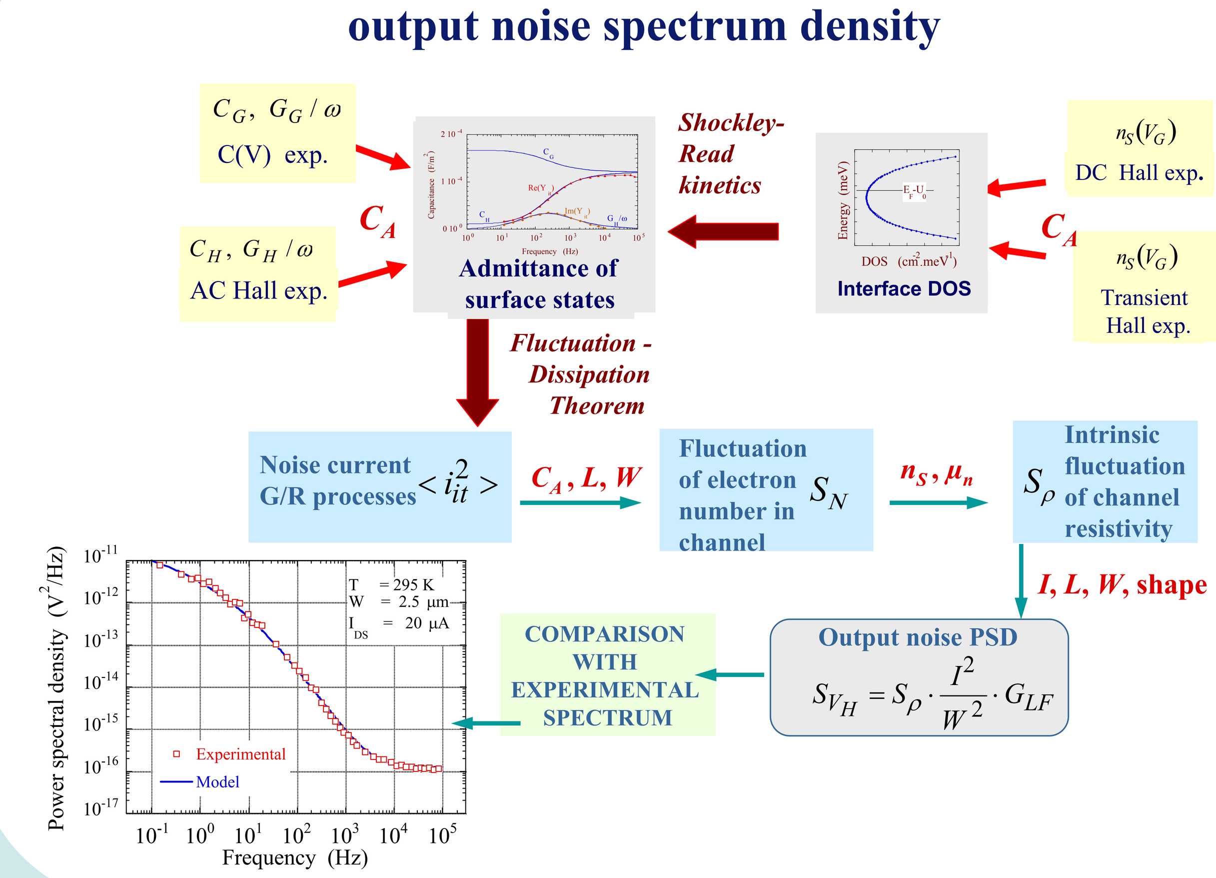



Output noise PSD for two different Hall outputs of the same 1D–array device, under a biasing current of 200 µA. Dots are experimental, full lines are models taking into account the thermal noise 4 *kTR* plus one (n°1) or two (n°2) lorentzian components. Bottom: for a "quiet" Hall output at T=76 K (SVlor=6×10-17 V2/Hz, cut off frequency fc = 8 Hz). Top: for a neighbor, more noisy Hall output at T=80 K (SVlor1=1.5×10-13 V2/Hz, SVlor2=10-15 V2/Hz, fc1 = 1 Hz, fc2 = 300 Hz. For output n°1, the noise voltage is so low at 1 Hz and lower, that noise measurements are disturbed by the LF noise of the preamplifier.




RTS signals recorded at the Hall output of a 1D array of sensors with *W*=4 µm at temperature 62 K. The bias current is 200 µA. Two different predominant RTS fluctuators can be recognized at 62 K.

## Procedure for the calculation of the output noise spectrum density




### Conclusions (G-R Noise)

- The predominant source of LF-noise in GaAs based quantum well Hall effect sensors depends on the operating temperature.
- For RT operation, it is the conductivity fluctuation due to the equilibrium generation-recombination on interface states at the surface of GaAs. The broad noise spectrum, with an intermediate form between lorentzian and pure 1/f form, is due to the continuous distribution of the energy of the interface states.
- At lower temperature, the activated transitions responsible for this noise freeze out, and a noise source linked to generation/recombination on traps in the vicinity of the 2D channel becomes the dominant one.
- For larger devices, the LF low-temperature noise appears as a true 1/*f* noise, whereas for micrometer size devices it resolves into discrete RTS signals originating in discrete fluctuators. In Hall crosses with an arm width of 4 µm, we find at 77K less than 1 fluctuator per each decade of the time constant. As expected, there is a general tendency of an increase of the noise voltage with decreasing Hall sensor dimensions. However, this tendency breaks down when the dimensions of the active layer are so small that the discrete RTS fluctuators become the dominant source of noise. Indeed, some 4×4 µm2 Hall crosses have less noise at 1 Hz than much larger 60×60 µm² sensors.


### References

1.J. Przybytek, V. Mosser, Y. Haddab, LF noise in cross Hall effect devices - geometrical study Proceedings of SPIE - Noise in Devices and Circuits, Santa Fe, New Mexico, USA 2003, ed. M.J. Deen, Z. Celik-Butler, M.E. Levinshtein, SPIE Publishing, 5113 (2003) 475-483
2.V. Mosser, G. Jung, J. Przybytek, M. Ocio,Y. Haddab, Low-frequency noise in AlGaAs/InGaAs/GaAs Hall micromagnetometers - Proceedings of SPIE - Noise and Information in Nanoelectronics, Sensors, and Standards, Santa Fe, New Mexico, USA 2003, ed. L.B. Kish, F. Green, G. Iannaccone, J.R. Vig, SPIE Publishing, 5115 (2003) 183-195


## Quantum Shot Noise

**Shot noise**
- consequence of the quantization of charge;
- can be used to obtain information on a system which is not available through conductance measurements;
- shot noise experiments can determine the charge and statistics of the quasiparticles relevant for transport;
- is generally more sensitive to the effects of electron-electron interactions than the average conductance.

$$\langle I\rangle=\frac{2e^2}{h}V\sum_{n=1}^{N}T_n$$ **Landauer formula** $\frac{2e^2}{h}$ conductance quantum, $T_n$ transmissin probability of the channel $n$

$$S=2e\frac{2e^2}{h}V\sum_{n=1}^{N}T_n(1-T_n)$$

PSD of the current through a single barrier, randomization introduced by transmission probability $$S_I(f)=\frac{\langle(\delta I)^2\rangle}{\Delta f}=2e\langle I\rangle(1-T)$$

***T*=1** → no shot noise

***T*<<1** → full shot noise (Poissonian) **(Schottky, 1918):** $S_I=2e\langle I\rangle$

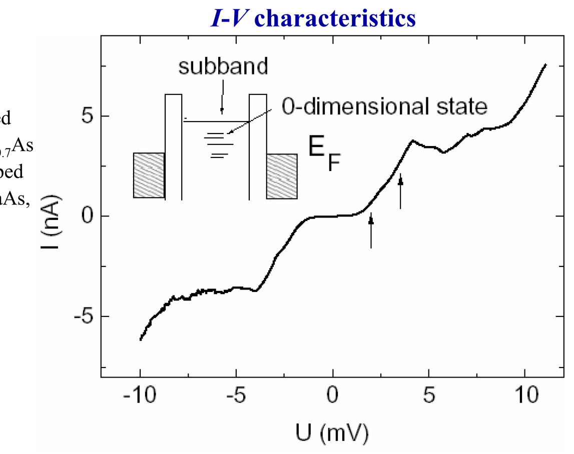
*0<T<1* ***intermediate situation,*** **reduction of noise by Fano factor** $F\equiv\alpha\equiv\frac{S_{real}}{2e\langle I\rangle}$

## Shot noise in tunneling through single localized states

A. Nauen , J. Koenemann, U. Zeitler, F. Hohls, R.J. Haug, *Physica* E 12 (2002) 865

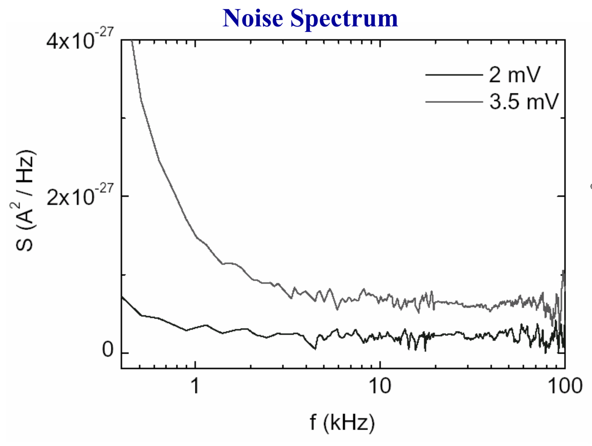
**DBRTS**
1µm diameter
***QW:*** 10 nm GaAs, undoped
***barriers:*** 5 i 6 nm $Al_{0.3}Ga_{0.7}As$
***contacts:*** Si $4\cdot10^{17}cm^{-3}$ doped
***spacers:*** 7 nm undoped GaAs,

***I-V*** **characteristics**



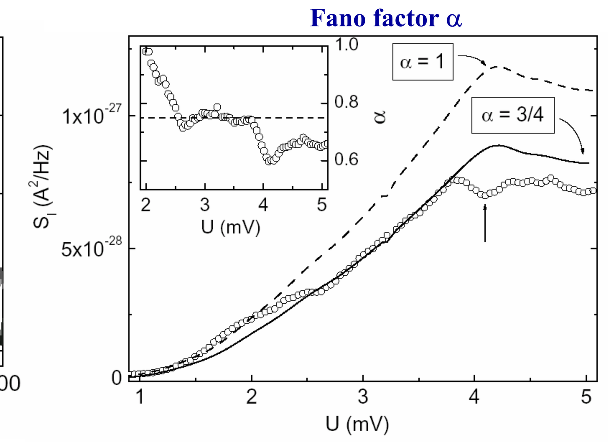

*I-V* characteristics of the sample in the single electron tunneling regime at *T*=1.3K. The steps in the curve are fingerprints of zero-dimensional impurities between the barriers. The arrows indicate to the voltage positions where we show the corresponding spectra in Fig. on the right side. Inset: schematical view of the electronic structure of the sample. From A. Nauen , J. Könemann, U. Zeitler, F. Hohls, R.J. Haug, *Physica* E 12 (2002) 865

**Noise Spectrum**




Noise spectra of the DBRTS at different bias voltages. At frequencies 20kHz the data have been smoothed using a boxcar average to compensate for the degrading signal-to-noise ratio at high frequencies due to capacitive loading of the current amplifier. From A. Nauen , J. Könemann, U. Zeitler, F. Hohls, R.J. Haug, *Physica* E 12 (2002) 865

**Fano factor α**




The noise power of the sample in the single electron tunneling regime at *T* = 1.6 K. The open circles represent the average noise power between 40 and 100 kHz. The plot has been smoothed using a five-point boxcar average. The dashed lines represent the theoretically calculated shot noise for α = 1, the straight line for a suppression of α = 0.75. The arrow indicates the voltage position where α reaches a value of 0.6. Inset: corresponding Fano-factor α. From A. Nauen , J. Könemann, U. Zeitler, F. Hohls, R.J. Haug, *Physica* E 12 (2002) 865

**„Fano spectroscopy"**

**α=1** for *U*<2mV effectively single barrier, impurities do not participate in tunneling process

**α=3/4** for 2.5 mV<*U*<3.8 mV - transport through many impurities randomly distributed in space and in energy (Y.V. Nazarov, J.J.R. Struben, Phys. Rev. B 53 (1996) 15466)

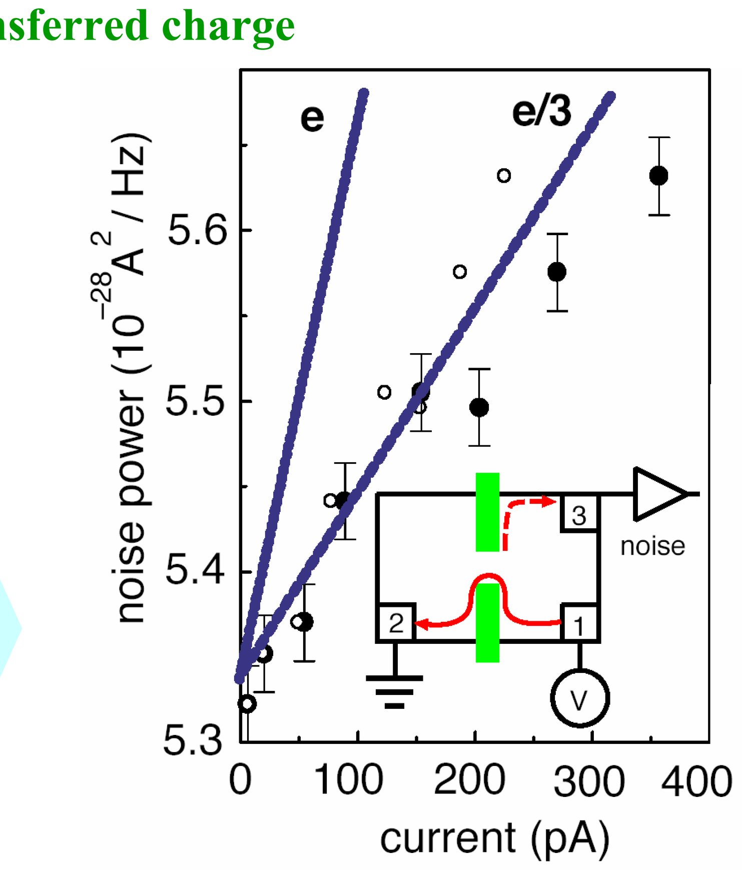
**α=0.6** for *U*>3.8 mV slight assymetry of the barriers (α=0.5 for symmetric barriers), tunneling transport through **a single impurity**

## Measuring the unit of transferred charge

In the regime of the fractional quantum Hall effect the tunneling from one edge of a Hall bar to the opposite edge proceeds in units of a fraction $q = e/(2p + 1)$ of the elementary charge (R. Laughlin theory). The integer $p$ is determined by the filling fraction $p/(2p + 1)$ of the lowest Landau level.
Independently, two groups (Ch.Glattli *et al.* and M.Reznikov) have measured Fano factor F = 1/3 in the fractional quantum Hall effect (see Figure).

Current noise for tunneling across a Hall bar on the 1/3 plateau of the fractional quantum Hall effect. The slopes for *e*/3 charge quasiparticles and charge *e* electrons are indicated. The data points with error bars (from the experiment of Saminadayar et al.) are the measured values at 25 mK, the open circles include a correction for finite tunnel probability. The inset shows schematically the setup of the experiment. Most of the current flows along the lower edge of the Hall bar from contact 1 to contact 2 (solid red line), but some quasiparticles tunnel to the upper edge and end up at contact 3 (dashed). The tunneling occurs predominantly at a narrow constriction, created in the Hall bar by means of a split gate electrode (shown in green). The current at contact 3 is first spectrally filtered, then amplified, and finally the mean squared fluctuation (the noise power) is measured.

Taken from Carlo Beenakker, Christian Schönenberger, *Physics Today*, May 2003, page 37 (also at http://www.lorentz.leidenuniv.nl /beenakkr/ mesoscopics/ topics/noise/physics_today_2003.pdf).
L. Saminadayar, D.C. Glattli, Y. Jin, and B. Etienne,
*Phys. Rev. Lett.* **79**, 2526 (1997).




### Conclusions (Shot Noise)

**Shot noise**
- can be used to obtain information on a system which is not available through conductance measurements;
- shot noise experiments can determine the charge and statistics of the quasiparticles relevant for transport;
- is generally more sensitive to the effects of electron-electron interactions than the average conductance.

## Conclusion (General):

**There is the signal in the noise !**


### References

1. *Ya.M. Blanter, M. Büttiker,* Shot Noise in Mesoscopic Conductors, *Physics Reports* **336** (2000) 1-166,
2. Sh. Kogan, Electronic Noise and Fluctuations in Solids, Cambridge University Press 1996