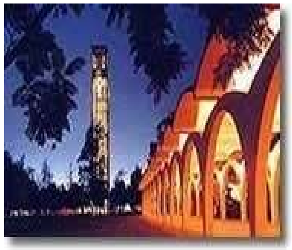
Low-Frequency Current Fluctuations in Graphene: 1/*f* Noise and Beyond



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Graphene Week 2014

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Outline

- → Introduction
  - → Why low-frequency noise is important
  - → Graphene device applications and noise
- → Noise Experiments with Graphene
  - → Graphene under irradiation
  - → Graphene multilayers
  - → Noise origin in graphene
- →Selective Graphene Sensors
  - → selectivity without functionalization
- → Conclusions

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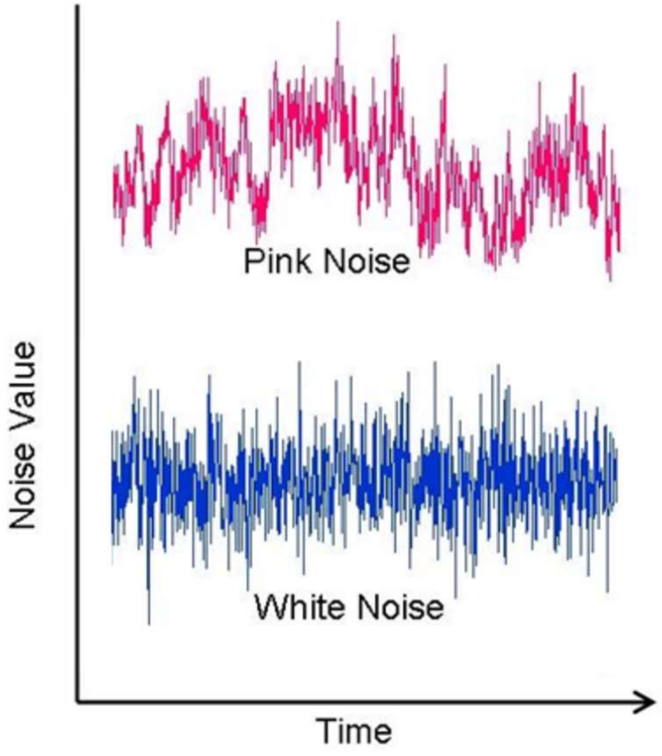
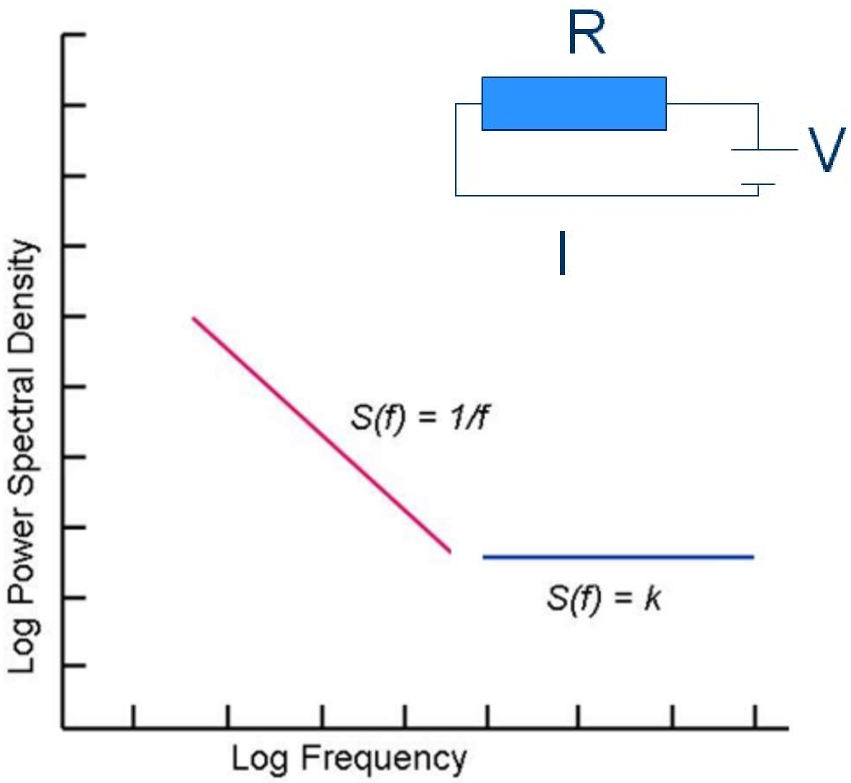
Low-Frequency Flicker Noise





Discovered in vacuum tubes - J. B. Johnson, Phys. Rev. 26, 71 (1925).

Fundamental Types of Electronic Noise

Electronics: noise is a random fluctuation in an electrical signal characteristic for all electronic devices.

Different Types of Intrinsic Electronic Noise:

Thermal noise:

$S_I = 4k_B T/R$

Shot noise:

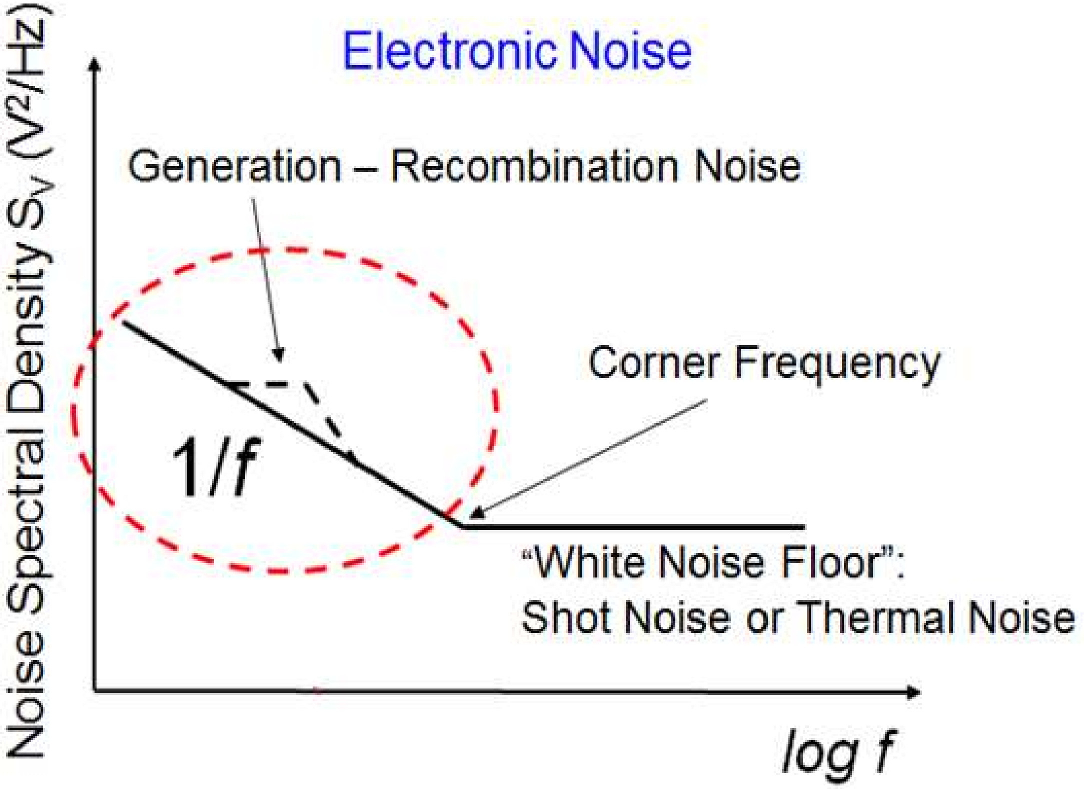
$S_I = 2e\langle I \rangle$

G-R noise:

$S_I \sim 1/(1+f^2\tau^2)$

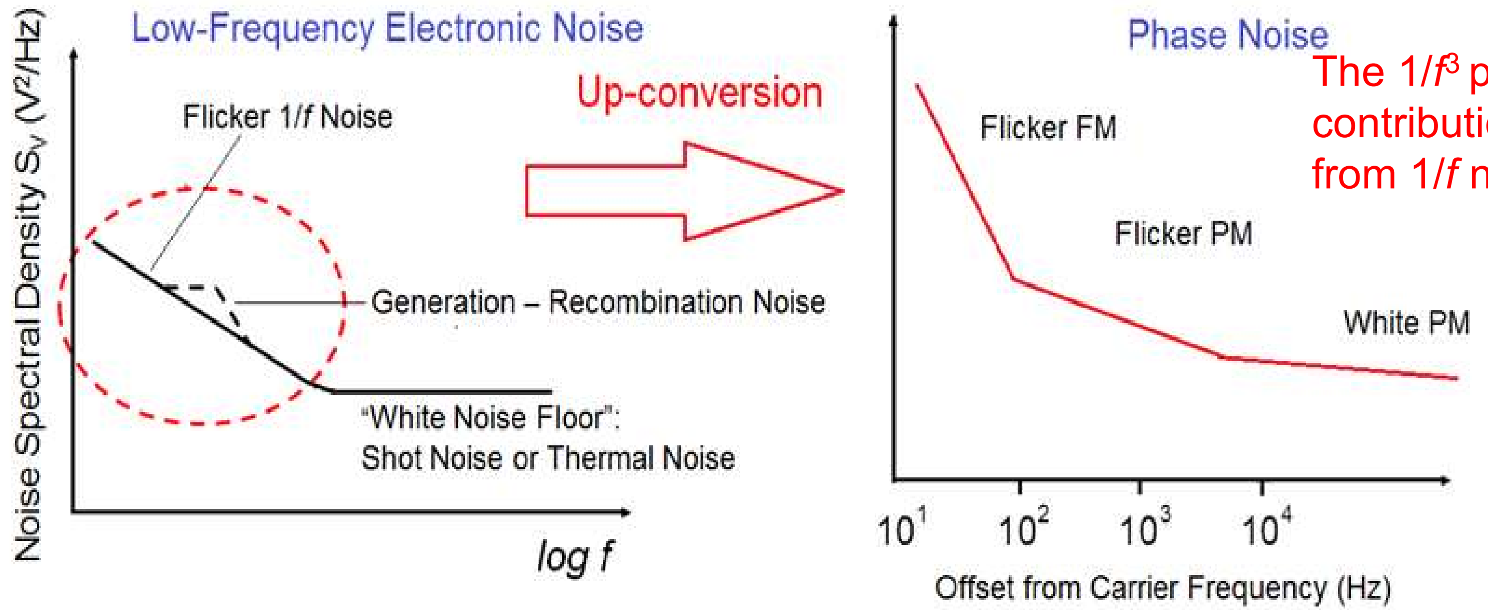
Flicker 1/f noise:

$S_I \sim I^2/f$



See A.A. Balandin (Ed.), *Noise and Fluctuations Control in Electronic Devices* (ASP, 2002).

Importance of 1/*f* Noise Reduction for Graphene: Sensors and Communications



The $1/f^3$ phase noise contribution comes from 1/*f* noise

$$E = \int (1/f^{\gamma})^2 df$$

→ The energy of 1/f noise increases as the measurement T (~1/*f*)

→ One cannot improve the signal-to-noise ratio by extending T

Communication systems: noise is an error or undesired random disturbance of a useful information signal introduced before or after the detector and decoder.

Low Frequency Noise as a “Show Stopper”

→ Non-linearity leads to 1/f noise up-conversion and contributions to the phase noise of the system

→ Device downscaling results in a higher noise spectral density

→ Gate current contribution to noise may become important

→ 1/f noise limits sensors’ sensitivity

→ Large device-to-device variations in noise

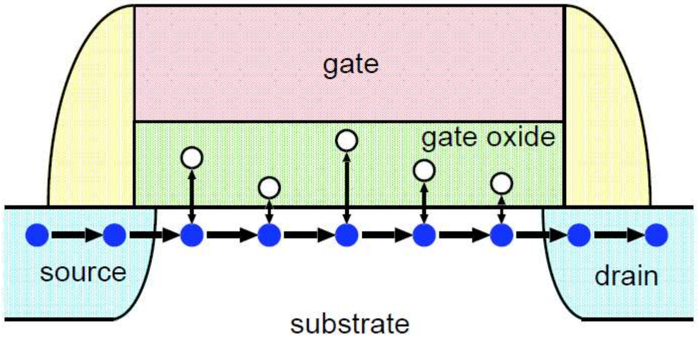
→ Graphene and thin films of van der Waals materials can be more susceptible to noise because they are flat surfaces exposed to traps in oxides.

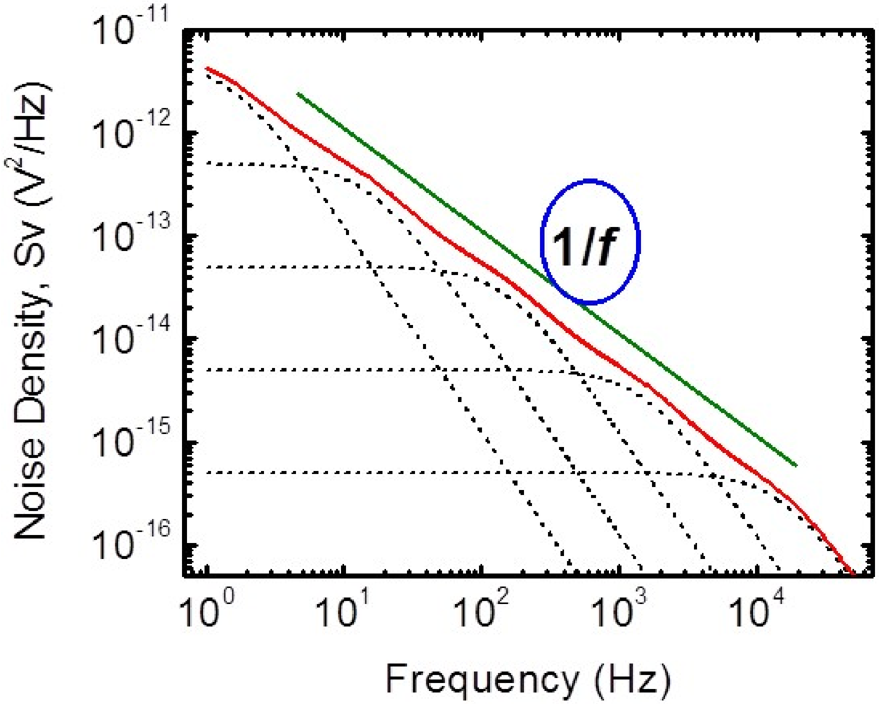
USEFUL 1/f NOISE: characterization tool to understand trap dynamics and electron transport in a given materials system

Physical Mechanism of 1/*f* Noise in Electronic Materials and Devices

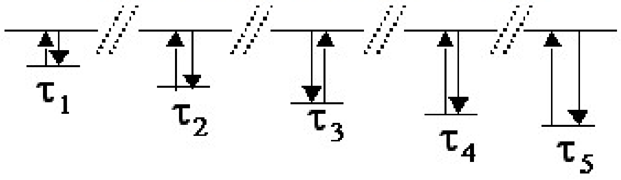
$$I \sim qN\mu$$

$$\delta I \sim q(\delta N)\mu + qN(\delta\mu)$$





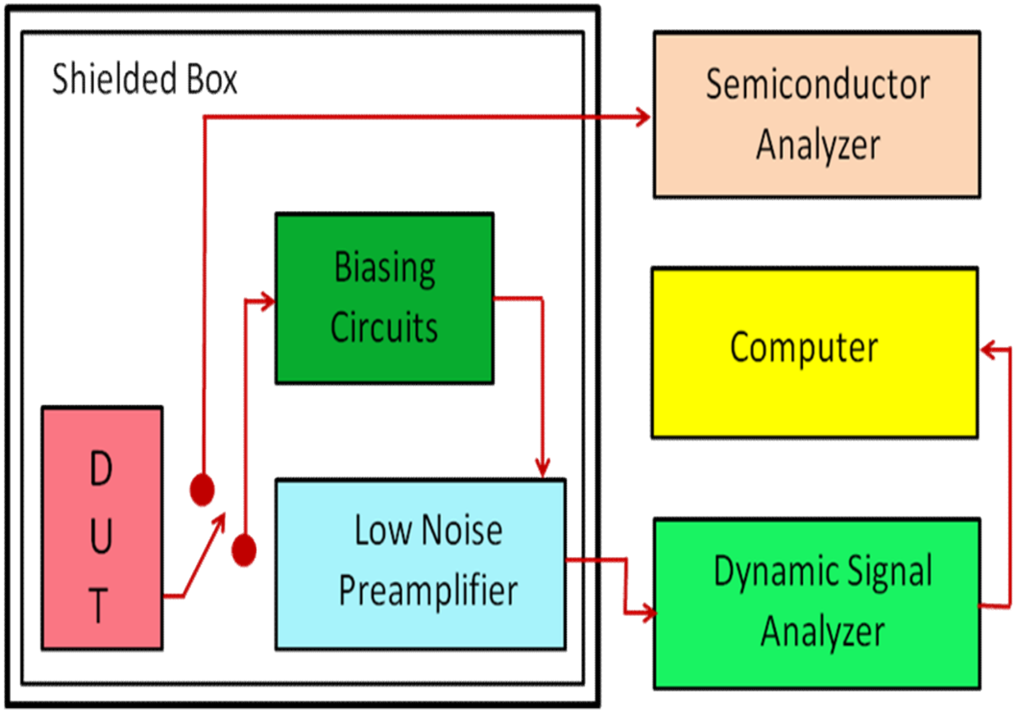
Series of levels

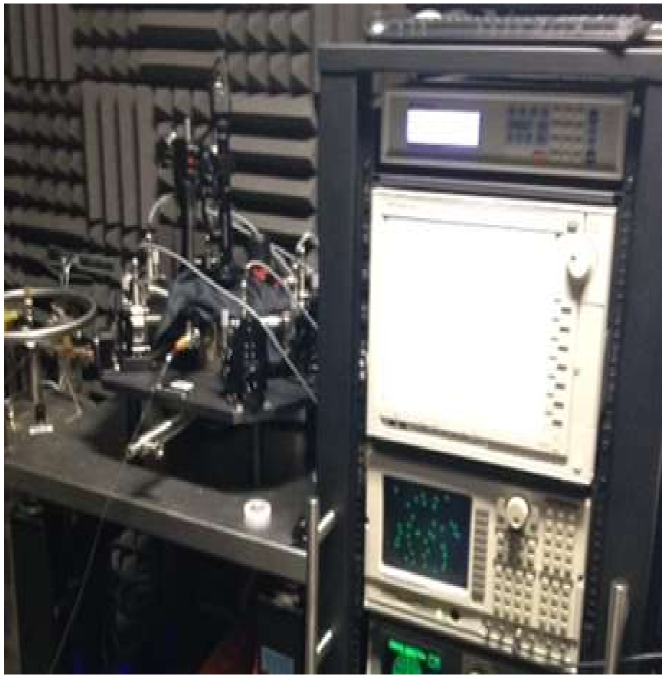


McWhorter's model: $g(\tau_N) = [\tau_N \ln(\tau_2/\tau_1)]^{-1}$

$$S_N(\omega) = 4\overline{\delta N^2}\int_{\tau_1}^{\tau_2} g(\tau_N)\frac{\tau_N}{1+(\omega\tau_N)^2}\,d\tau_N$$

Low-Frequency Noise Measurements

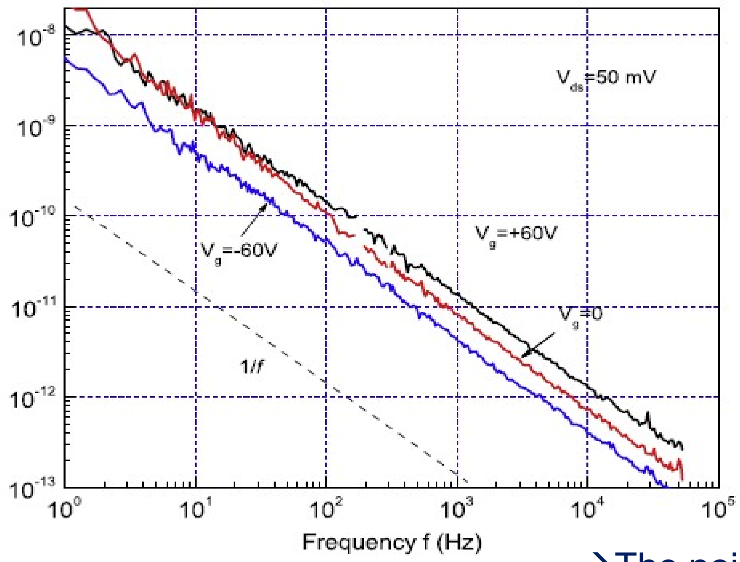




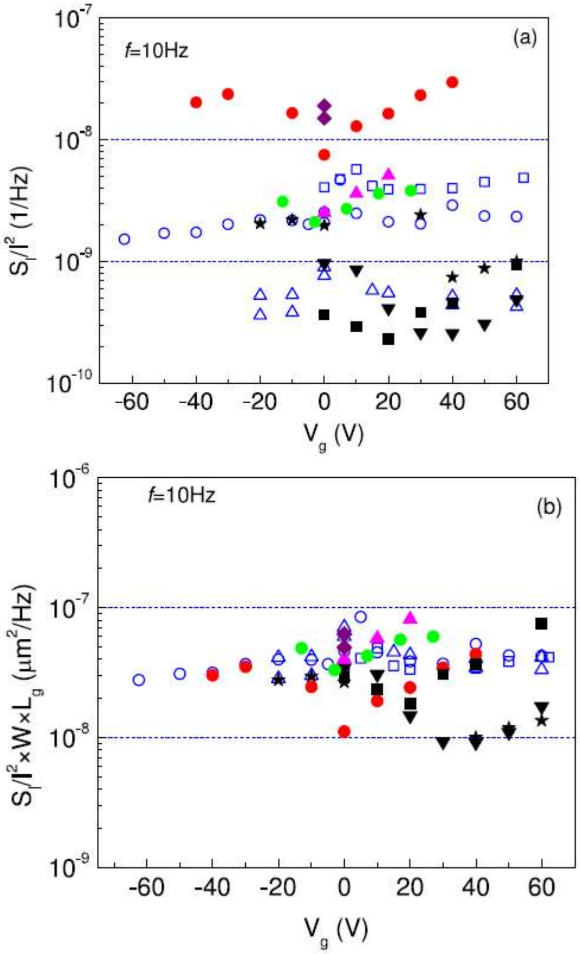
- → The noise measurement set-up is placed inside a special room with the metal and acoustic protection from the environmental noises and electro-magnetic fields

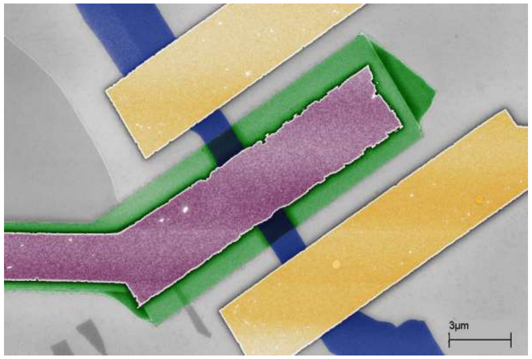
- → Low noise batteries are used for the biasing of the devices

Electronic Noise in Graphene Devices



S. Rumyantsev, G. Liu, W. Stillman, M. Shur and A.A. Balandin, *J. Physics: Condensed Matter*, 22, 395302 (2010).

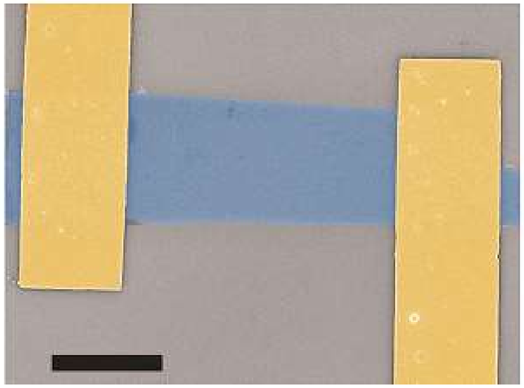


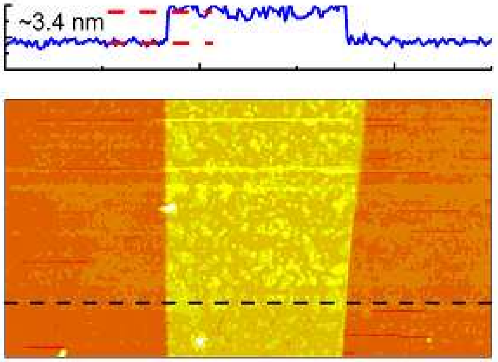


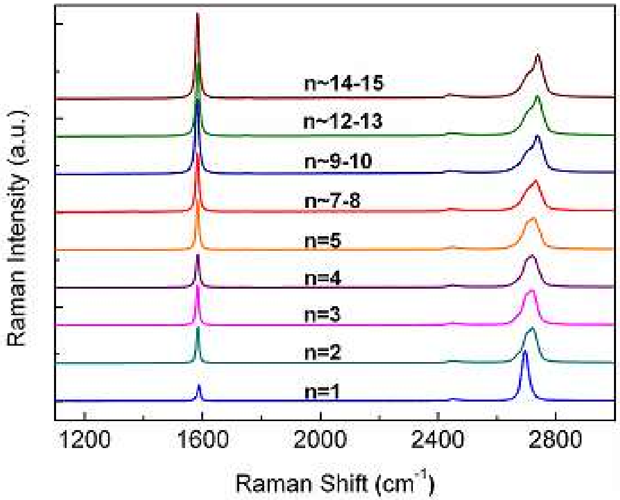
→The noise level in graphene transistors scales with the graphene channel area, which suggests that the dominant noise source is graphene channel itself.

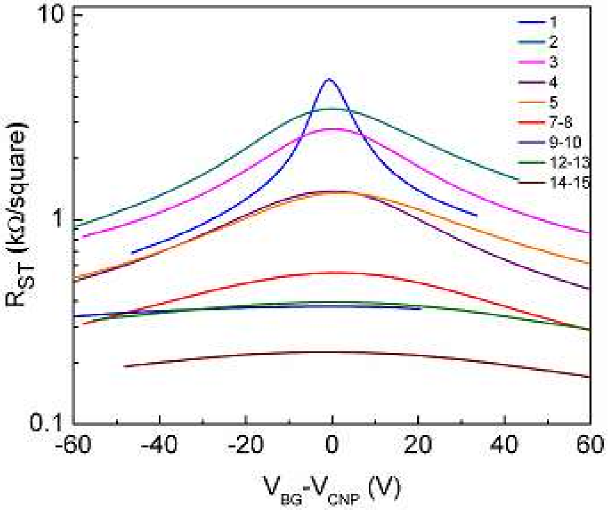
→ No clear G-R peaks observed in graphene devices.

Current Fluctuations in Few-Layer Graphene









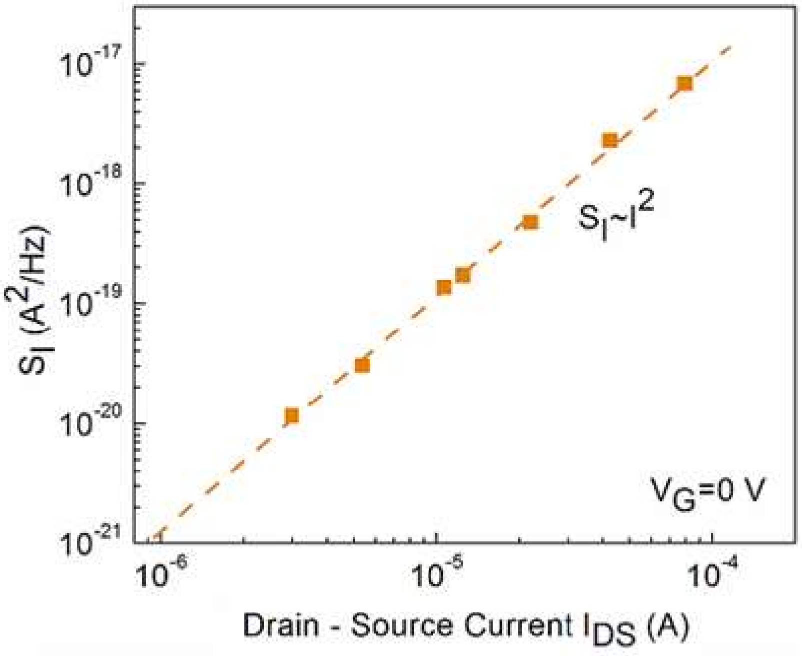
Motivations:

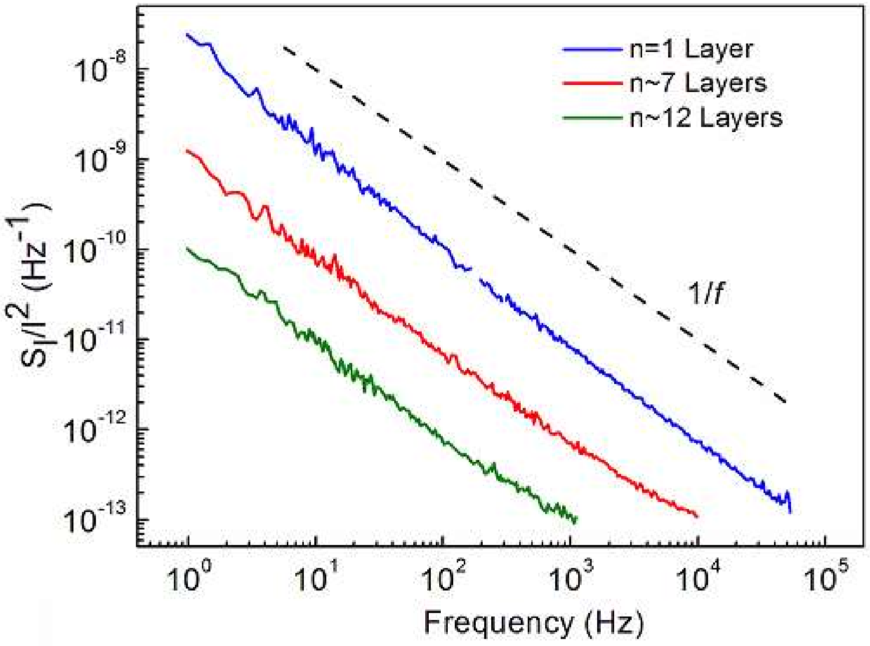
- → Practical task of noise scaling with the thickness
- → Possibility of addressing an old problem of origin of noise: surface vs. volume

The back-gated devices were fabricated by the electron-beam lithography with Ti/Au (6-nm/60-nm) electrodes.

R_{ST} is sheet resistance

Electronic Noise in Graphene Devices





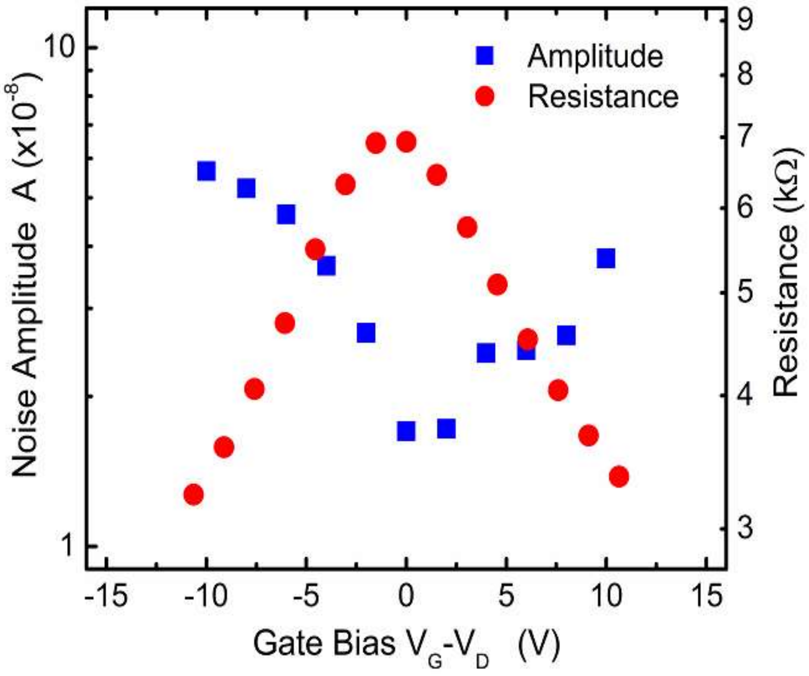
To minimize the influence of the contact resistance, most of the noise measurements were performed close to CNP.

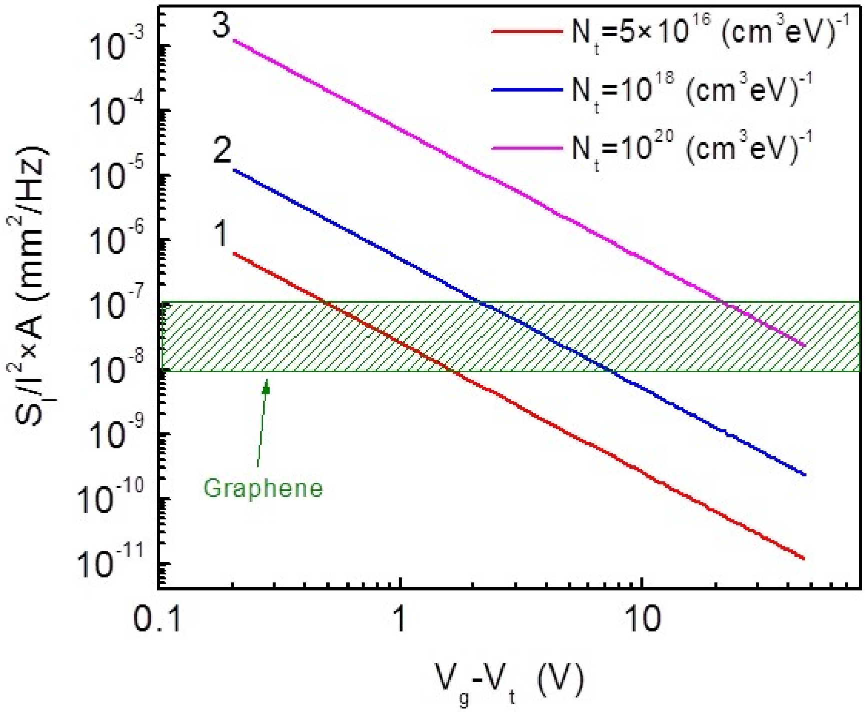
Graphene channel area A varied from 1.5 to 70 μm^2

The S_I proportionality to I^2 implies that the current does not drive the fluctuations but merely makes them visible as in other homogeneous conductors.

Specifics of Electronic Noise in Graphene

$$A = (1/N)\Sigma_{m=1}^{N} f_m S_{I_m} / I_m^2$$



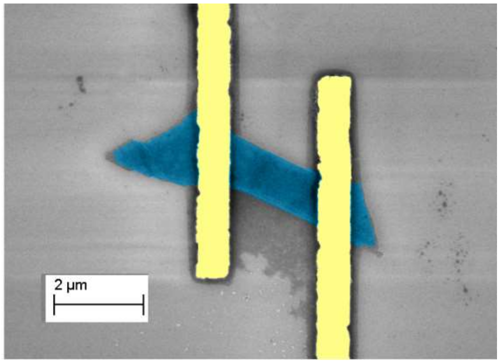


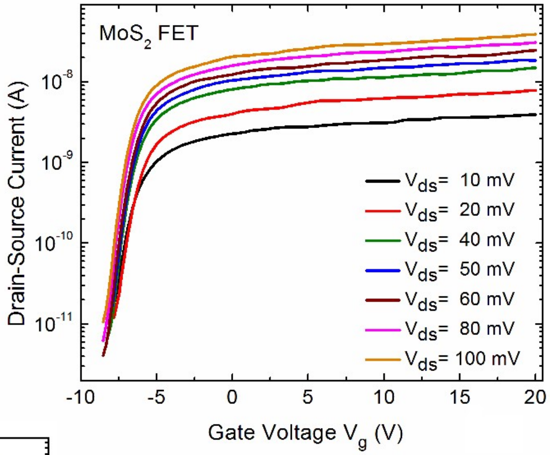
In some graphene devices, V-shape becomes M-shape dependence at lager bias range

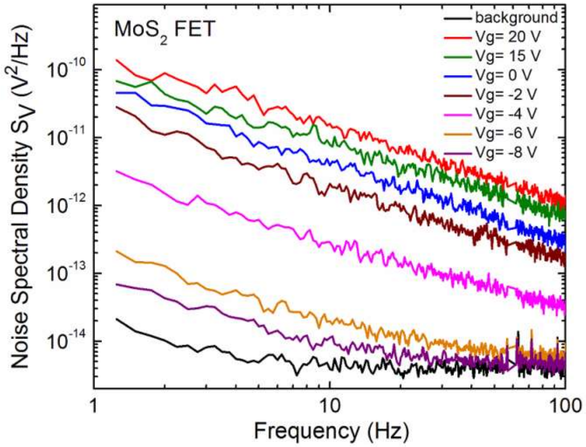
S_I/I^2 =10^{-9} to 10^{-7} Hz^{-1} at f=10 Hz or A=10^{-9} – 10^{-7}

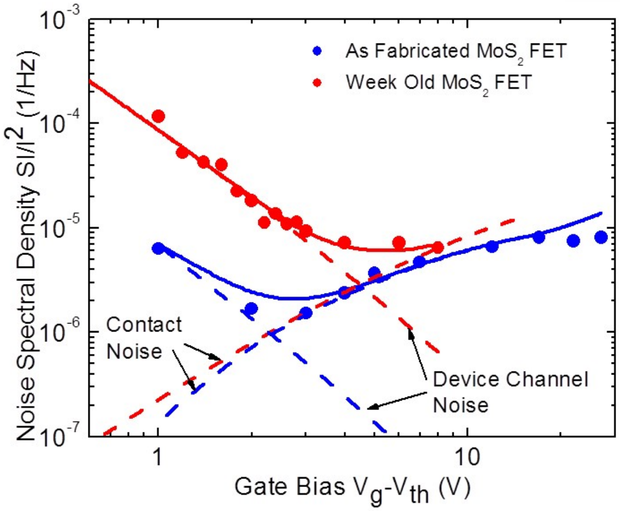
(S_I/I^2)L×W =10^{-8} – 10^{-7} μm^2/Hz

Noise in MoS_2 Thin Film Transistors









$$\frac{S_I}{I_{ds}^2}=\frac{S_{RCH}}{R_{CH}^2}\frac{R_{CH}^2}{(R_{CH}+R_C)^2}+\frac{S_{RC}}{R_C^2}\frac{R_C^2}{(R_{CH}+R_C)^2}$$

Here S_{RCH}/R_{CH}^2 is the noise spectral density of the channel resistance fluctuations, R_{CH} is the resistance of the channel, R_C is the contact resistance, and S_{RC}/R_C^2 is the noise spectral density of the contacts resistance fluctuations.

J. Renteria, R. Samnakay, S. L. Rumyantsev, C. Jiang, M. S. Shur, and A. A. Balandin, Low-frequency 1/f noise in MoS_2 transistors: Relative contributions of the channel and contacts, Appl. Phys. Lett., **104**, 153104 (2014).

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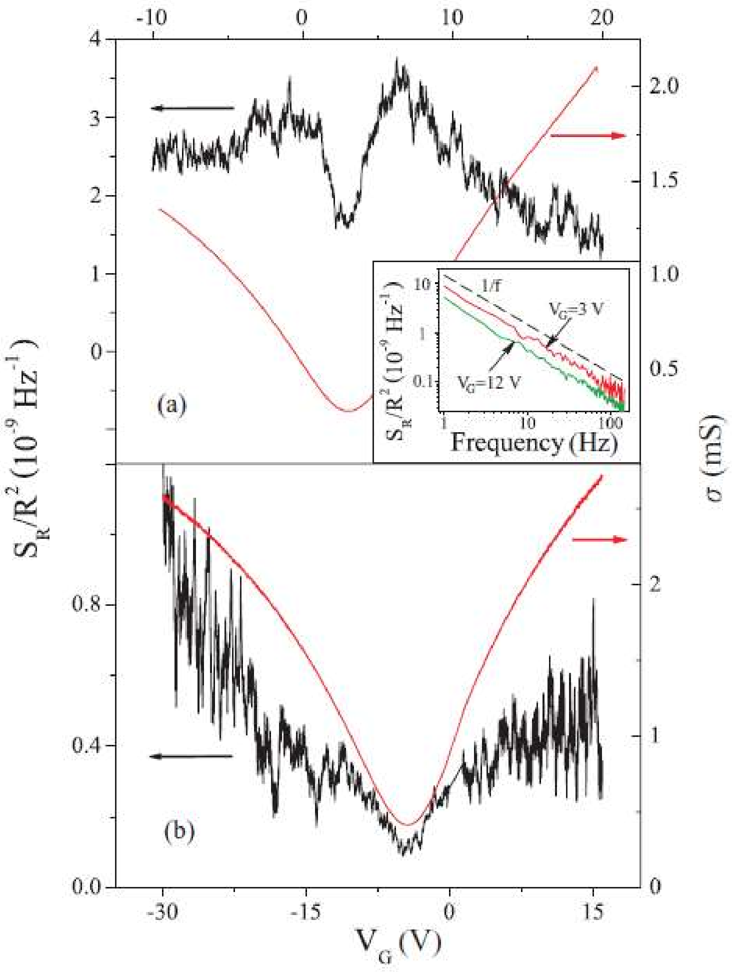
The “V” and “M” Shape Gate Bias Dependence of 1/*f* Noise in Graphene

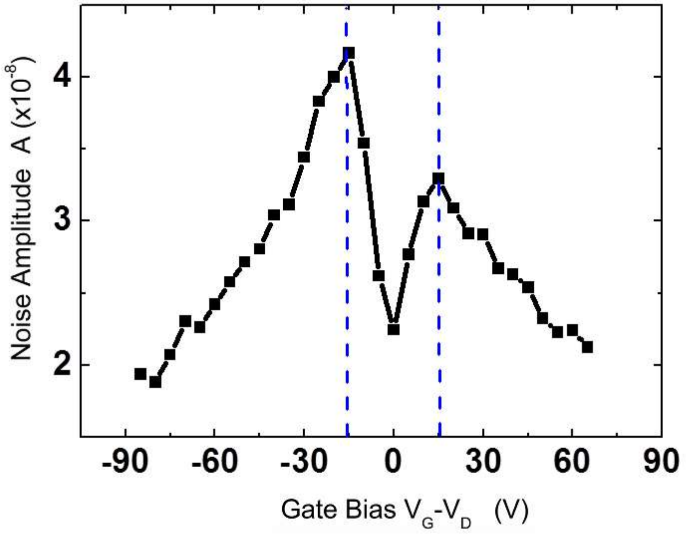


← A.A. Kaverzin, A.S. Mayorov, A. Shytov and D.W. Horsell, Phys. Rev. B, 85, 075435 (2012)

← Interplay of long-range (water) and short-range (lattice defects) scattering; M shape becomes V shape after annealing

Alternative Explanation

The spatial charge inhomogeneity related to the presence of the electron and hole puddles in graphene →



Xu, G. et al. Effect of spatial charge inhomogeneity on 1/f noise behavior in graphene. Nano Lett. 10, 3312 (2010).

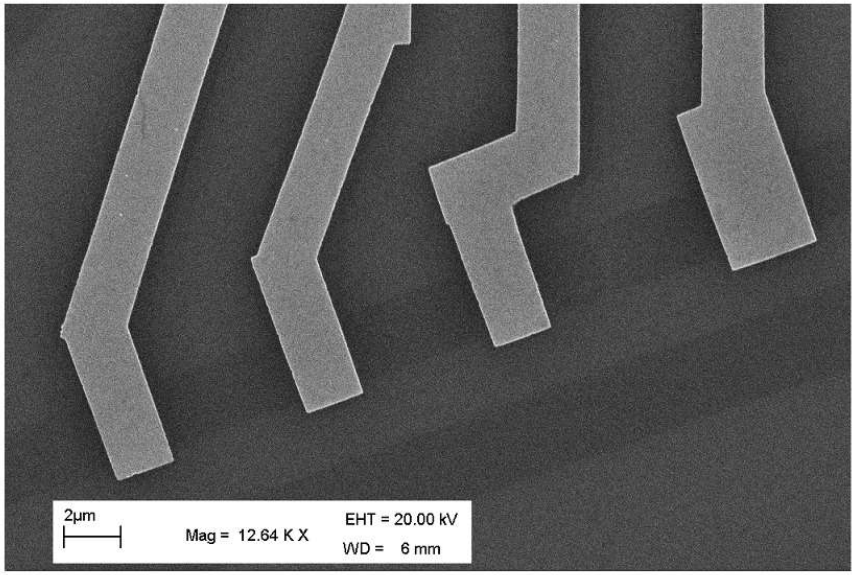
Investigation of 1/*f* Noise in Graphene Devices under Irradiation

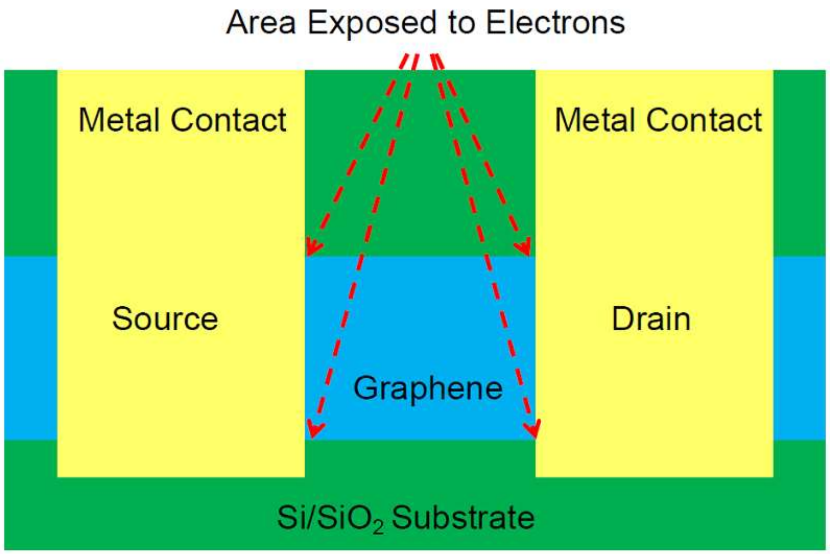
Goal

Controlled introduction of defects by electron beam irradiation and observation of the evolution of 1/f noise level

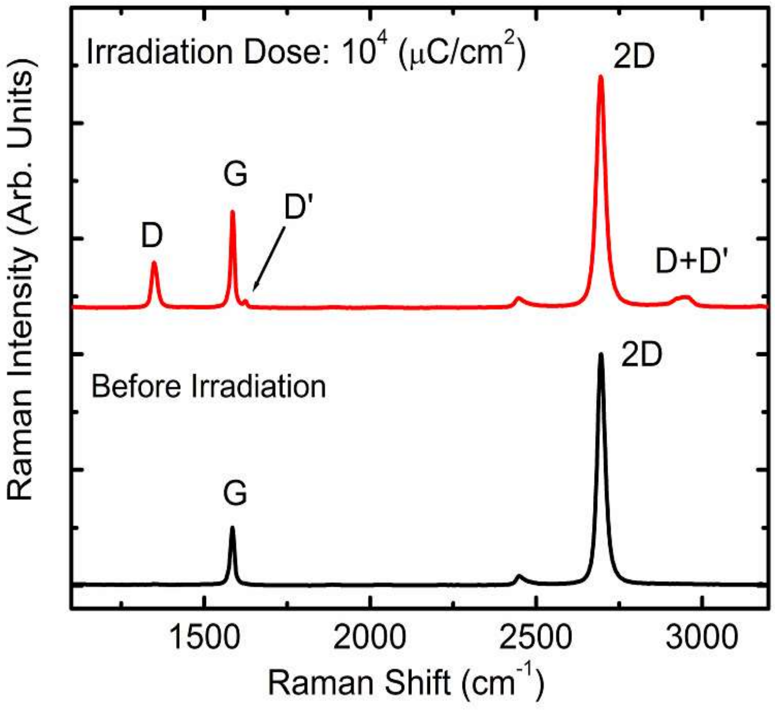
Methodology

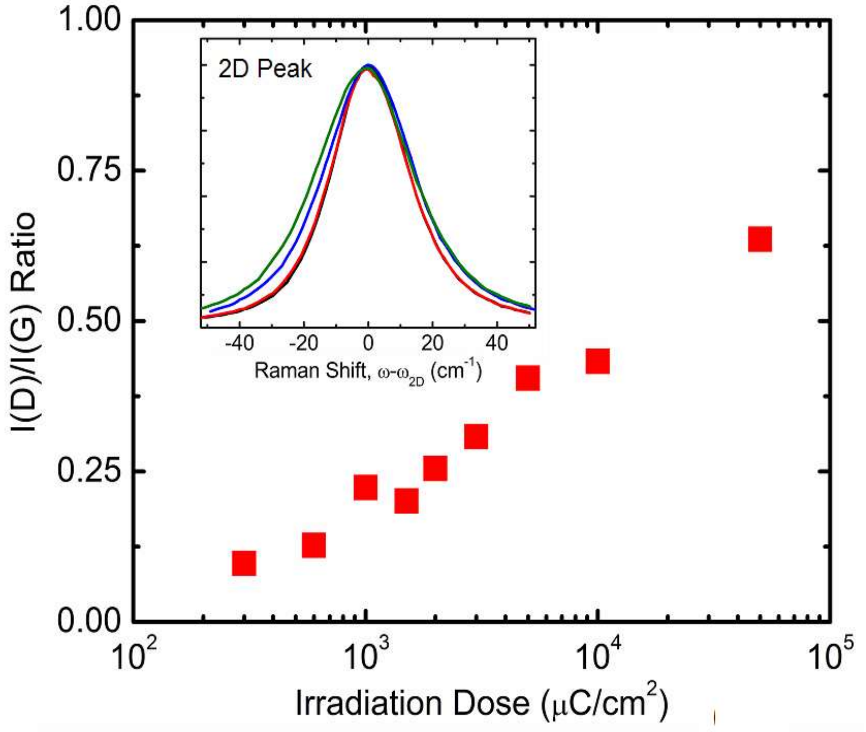
Step I: Raman of pristine graphene
Step II: IV characteristics and noise measurements
Step III: E-beam irradiation of the device
Step III: Raman of the irradiated device
Step IV: IV characteristics and noise measurements





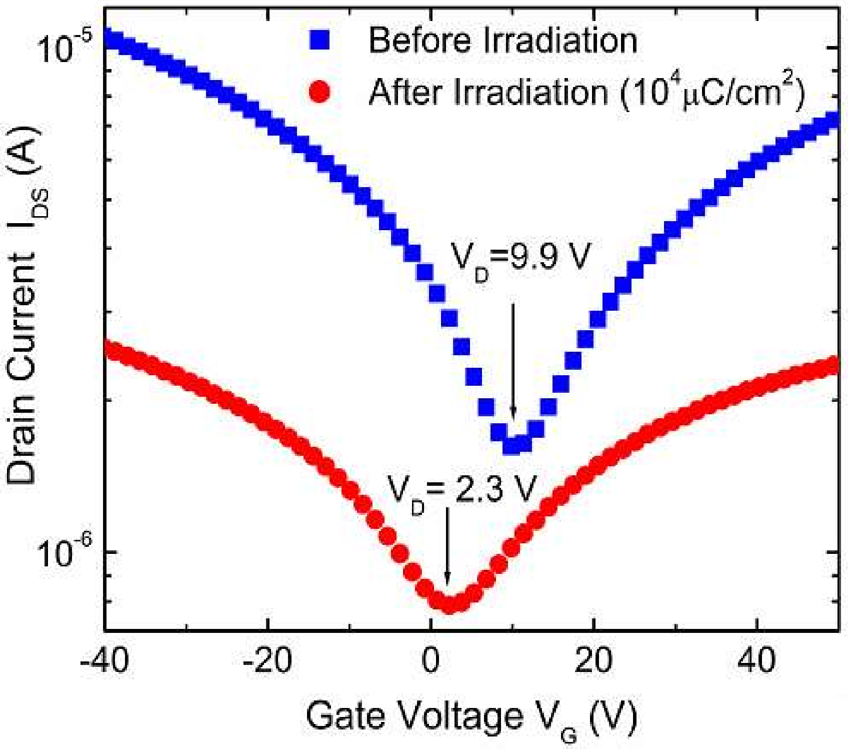
Introduction of Structural Defects to Graphene by Electron Beam Irradiation

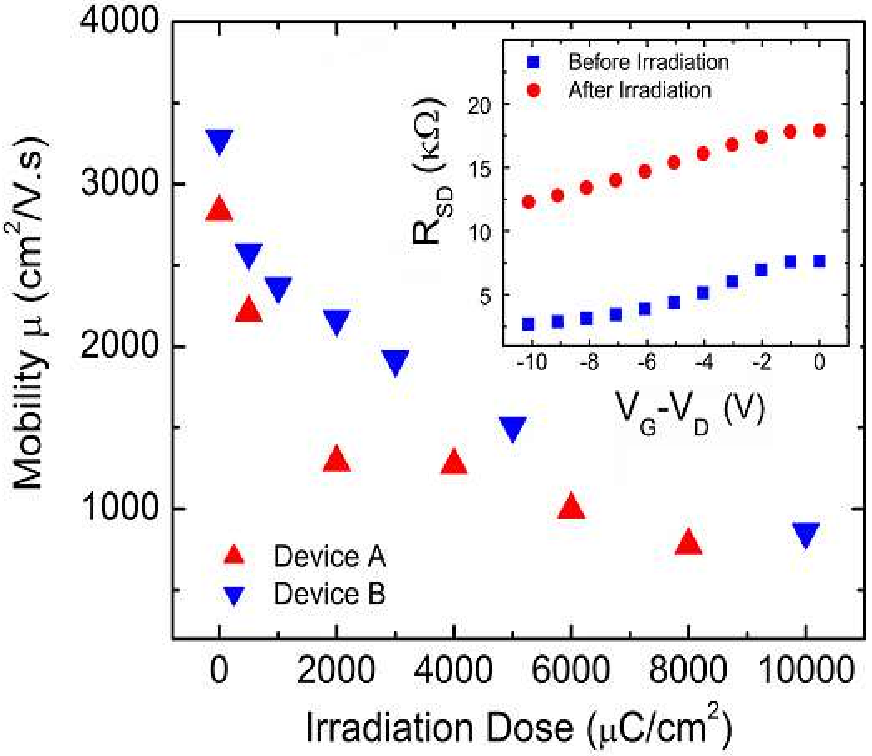




The electron energy was set to 20 keV in order to exclude the severe knock-on damage to the graphene crystal lattice, which starts at ~50 keV

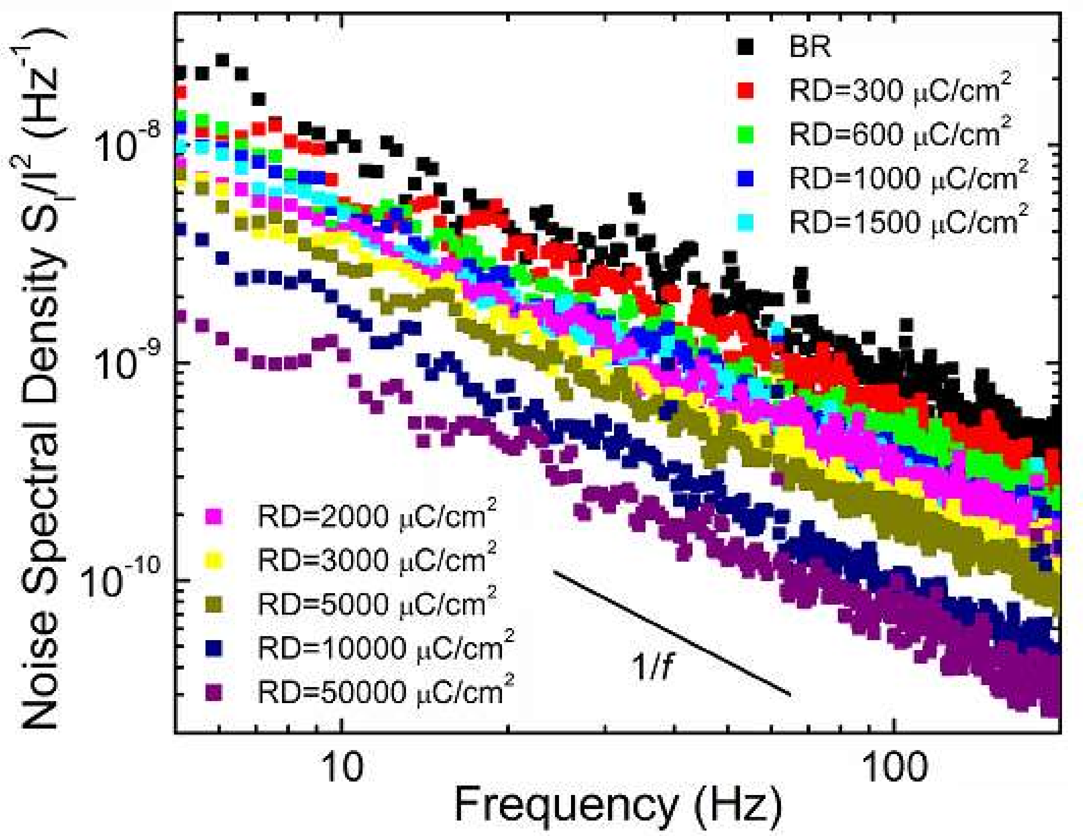
Electron Beam Irradiation Effects on Electronic Properties of Graphene





The Dirac point shift to negative side was observed for most devices, although in a very few cases, we recorded a positive shift after some irradiation steps.

Electronic Noise Suppression via Electron Beam Irradiation



Collaboration with
Prof. Michael Shur
Dr. Sergey Rumyantsev

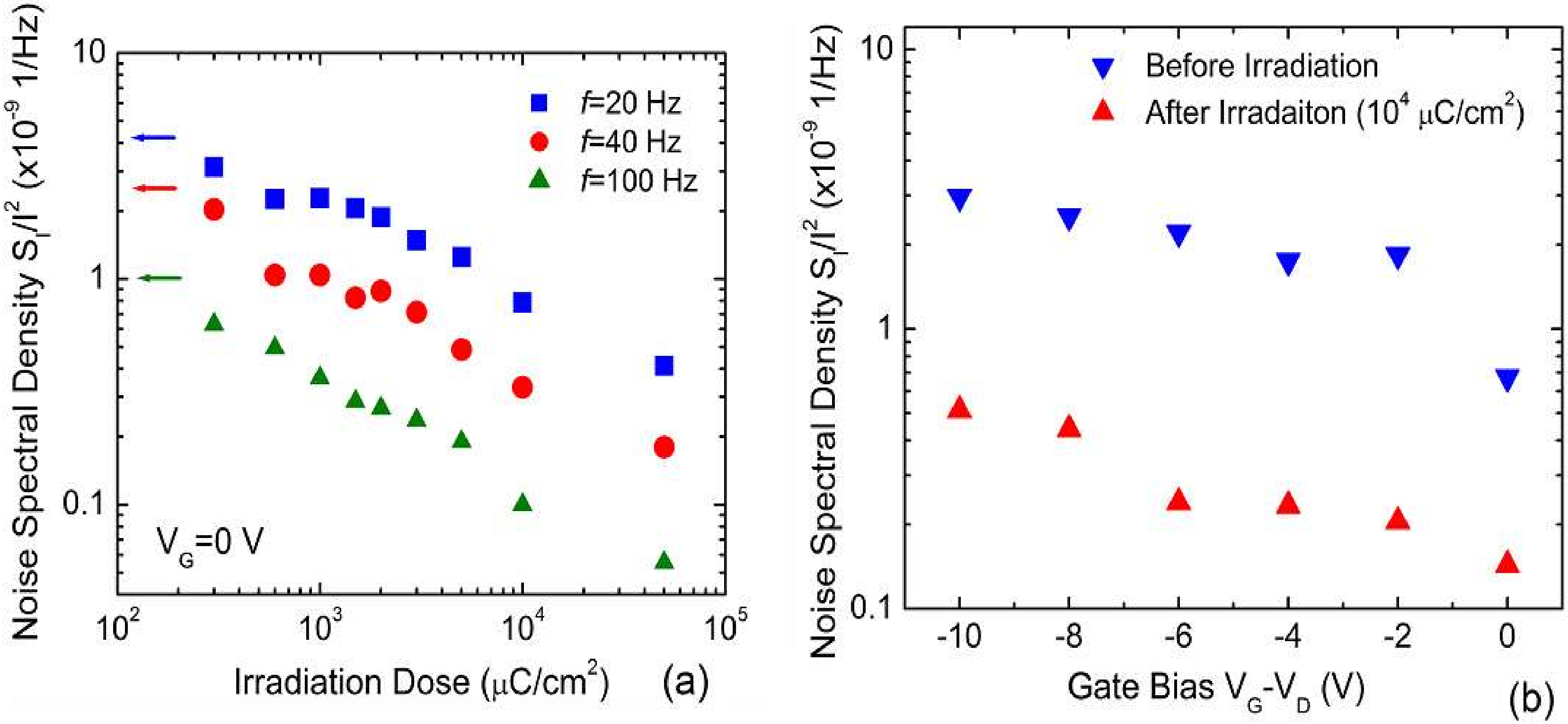
The noise was measured in the linear region of the drain bias keeping the source at a ground potential.

The flicker 1/*f* noise is usually associated with structural defects.

Introduction of defects by irradiation normally results in increased 1/*f* noise and reduced mobility

M.Z. Hossain, S. Rumyantsev, M.S. Shur and A.A. Balandin, "Reduction of 1/f noise in graphene after electron-beam irradiation," *Applied Physics Letters*, **102**, 153512 (2013).

Low-Frequency Noise Suppression via Electron Beam Irradiation



Noise reduces monotonically with the increasing RD for the entire range of negative gate-bias voltages, V_G-V_D. The same trend was observed for the positive gate bias.

Possible Mechanisms of the 1/*f* Noise and its Suppression in Graphene

McWhorter model of the number of carriers fluctuations:

$$\frac{S_I}{I^2} = \frac{\lambda k T N_t}{f A V n^2}$$

→ N_t is the concentration of the traps near the E_F responsible for noise
→ *A* is the gate area
→ *n* is the carriers concentrations
→ λ is the tunneling constant

Yu. M. Galperin, V. G. Karpov, and V. I. Kozub, Sov. Phys. JETP, 68, 648 (1989).

A. P. Dmitriev, M. E. Levinshtein, and S. L. Rumyantsev, J. Appl. Phys., 106, 024514 (2009).

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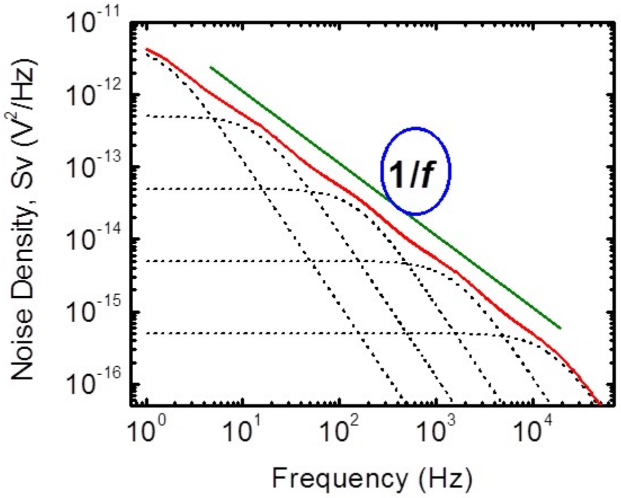


→ N_t is not the total concentration of traps!

→ Reduction in N_t after irradiation? – possible but unlikely

→ Noise should increase at some V_G – not observed

$$g(\tau_N) = [\tau_N \ln(\tau_2/\tau_1)]^{-1}$$

$$S_N(\omega) = 4\overline{\delta N^2}\int_{\tau_1}^{\tau_2} g(\tau_N)\frac{\tau_N}{1+(\omega\tau_N)^2}d\tau_N$$

Possible Mechanisms of the 1/*f* Noise in Graphene

Noise spectral density of the elementary fluctuation in the mobility fluctuation model:

$$\frac{S_I}{I^2} \propto \frac{N_t^{\mu}}{V} \frac{\tau\varsigma(1-\varsigma)}{1+(\omega\tau)^2} l_0^2 (\sigma_2 - \sigma_1)^2$$

- → $N_{t\mu}$ is concentration of the scattering centers contributing to 1/*f* noise
- → l_0 is MFP of the charge carriers
- → ζ is the probability for a scattering center to be in the state with the cross-section σ_1

Yu. M. Galperin, V.G. Karpov, V.I Kozub, *Sov. Phys. JETP* **68**, 648–653 (1989).

Yu. M. Galperin, V.L. Gurevich and V.I. Kozub, *Europhys. Lett.* **10,** 753–758 (1989).

A.P. Dmitriev, M.E. Levinshtein, S.L. Rumyantsev, *J. Appl. Phys.* **106,** 024514 (2009).

Collaboration with
Prof. Michael Shur
Dr. Sergey Rumyantsev

→ $N_{t\mu}$ may change during the irradiation or may stay about the same

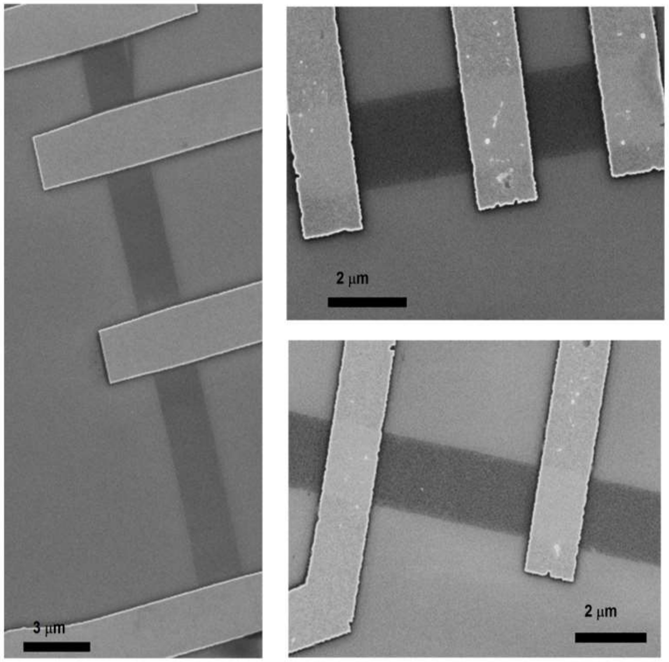
→ N_t that limit electron mobility increases

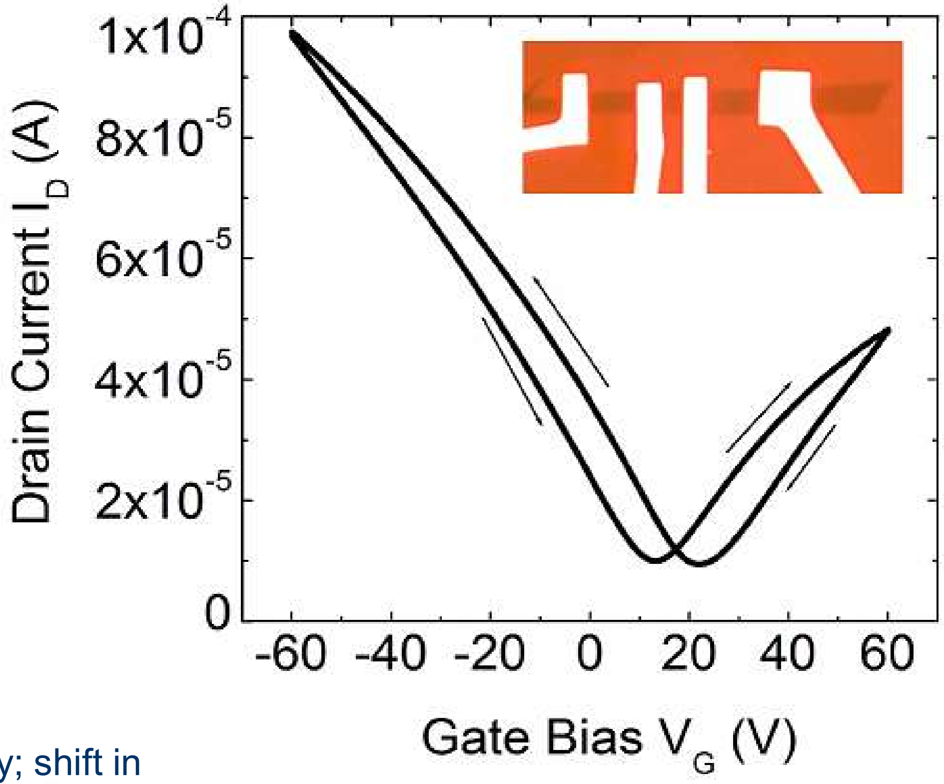
→ Noise is defined by the electron MFP: S_I/I^2 $(\sim l_0^2)$

→ Reduced mobility results in reduced MFP

→ In graphene μ is limited by the scattering from charged defects even at RT

Can Low-Frequency Fluctuations be a Signal Rather then Noise?

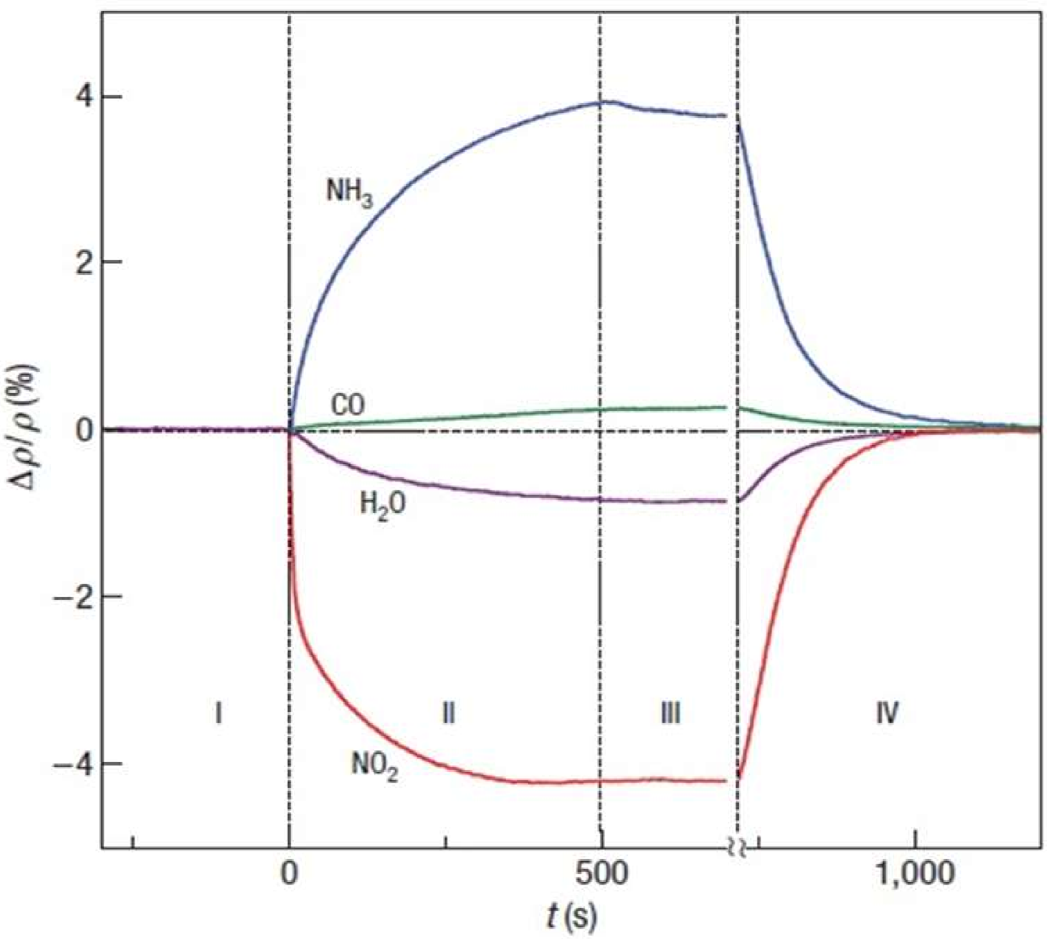




→High gas sensitivity (<1 ppb)
→Linear response to the gas concentration
→ Sensing parameters: change in resistivity; shift in Dirac point voltage; frequency of the surface acoustic waves (SAW)

Look for G-R bulges, which can be informative → sensor selectivity

Graphene Sensors: “Ultimate Sensitivity”

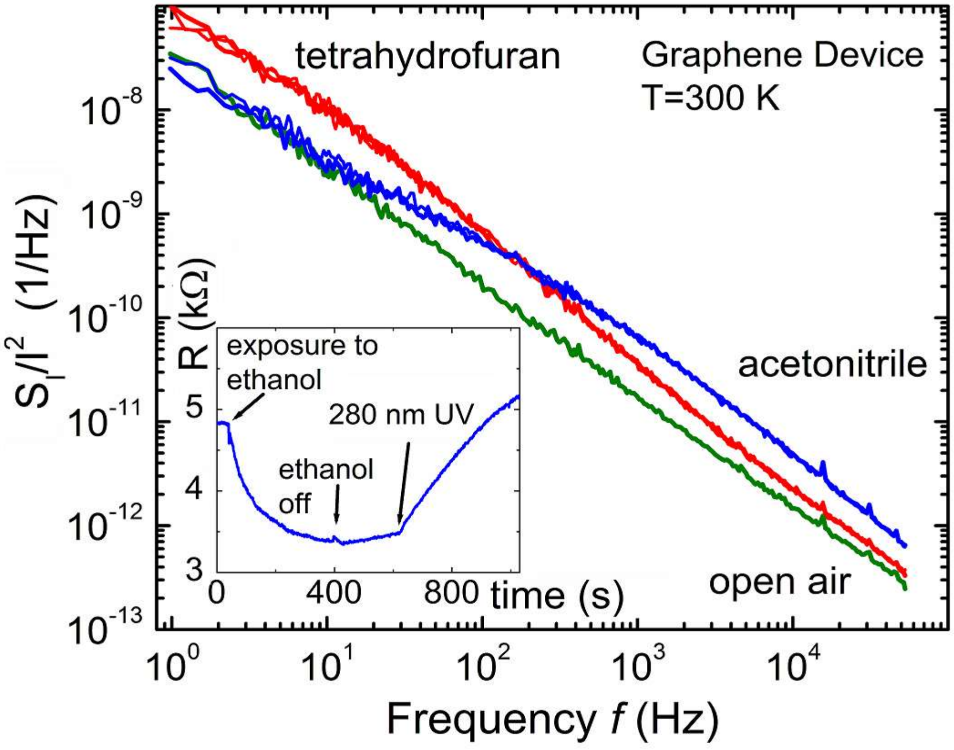


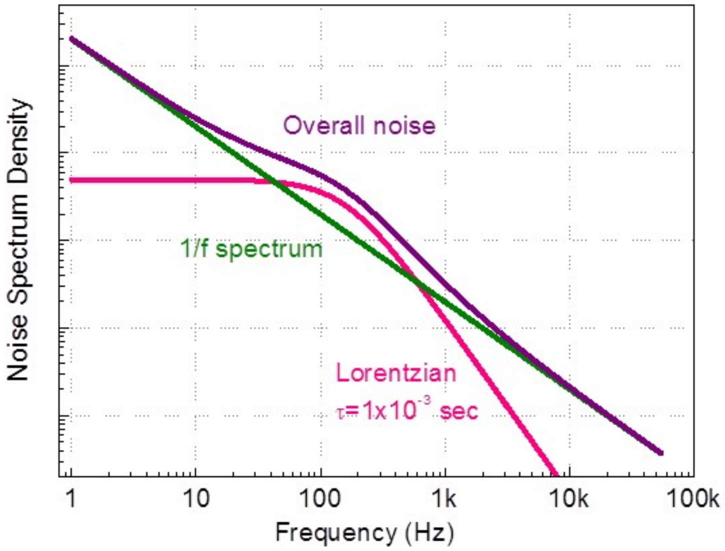
Ultimate sensitivity of graphene to chemical agents on its surface:

Changes in resistivity, caused by graphene’s exposure to various gases diluted in concentration to 1 ppm.
I: the device is in vacuum before its exposure;
II: exposure to a diluted chemical; III: evacuation of the experimental set-up;
IV: annealing at 150 C.
The response time was limited by our gas-handling system and a several-second delay in our lock-in-based measurements.

The data are from F. Schedin, A. Geim, S. Morozov, E.W. Hill, P. Blake, M.I. Katsnelson, K.S. Novoselov, *Nature Materials*, **16**, 652 (2007).

Generation – Recombination Bulges in Spectrum of Graphene under Gas Exposure

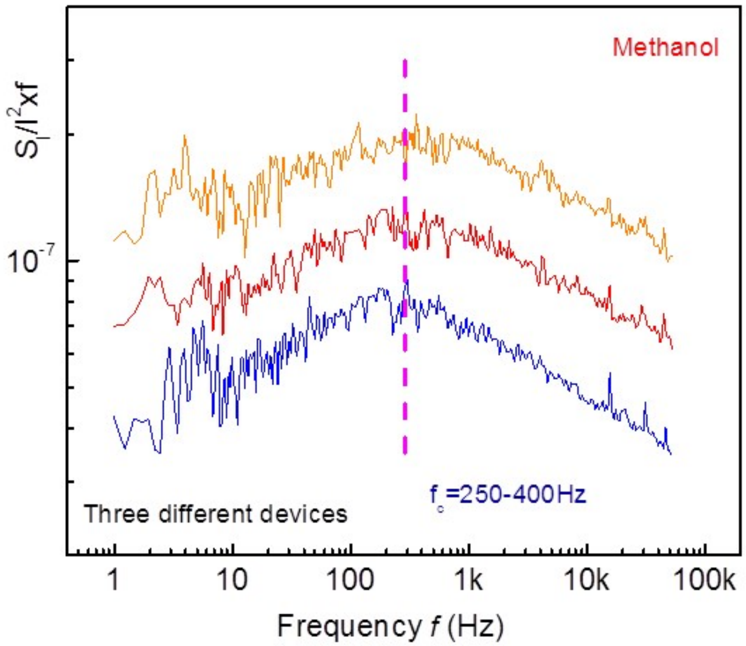


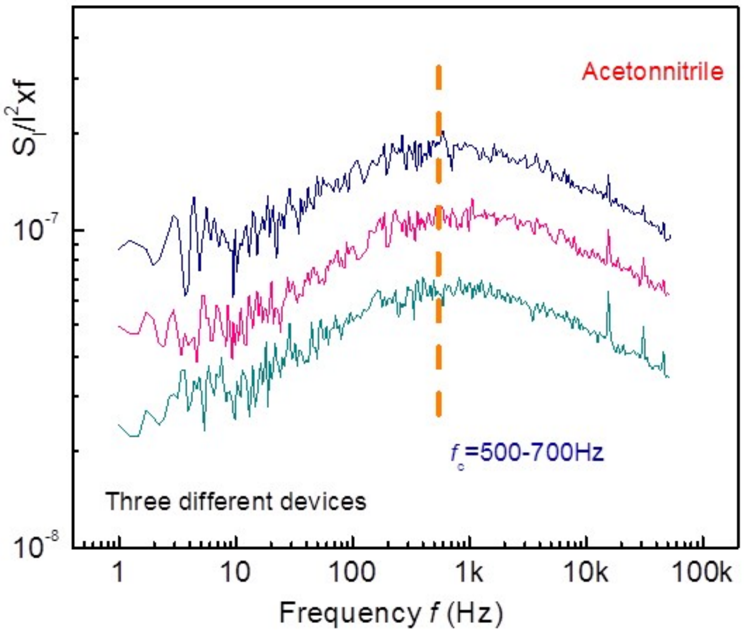


Superposition of a Lorentzian noise with defined relaxation time on a 1/f noise results in a bulge with specific frequency $S \propto \frac{1}{1+(\omega\tau)^2}$

- → Vapors generated by bubbling dry carrier gas - air – through solvent and diluting the gas flow with dry carrier gas
- → Vapors generated at ~0.5 P/P_o, where P during the experiment and P_o is the saturated vapor pressure
- → Measurements performed at V_G=0 V ("hole" region of graphene I-V)
- → The contact resistance per unit width: 0.2 – 2.0 Ω-mm

Reproducibility of G-R Bulges in Spectrum of Graphene under Vapor and Gas Exposure



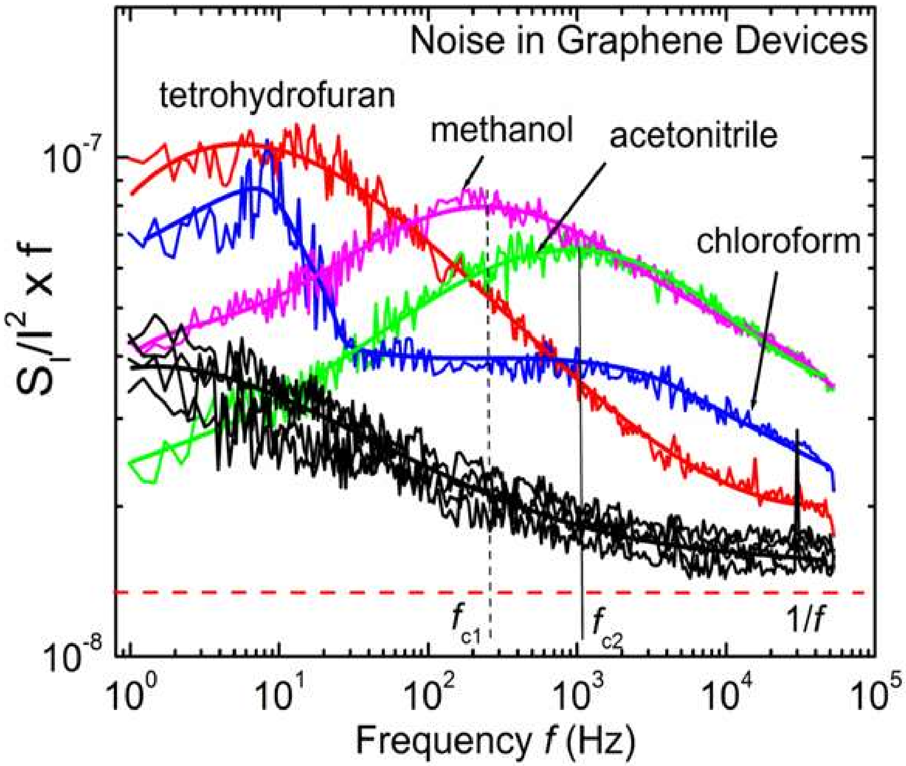


- → The characteristics frequency f_c of Lorentzian peaks with certain vapor gases is reproducible for different graphene devices
- → The gas molecules can create specific traps and scattering centers in graphene, which lead to either number of carriers fluctuation due to the fluctuations of traps occupancy or to the mobility fluctuations due to fluctuations of the scattering cross sections

Selective Gas Sensing with Pristine Graphene FETs

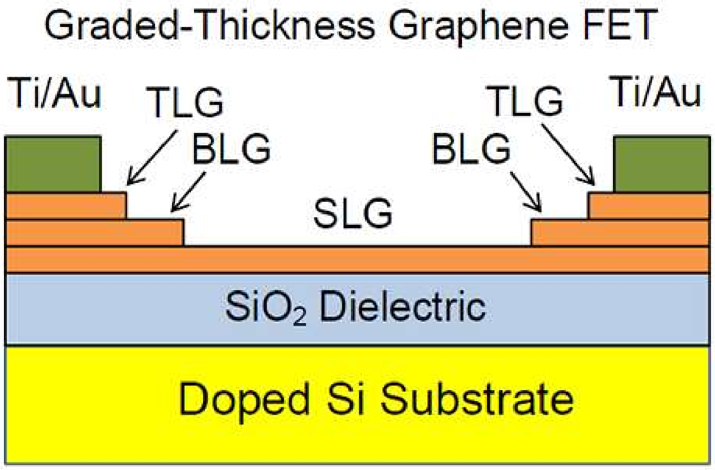
Combination of resistance change and low-frequency fluctuations signals allows one to build ultra-sensitive and selective sensor with pristine graphene – no surface functionalization and no labeling

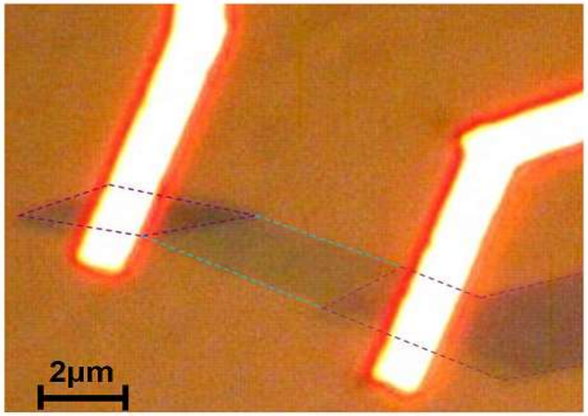
Table X: Noise Spectroscopy	**Lorentzian Bulge S_I/I^2 f (Hz)**	**Resistance ΔR/R %**
Ethanol	400 - 500	-50
Methanol	250 - 400	-40
Tetrahydrofuran	10 – 20	+18
Chloroform	7-9 and 1300 - 1600	-25
Acetonitrile	500 - 700	-35
Toluene	No peak	+15
Methylene Chloride	No peak	-48

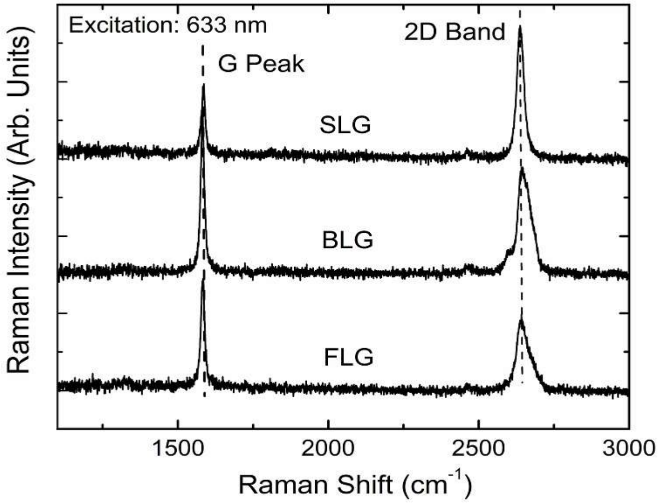


S. Rumyantsev, G. Liu, M. Shur and A.A. Balandin, "Selective gas sensing with a single pristine graphene transistor," *Nano Letters*, **12**, 2294 (2012).

Graphene Thickness-Graded FETs



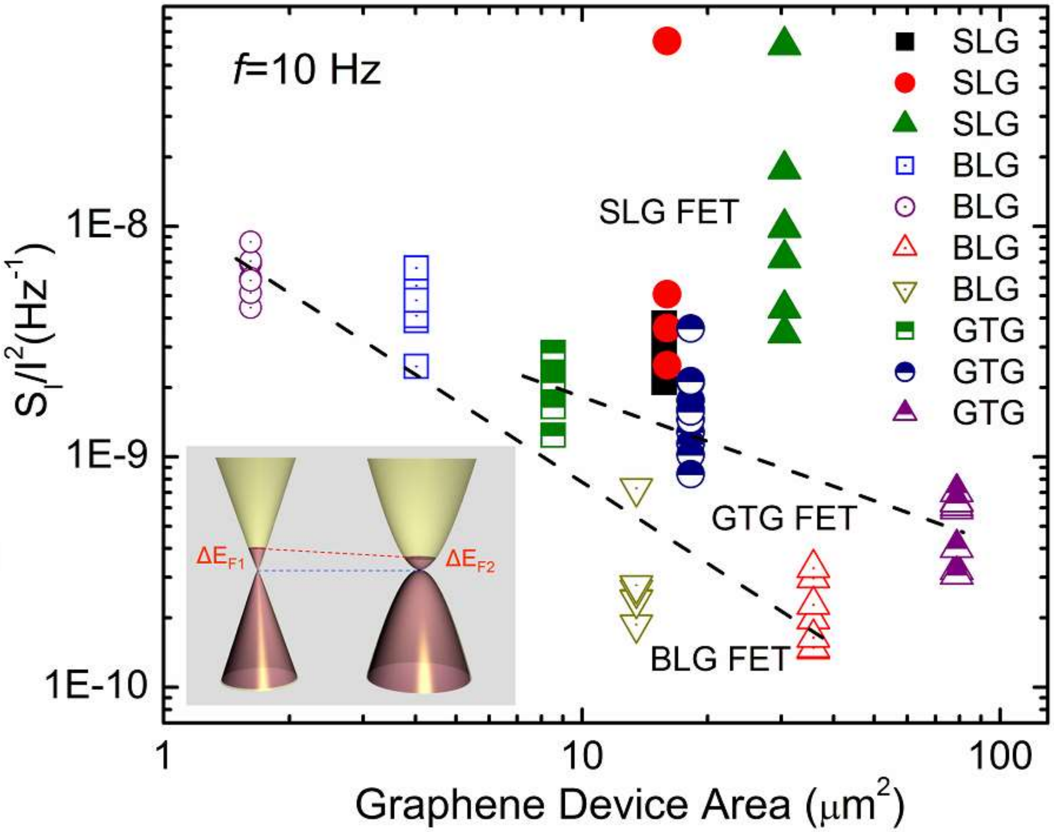




The SLG, GTG and BLG FETs, fabricated using the same process, had the RT electron mobility values: ~5000 – 7000 cm^2/Vs, ~4000 – 5000 cm^2/Vs and ~1000 – 2000 cm^2/Vs, respectively

G. Liu, S. Rumyantsev, M. Shur and A.A. Balandin, Graphene thickness-graded transistors with reduced electronic noise, *Appl. Phys. Lett.*, 100, 033103 (2012).

1/*f* Noise in Thickness Graded Graphene: Comparison with SLG and BLG



The same amount of the charge, transferred owing to the metal contact doping, leads the smaller local Fermi level shift in BLG devices than in SLG devices.

Local shifts of the Fermi level position in graphene: ΔE_F=-0.23 eV and ΔE_F =0.25 eV were reported for Ti and Au contacts to graphene.

G. Liu, S. Rumyantsev, M. Shur and A.A. Balandin, Graphene thickness-graded transistors with reduced electronic noise, *Appl. Phys. Lett*., 100, 033103 (2012).

Conclusions

→ Typical graphene transistors reveal rather low level of the low-frequency noise: $S_I/I^2 = 10^{-9}$ to 10^{-7} Hz^{-1} at f=10 Hz or $A=10^{-9} – 10^{-7}$

→ The gate dependence of 1/*f* noise in graphene reveals characteristic V-shape or M-shape – different from that in conventional semiconductors and metals

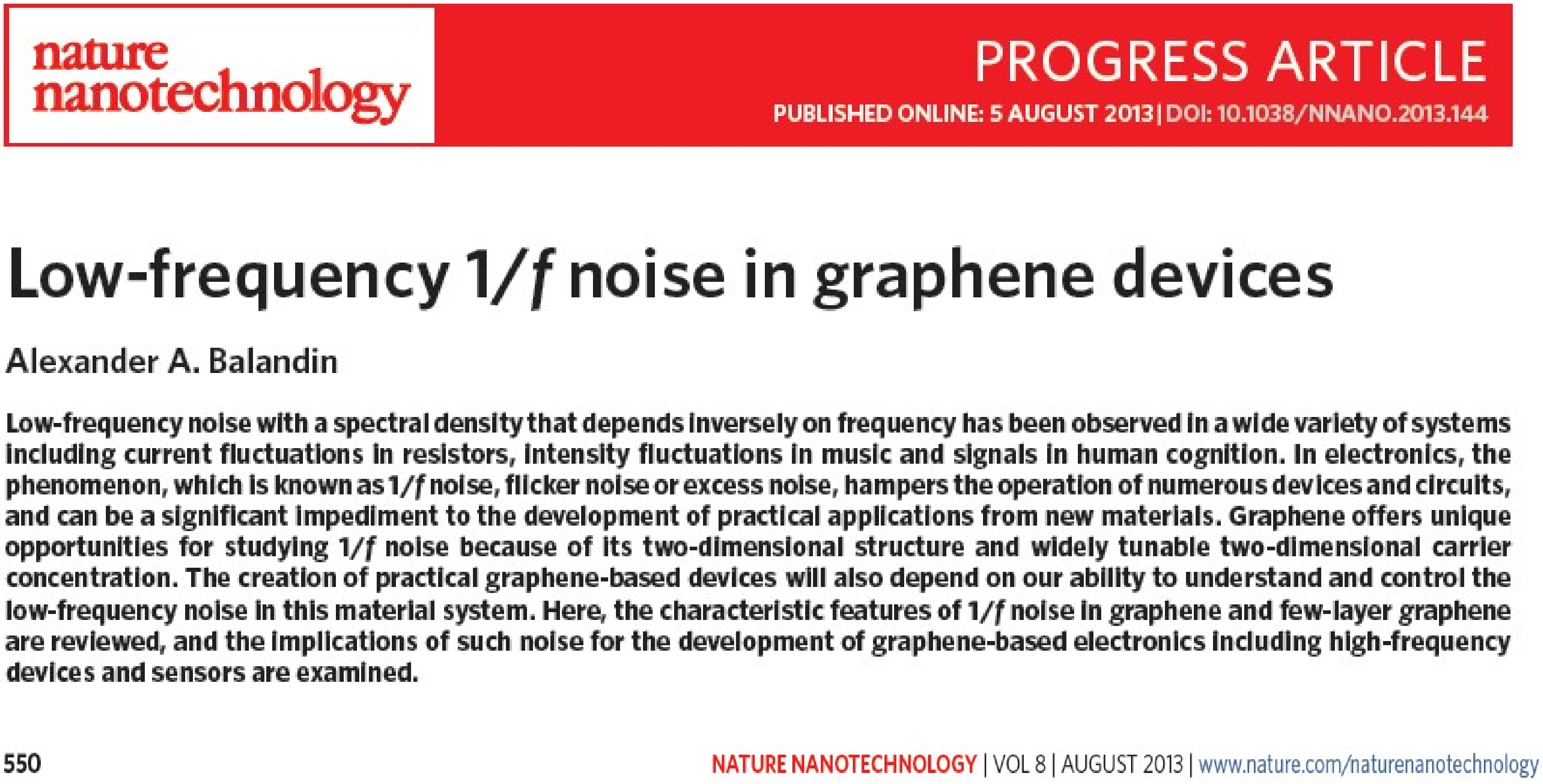
→ It is possible to reduce 1/*f* noise via electron beam irradiation and thickness grading

→ Noise reduction after irradiation is better explained by the mobility fluctuation models

→ Noise scaling in graphene multilayers sheds light on the old problem of noise origin: surface vs. volume

→ Low-frequency current fluctuations can be used for selective sensing with graphene

Details on the State of the Art in $1/f$ Noise in Graphene



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PROGRESS ARTICLE

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Low-frequency $1/f$ noise in graphene devices

Alexander A. Balandin

Low-frequency noise with a spectral density that depends inversely on frequency has been observed in a wide variety of systems including current fluctuations in resistors, intensity fluctuations in music and signals in human cognition. In electronics, the phenomenon, which is known as $1/f$ noise, flicker noise or excess noise, hampers the operation of numerous devices and circuits, and can be a significant impediment to the development of practical applications from new materials. Graphene offers unique opportunities for studying $1/f$ noise because of its two-dimensional structure and widely tunable two-dimensional carrier concentration. The creation of practical graphene-based devices will also depend on our ability to understand and control the low-frequency noise in this material system. Here, the characteristic features of $1/f$ noise in graphene and few-layer graphene are reviewed, and the implications of such noise for the development of graphene-based electronics including high-frequency devices and sensors are examined.

550 NATURE NANOTECHNOLOGY | VOL 8 | AUGUST 2013 | www.nature.com/naturenanotechnology

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