Low-Frequency 1/f Noise in Low-Dimensional Materials and Devices

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April 2022

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Joshua Tree Park

Highlights of Research Activities

Graphene thermal field and thermal management

- The MRS Medal (2013)

Quazi-1D van der Waals materials

- The Vannevar Buch Faculty Fellow (2021)

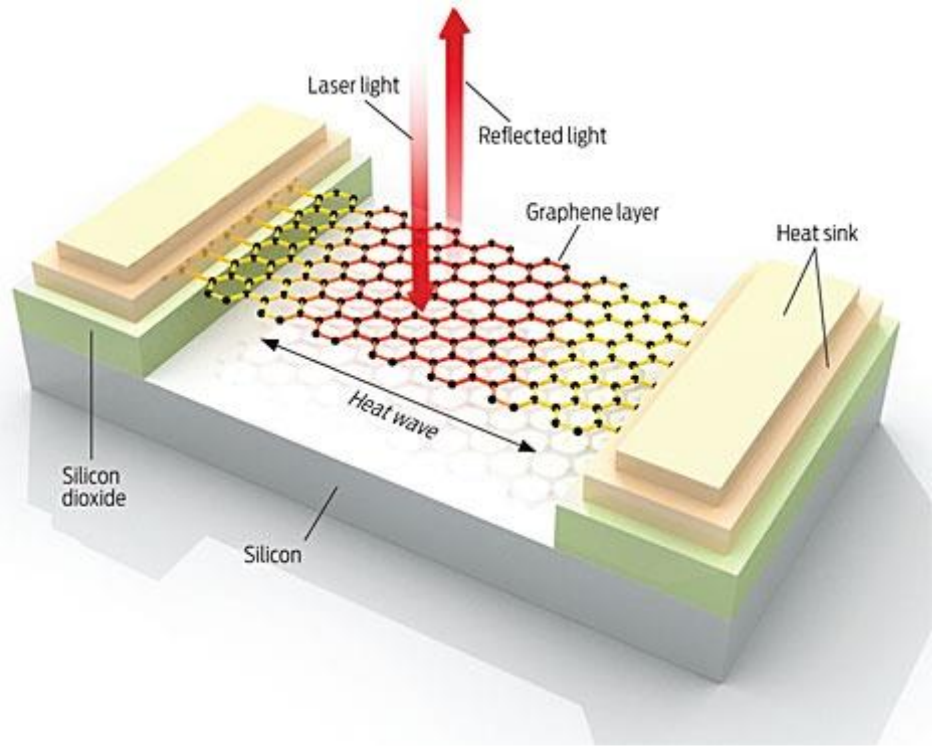
Nanoscale phonon engineering

- IEEE Pioneer of Nanotechnology Award (2011)

Raman and Brillouin-Mandelstam spectroscopy

- The Brillouin Medal (2019)

Low-frequency noise spectroscopy



https://balandingroup.ucr.edu/

Outline

→Part I: Noise Background and History

→Part II: Noise in Graphene

  → Noise reduction and other highlights

  → Graphene under irradiation

→Part III: Noise as the Signal

  → Graphene *vs.* MoS_2

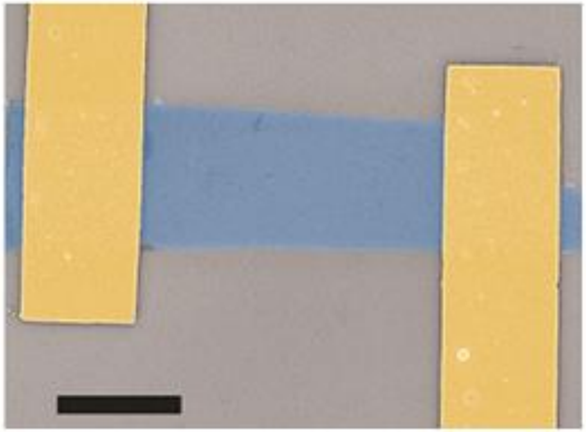
→Part IV: Noise in 2D CDW Materials

  → 2D CDW quantum materials

  → Noise spectroscopy of CDWs

→Part IV: 1D van der Waals Materials

  → Going from 2D to 1D – again!



Part I: Noise Basics and Brief History

In electronics, noise is a random fluctuation in an electrical signal characteristic for all electronic devices.

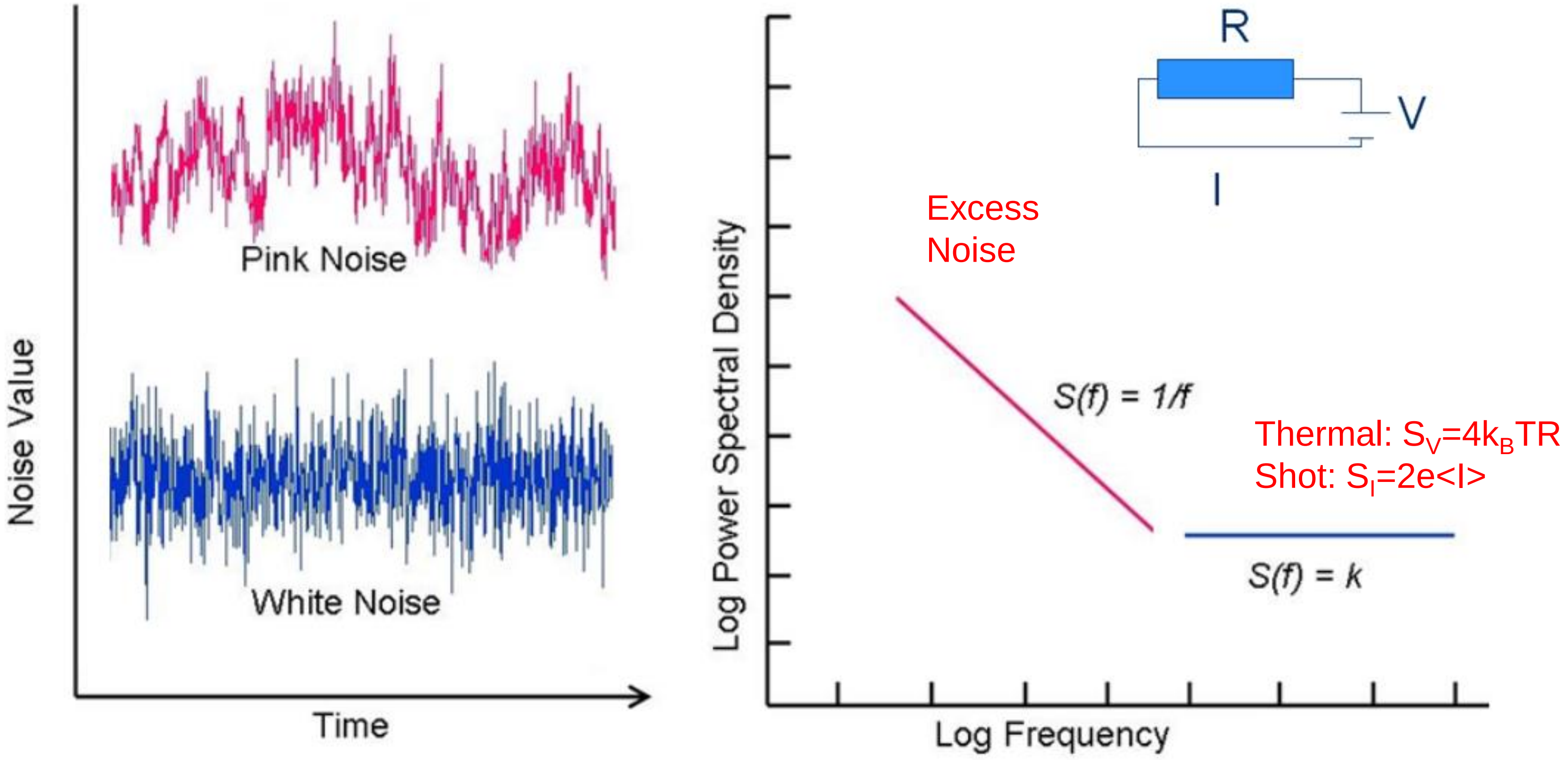
→ Noise is an unwanted disturbance in an electrical signal. In communication systems, noise is an error or undesired random disturbance of a useful information signal.

→ Low-frequency noise with the spectral density $S(f) \sim 1/f^{\gamma}$ (where f is the frequency and $\gamma \approx 1$ is a parameter) → "1/f noise" or "excess noise"

- P. Dutta and P.M. Horn, Low-frequency fluctuations in solids: 1/f noise, Reviews of Modern Physics, 53, 497 (1981)
- Sh. M. Kogan, Low-frequency current noise with a 1/f spectrum in solids, UFN, 145, 285 (1985)
- Edoardo Milotti, 1/f noise: a pedagogical review, arXiv: physics/ 0204033 (2002)

Nano-Device Laboratory

Basics of Electronic Noise – Fluctuations are Everywhere



Excess Noise

Thermal: $S_V=4k_BTR$
Shot: $S_I=2e\langle I\rangle$

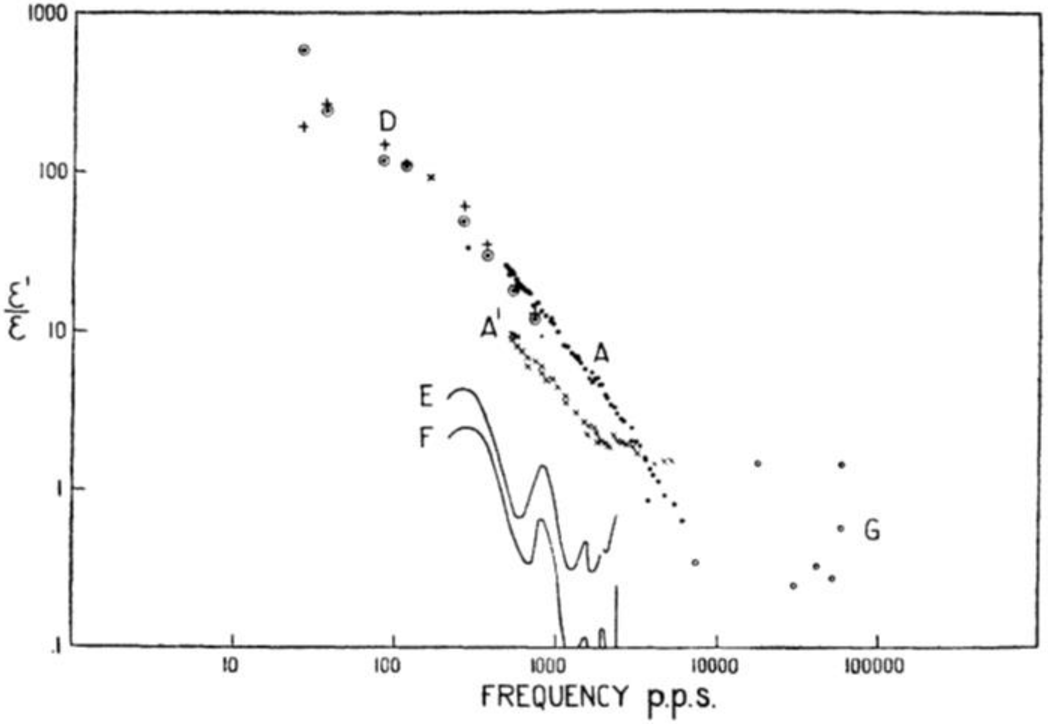
Adapted from L. M. Ward and P. E. Greenwood, Scholarpedia, 2, 1537 (2007)

Brief History of 1/f Noise
– J. B. Johnson's Discovery

THE SCHOTTKY EFFECT IN LOW FREQUENCY CIRCUITS

By J. B. Johnson

* Received April 11, 1925—Ed.



- The 1/f noise was discovered by Johnson (1925) in data from an experiment designed to test Schottky's (1918) theory of shot noise in vacuum tubes.
- The noise in Johnson's experiment was not white at low frequency.
- Schottky (1926) described mathematically the "flicker noise" with a slow relaxation process.

J. B. Johnson, Phys. Rev. 26, 71 (1925).

Mathematical Background for Noise Studies

$$S(f) = \underset{T\to\infty}{Lt}\left(\frac{1}{2T}\right)\left|\int_{-T}^{T} dt\, X(t)\, e^{-i2\pi ft}\right|^{2} \qquad (1)$$

$$C(\tau) = \underset{T\to\infty}{Lt}\left(\frac{1}{2T}\right)\int_{-T}^{T} dt\, X(t+\tau)X(t) \qquad (2)$$

$$S(f, T) = C\int_{-\infty}^{\infty} dt\, e^{-j2\pi ft}\varphi(t) \qquad (3)$$

$$S(f) \propto \frac{2\tau}{1+(2\pi f\tau)^{2}} \qquad (4)$$

$$S(f) \propto \int_{0}^{\infty} d\tau\, F(\tau)\frac{2\tau}{1+(2\pi f\tau)^{2}} \qquad (5)$$

The power spectrum *S(f)* quantifies the noise in the frequency domain

Wiener–Khintchine theorem connects *S(f)* with the autocorrelation function.

To get *S(f)* ~ $f^{-\alpha}$ one needs $C(\tau) \sim |\tau|^{\alpha-1}$

S(f) becomes frequency dependent because there is a finite relaxation time associated with fluctuating quantity

Debye relaxation function $\phi(t) \sim \exp(-t/\tau)$ one gets Lorentzian

$F(\tau) \sim \tau^{-\alpha}$ would give $S(f) \sim f^{-2+\alpha}$

A.K. Raychaudhuri, Measurement of 1/f noise and its application in materials science, Current Opinion in Solid State and Materials Science 6 (2002) 67–85

Superposition of Lorentzians

Superposition of Lorentzians can give approximately 1/f spectrum

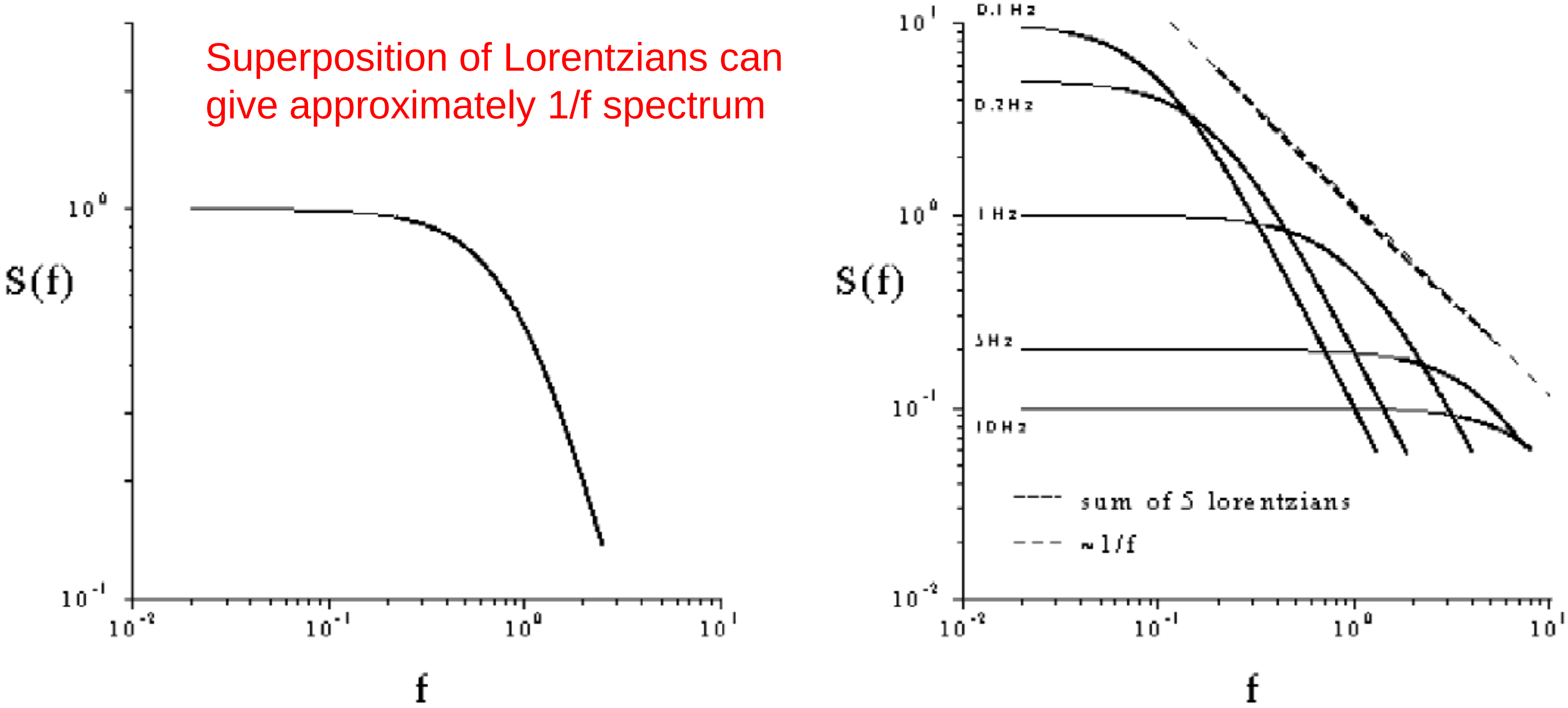


Fig. 1. (a) The Lorentzian power spectra of a single fluctuator ($\tau^{-1} = 1$ Hz). (b) Generation of a power law $S(f)$ from superposition of Lorentzians. In this case five Lorentzians have been used. τ^{-1} is marked in the graph.

Adapted from A.K. Raychaudhuri, Current Opinion in Solid State and Materials Science 6 (2002) 67–85

Early Models of 1/f Noise – Schottky and Surdin Models

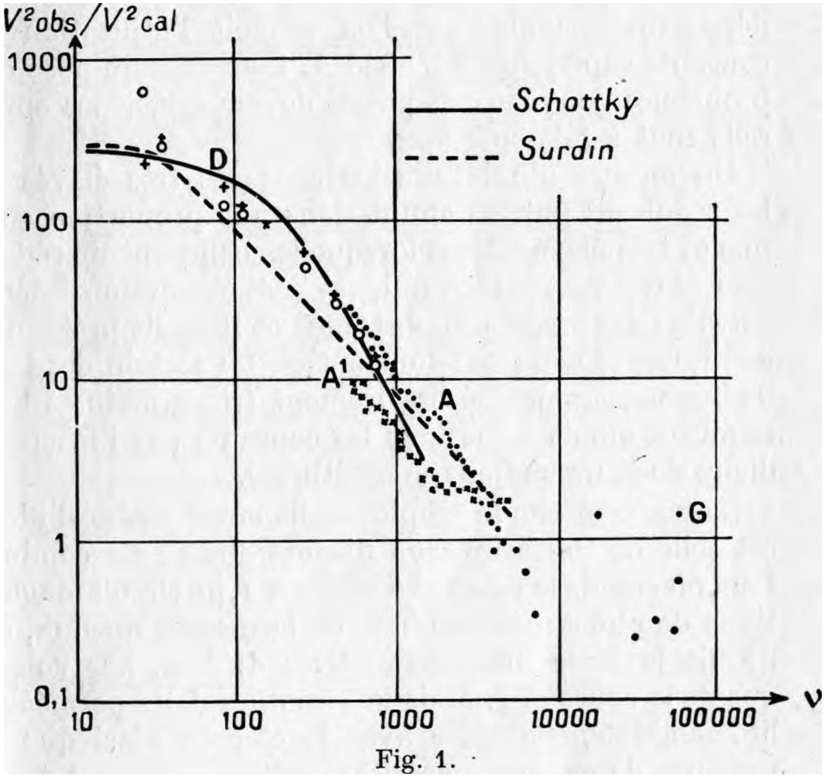


Fig. 1.

Schottky: $N(t)=N_0e^{-\lambda t}$

Surdin: $g(\tau)d\tau = d\tau/\tau \ln(\tau_h/\tau_l)$.

$$\alpha_1 << \alpha_2 << 2\pi\nu$$

$$\overline{i_\nu^2} = \frac{4I^2}{k^2T^2}\left(\frac{\partial W}{\partial N}\right)^2 \frac{\alpha_2\,\overline{M^2}}{4\pi^2\nu^2 \log\frac{\alpha_2}{\alpha_1}}$$

- The idea of 1/f noise as an envelope of Lorentzians with different time constants.
- Addition of Lorentzians with different τ values produced a 1/f spectrum if the weight of τ_i is proportional to $1/\tau_i$.

M. Surdin, “Fluctuations de courant thermionique et le ‘flicker effect’,” J. de Physique Radium. (Paris.), 10, 188–189 (1939).

1/f Noise Observed in Numerous Materials, Devices, and Beyond

- Since the first observation by Johnson (1925), the fluctuation processes with $1/f^{\gamma}$ (with $0.5 \lesssim \gamma \lesssim 1.5$) power spectra at low frequencies f have been observed in physics, technology, biology, astrophysics, geophysics, economics, psychology, language and music.

- Reviews by Press (1978), Hooge (1981), Dutta and Horn (1981), Kogan (1985), Weissman (1988), Van Vliet (1991), Milotti (2002).

The common name for this noise type does not imply the existence of a single physical mechanism that gives rise to all its manifestations.

- Electronics: fluctuations in the mobility *vs.* fluctuations in the number of charge carriers:

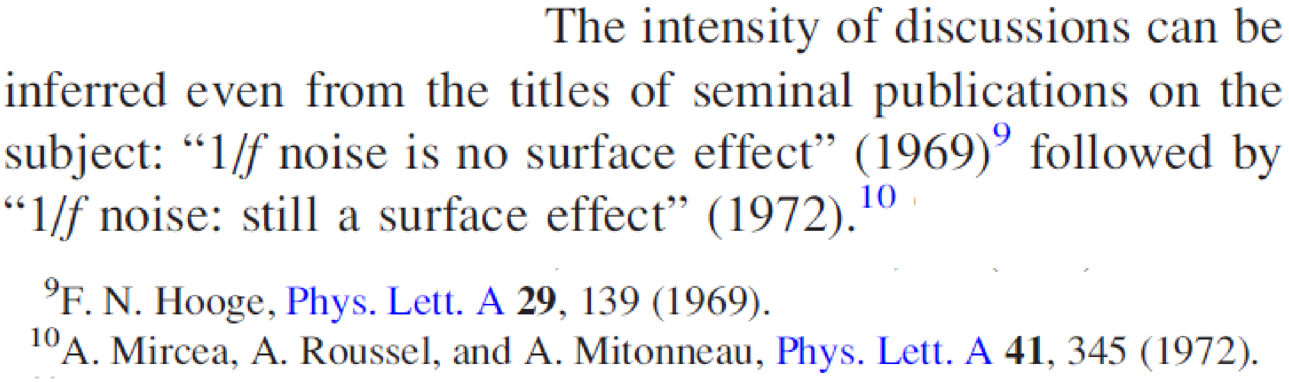
$$R = \rho \frac{L}{S} = \frac{1}{\sigma} \frac{L}{S} = \frac{1}{en\mu} \frac{L}{S}$$

Persistent Questions for 1/f Noise in Metals and Semiconductors

- Fluctuations in the mobility *vs.* fluctuations in the number of charge carriers:

$$R = \rho\frac{L}{S} = \frac{1}{\sigma}\frac{L}{S} = \frac{1}{en\mu}\frac{L}{S}$$

- Fluctuations in the volume of the material or on the surface:



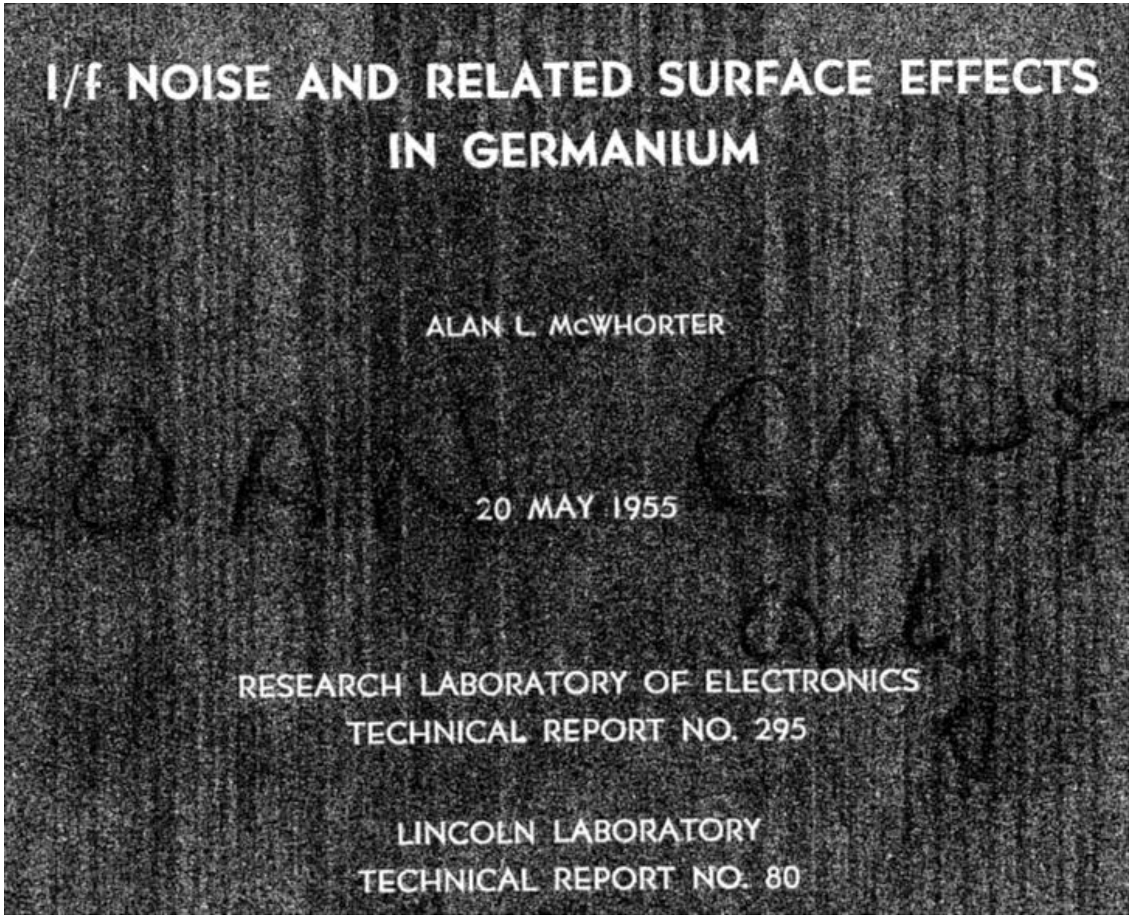
The intensity of discussions can be inferred even from the titles of seminal publications on the subject: "1/*f* noise is no surface effect" (1969)[9] followed by "1/*f* noise: still a surface effect" (1972).[10]

[9] F. N. Hooge, Phys. Lett. A **29**, 139 (1969).

[10] A. Mircea, A. Roussel, and A. Mitonneau, Phys. Lett. A **41**, 345 (1972).

- Low-frequency limit; etc.

McWhorter Model for 1/f Noise in Semiconductors



1/f NOISE AND RELATED SURFACE EFFECTS
IN GERMANIUM

ALAN L. McWHORTER

20 MAY 1955

RESEARCH LABORATORY OF ELECTRONICS
TECHNICAL REPORT NO. 295

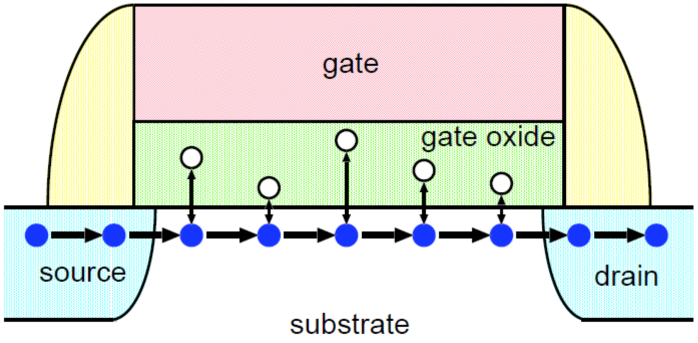
LINCOLN LABORATORY
TECHNICAL REPORT NO. 80

- → Noise is due to the fluctuations in the number of charge carriers
- → One of few conventionally accepted models
- → Many modifications of the model exist

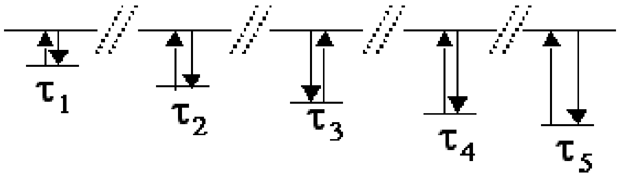
Mechanism of 1/*f* Noise in Electronic Materials – McWhorter Model

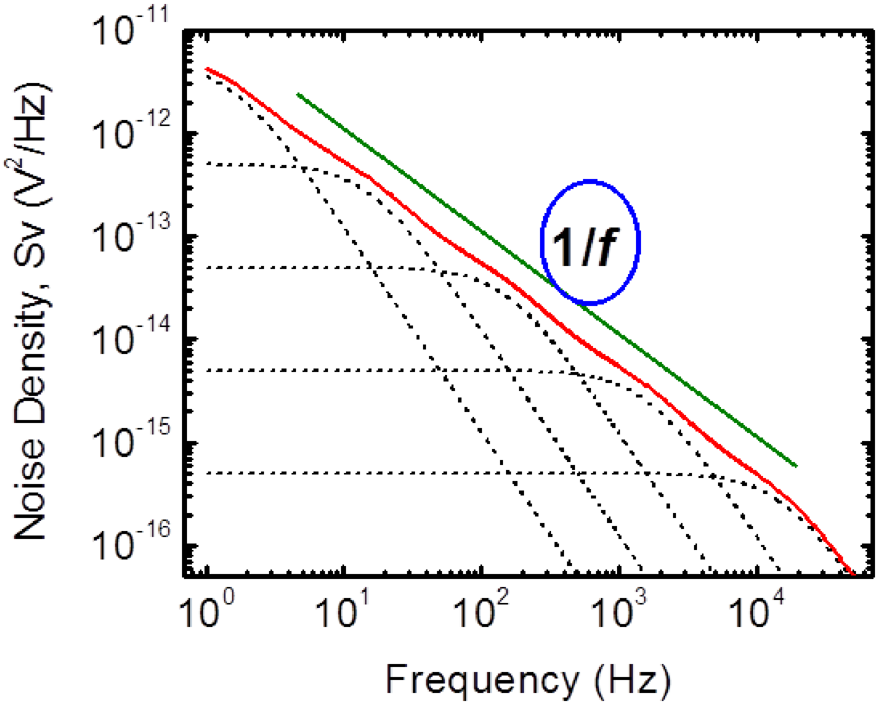
$$I \sim qN\mu$$

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



Series of levels

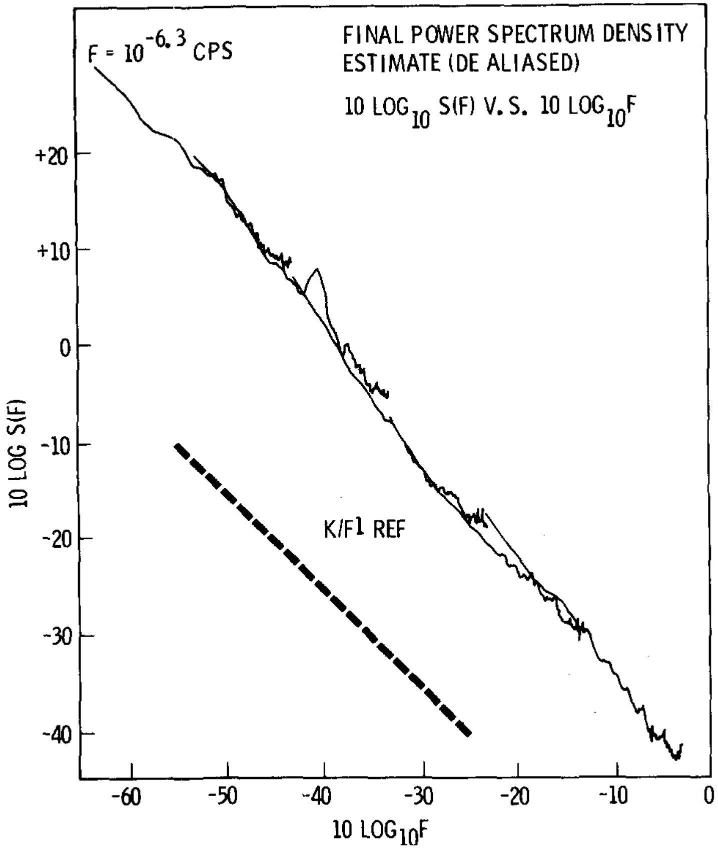




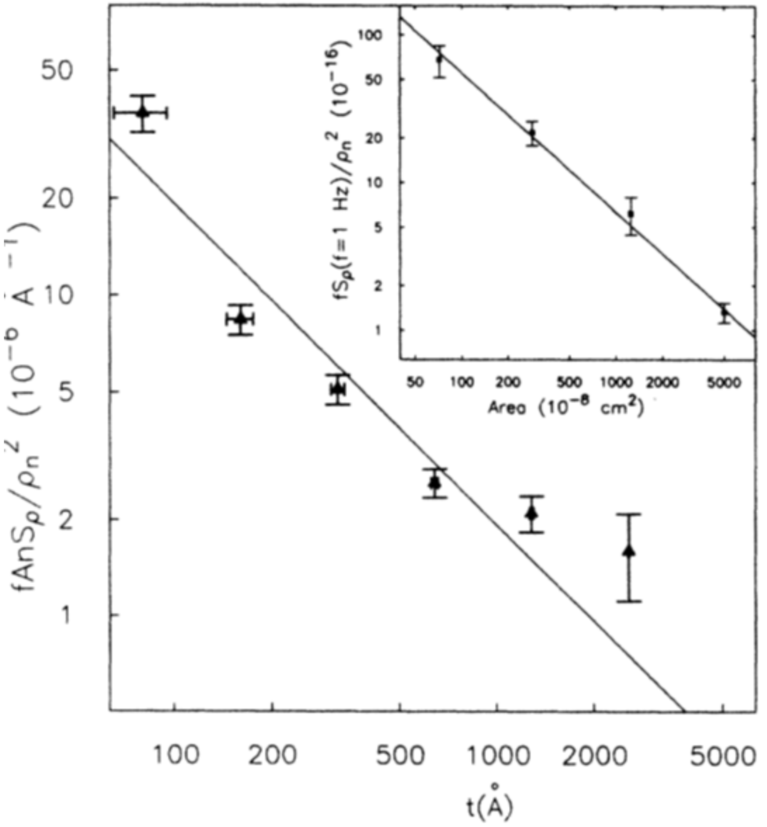
McWhorter's model: $g(\tau_N) = [\tau_N \ln(\tau_2 / \tau_1)]^{-1}$

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

Experimentally Established Characteristics of 1/f Noise



M. A. Caloyannides, J. Appl. Phys., 45, 307 (1974)



N. M. Zimmerman, et al., Phys. Rev. B, 34, 773 (1986).

Comparing 1/f Noise in Different Systems – Figure of Merit

Empirical Hooge relation:

$$\frac{S_R}{R^2} = \frac{S_G}{G^2} = \left(\frac{S_V}{V^2}\right)_I = \left(\frac{S_I}{I^2}\right)_V = \frac{\alpha_H}{fN}$$

F.N. Hooge, 1/f Noise, Physica, 83 B, 14 – 23 (1976)

→ From constant 2×10^{-3} to a parameter without model assumption

→ The relation normalizes the relative noise to one electron. The only assumption behind this equation is that the electrons are independent.

Lode K. J. Vandamme and F. N. Hooge, What do we certainly know about 1/f noise in MOSTs? IEEE Trans. Electron Devices, 55, 3070 (2008).

Metrics: normalized noise spectral density (volume or area) and noise amplitude

The 1/f Noise Among Other Types of Electronic Noise

Intrinsic Electronic Noise

Thermal noise:

$S_I=4k_BT/R$

Shot noise:

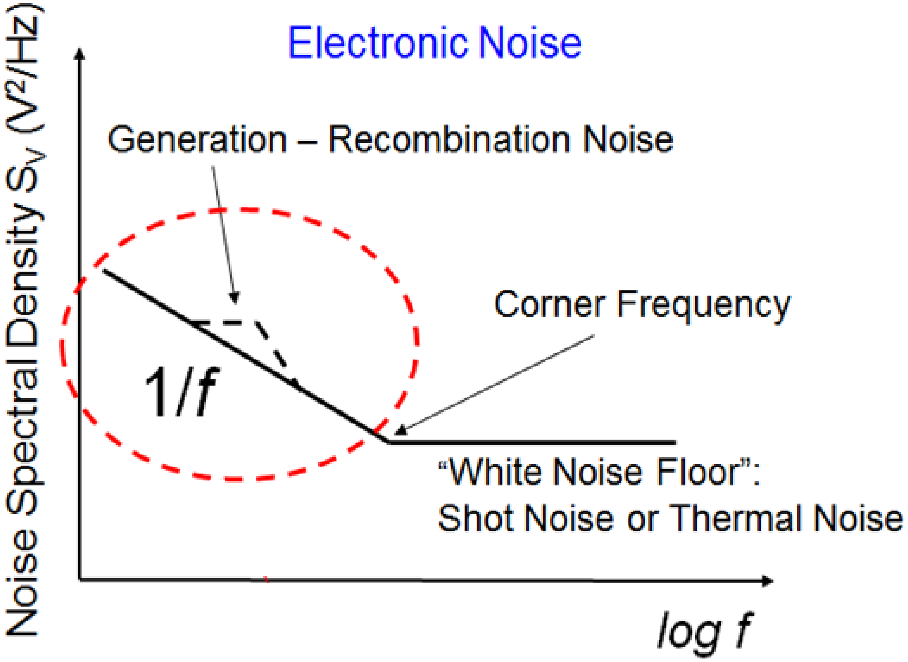
$S_I=2e\langle I\rangle$

G-R noise:

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

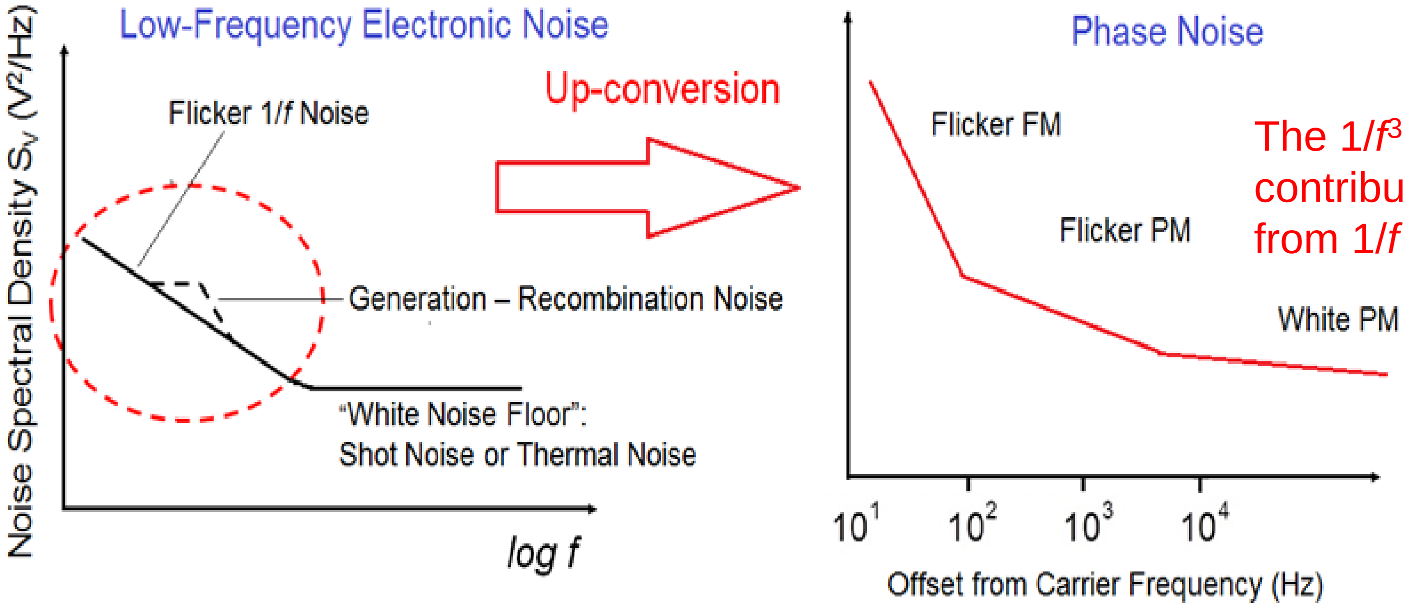
Flicker 1/f noise:

$S_I \sim I^2/f$



Adapted from A.A. Balandin (Ed.), *Noise and Fluctuations Control in Electronic Devices* (ASP, Los Angeles 2002).

Importance of 1/*f* Noise Reduction: 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

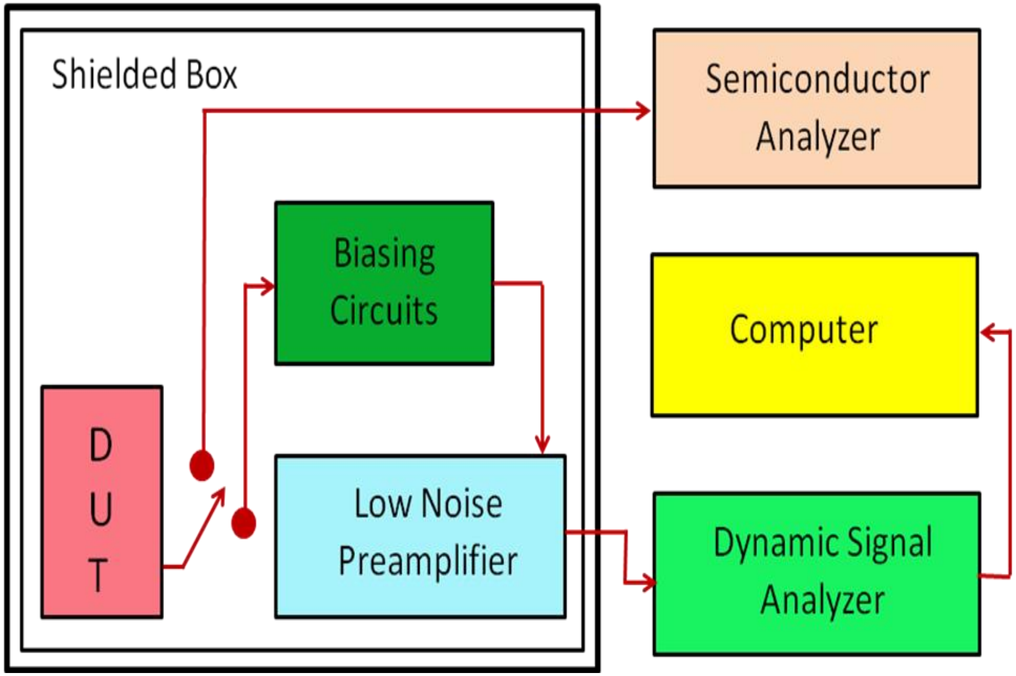
Communication systems: noise is an error or undesired random disturbance of a useful information signal introduced before or after the detector and decoder.

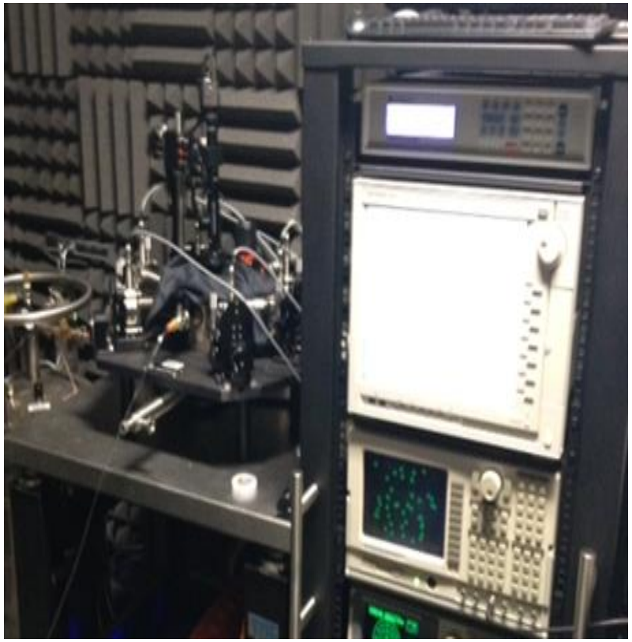
Importance of the Excess Noise: From the “Show Stopper” to the Useful Signal

- 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
- The 1/f noise limits sensors’ sensitivity
- Large device-to-device variations in noise
- Graphene and other low-dimensional van der Waals materials can be more susceptible to noise because they are surfaces exposed to traps

- Characterization tool to understand trap dynamics and electron transport in a given materials system
- Quality assessment tool ← see the poster on noise in diamond diodes
- Noise as a sensing signal
- Monitoring phase transitions ← see the poster on 2D AFM materials

Low-Frequency Noise Measurements

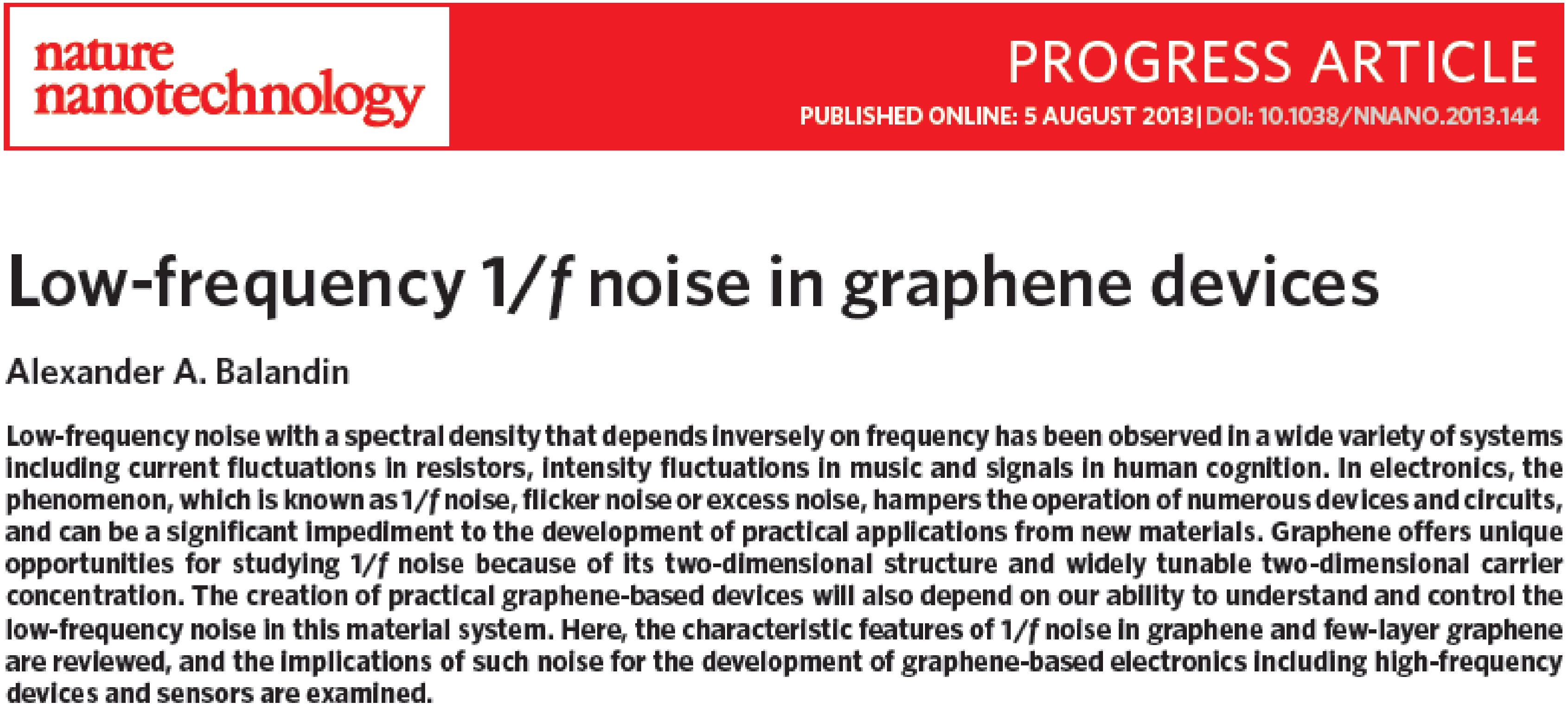




→ The noise measurement set-up is placed inside a special room with the metal and acoustic protection from the environmental noises and electro-magnetic fields

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

Part II: 1/*f* Noise in Graphene



nature nanotechnology

PROGRESS ARTICLE

PUBLISHED ONLINE: 5 AUGUST 2013 | DOI: 10.1038/NNANO.2013.144

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

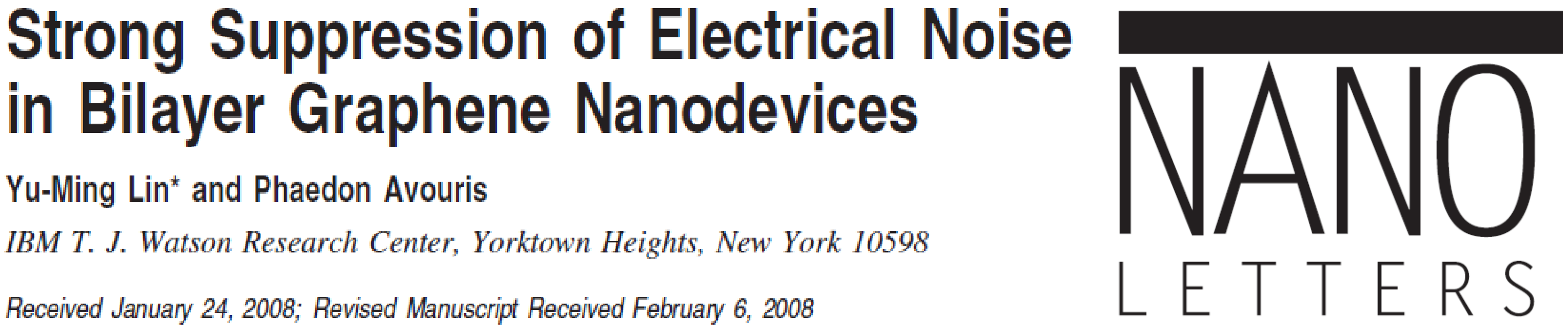
Alexander A. Balandin

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.

A. A. Balandin, "Low-frequency 1/f noise in graphene devices," Nature Nano, 8, 549–555 (2013).

The Frist Papers on 1/f Noise in Graphene and Bilayer Graphene

Why study noise in graphene? – There are both physics and applications related reasons



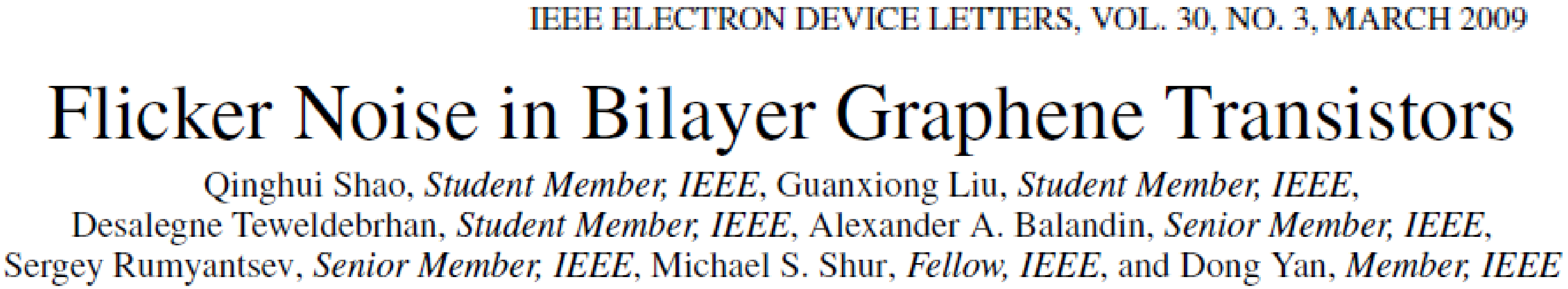
Strong Suppression of Electrical Noise in Bilayer Graphene Nanodevices

Yu-Ming Lin* and Phaedon Avouris

IBM T. J. Watson Research Center, Yorktown Heights, New York 10598

Received January 24, 2008; Revised Manuscript Received February 6, 2008

NANO LETTERS



IEEE ELECTRON DEVICE LETTERS, VOL. 30, NO. 3, MARCH 2009

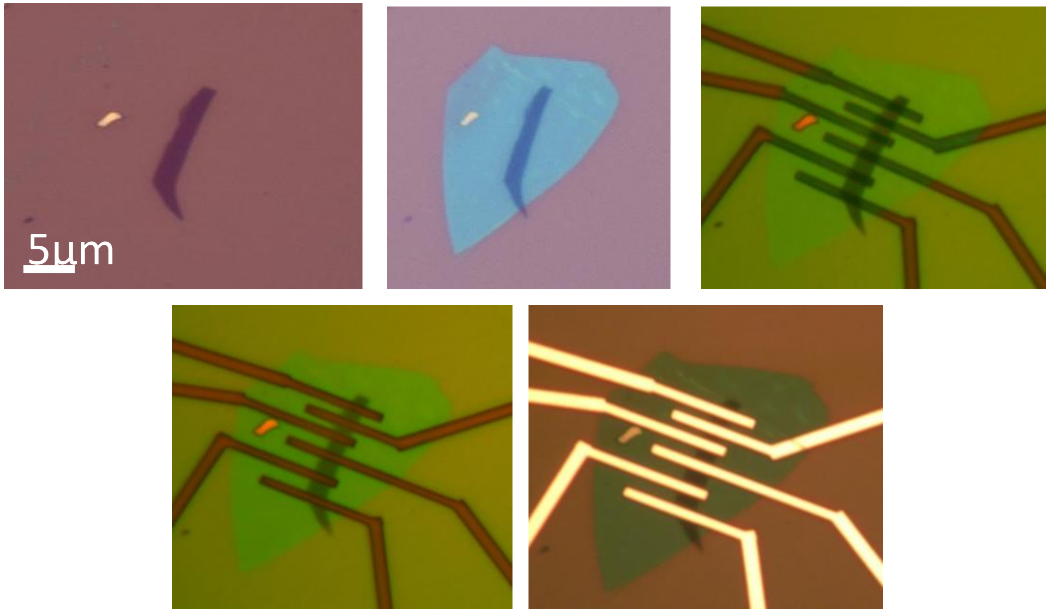
Flicker Noise in Bilayer Graphene Transistors

Qinghui Shao, *Student Member, IEEE*, Guanxiong Liu, *Student Member, IEEE*,
Desalegne Teweldebrhan, *Student Member, IEEE*, Alexander A. Balandin, *Senior Member, IEEE*,
Sergey Rumyantsev, *Senior Member, IEEE*, Michael S. Shur, *Fellow, IEEE*, and Dong Yan, *Member, IEEE*

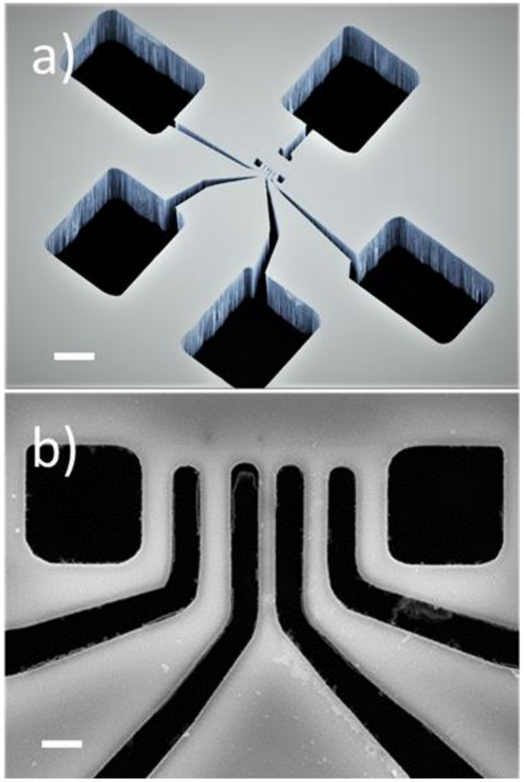
| Nano-Device Laboratory >

Fabrication of Test Structures with Van der Waals Materials

E-Beam Lithography

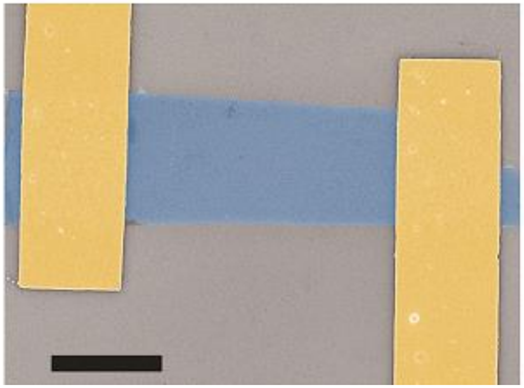


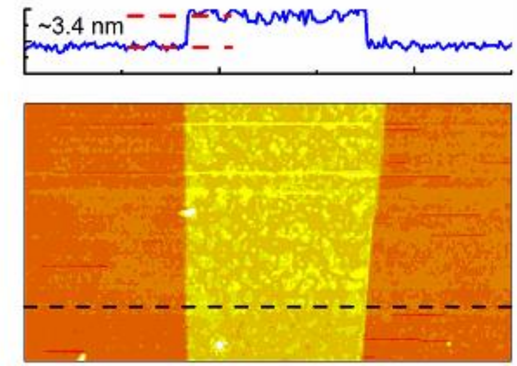
Shadow Mask Method



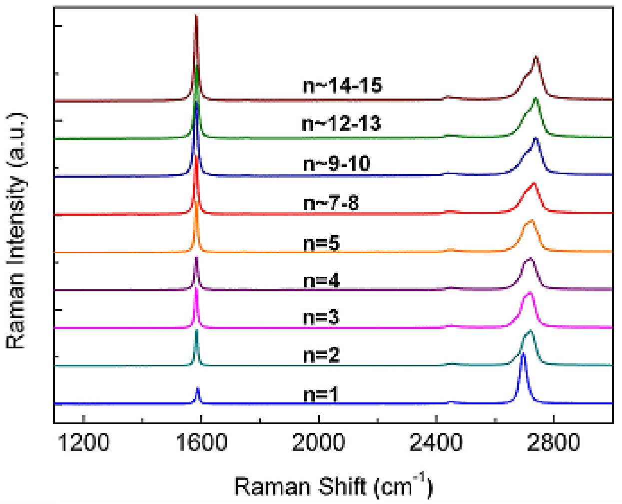
M. A. Stolyarov, et al., Nanoscale, 8, 15774 (2016).
A. Geremew, et al., IEEE Electron Device Lett., 39, 735 (2018).
A. Mohammadzadeh, et al., Appl. Phys. Lett., 118, 223101 (2021).

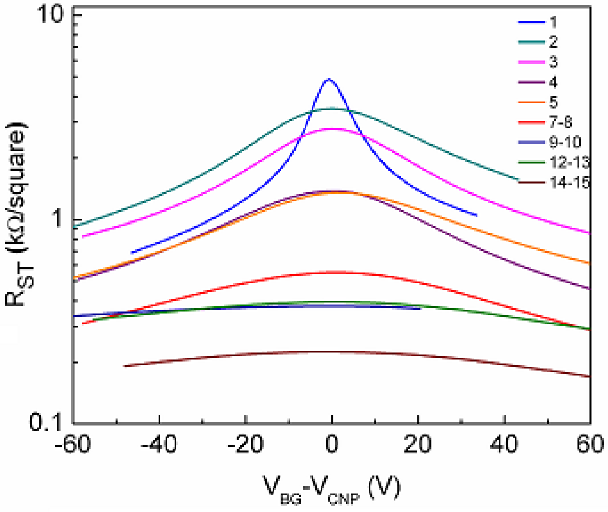
High-Quality Few-Layer Graphene Samples





- → Practical task of noise scaling with the thickness
- → Possibility of addressing the problem of origin of noise



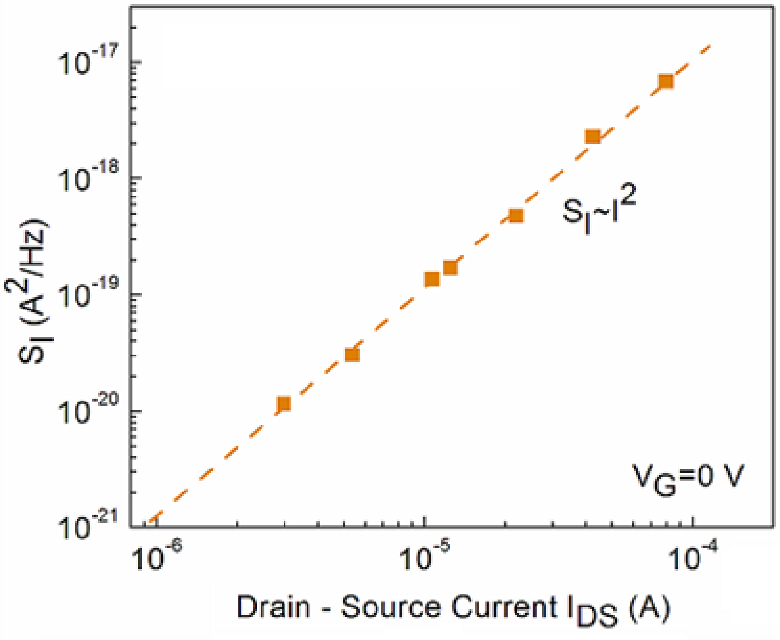


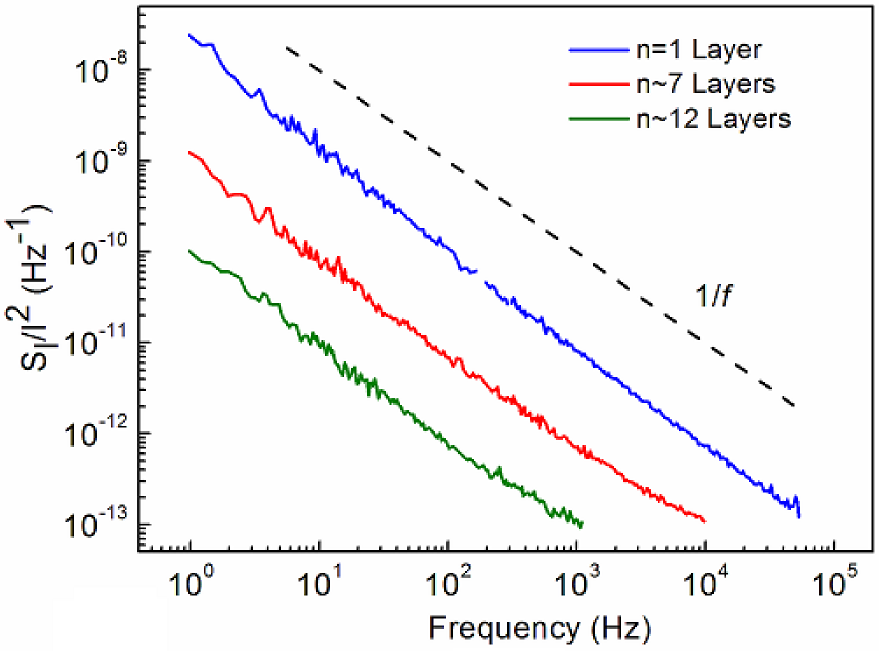
The back-gated devices were fabricated by the electron-beam lithography with Ti/Au (6-nm/60-nm) electrodes.

R_{ST} is sheet resistance

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

Low-Frequency Noise in Few-Layer Graphene Devices



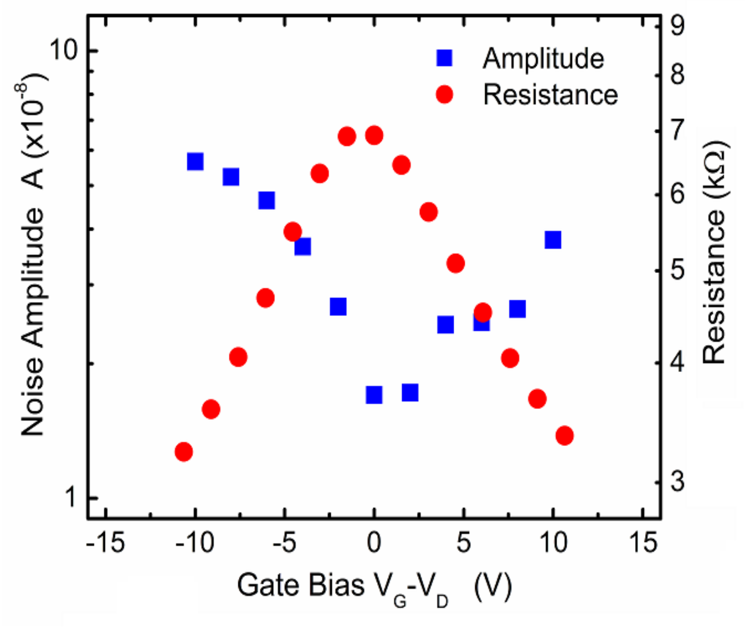


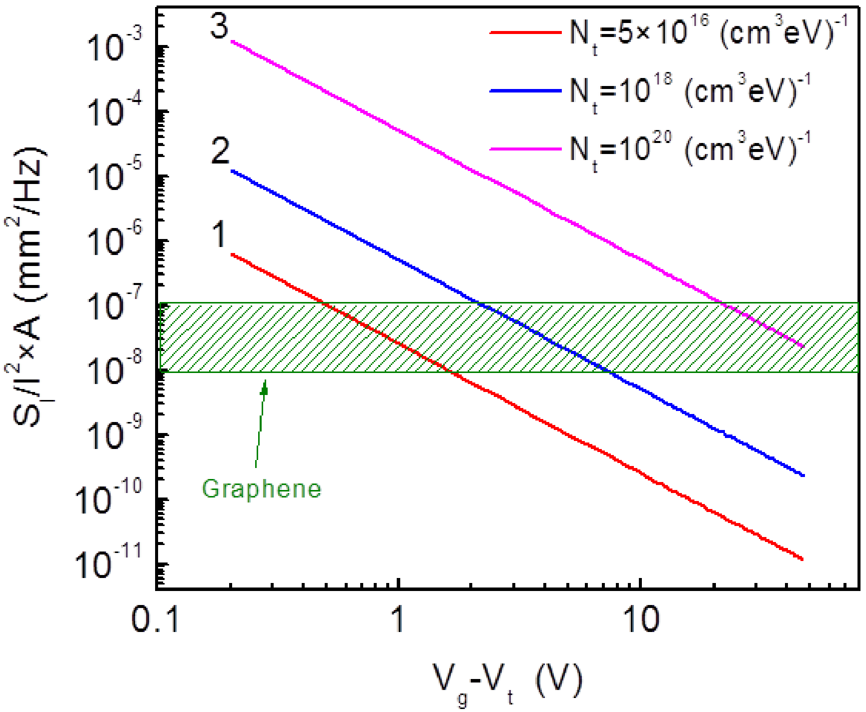
→ The 1/f noise in FLG is dominated by the volume noise when the thickness exceeds 7 atomic layers (~2.5 nm). The 1/f noise is the surface phenomenon below this thickness.

G. Liu, S. Rumyantsev, M. S. Shur, and A. A. Balandin, “Origin of 1/ f noise in graphene multilayers: surface vs. volume,” Appl. Phys. Lett., **102**, 93111 (2013).

Features 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 at lager biases

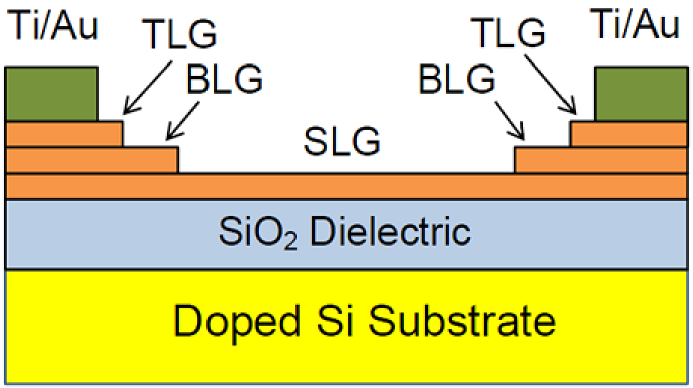
S_I/I^2 =10^{-9} to 10^{-7} Hz^{-1} at f=10 Hz or A=10^{-9} – 10^{-7}

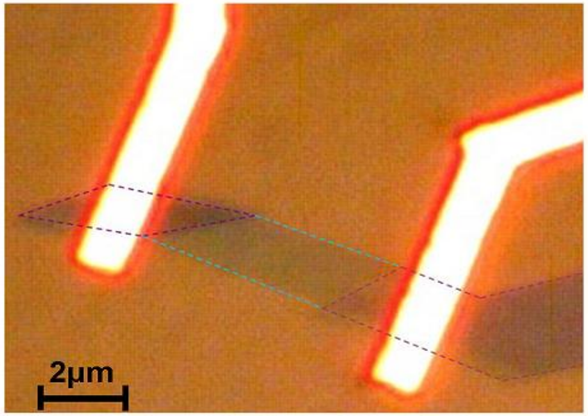
$(S_I/I^2)L\times W$ =10^{-8} – 10^{-7} μm^2/Hz

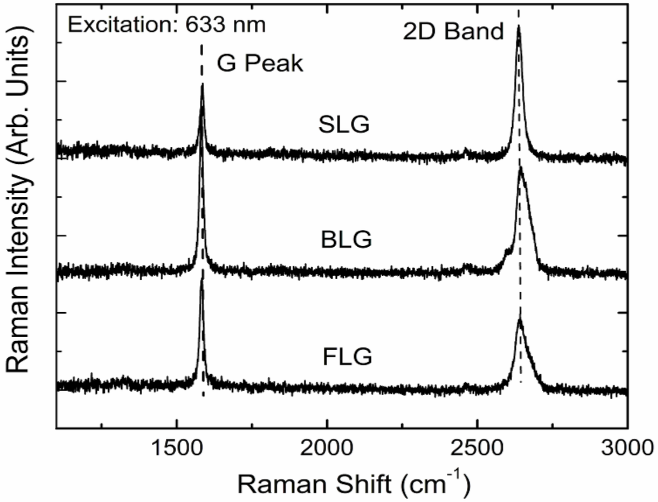
S. Rumyantsev, G. Liu, M. Shur, and A. A. Balandin, "Electrical and noise characteristics of graphene FETs: ambient effects, noise sources and physical mechanisms.," J. Phys. Condens. Matter, 22, 395302 (2010).

Thickness-Graded Few-Layer Graphene FETs

Graded-Thickness Graphene FET



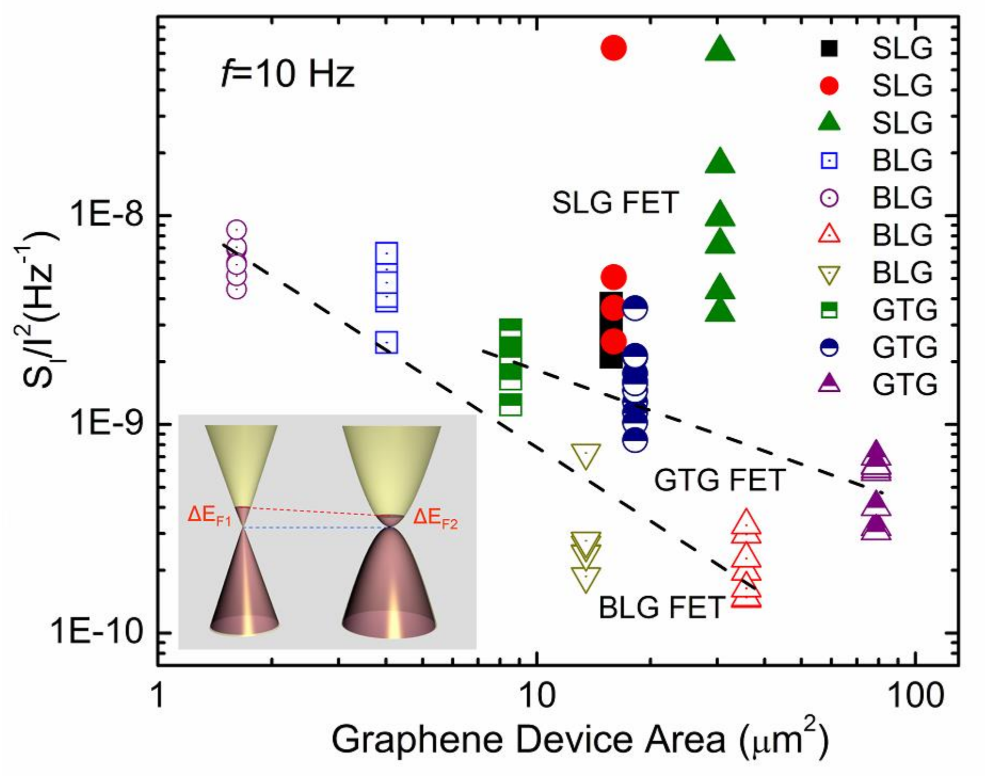




The SLG, GTG and BLG FETs, fabricated using the same process, had the RT electron mobility values: ~5000 – 7000 cm^2/Vs, ~4000 – 5000 cm^2/Vs and ~1000 – 2000 cm^2/Vs, respectively

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



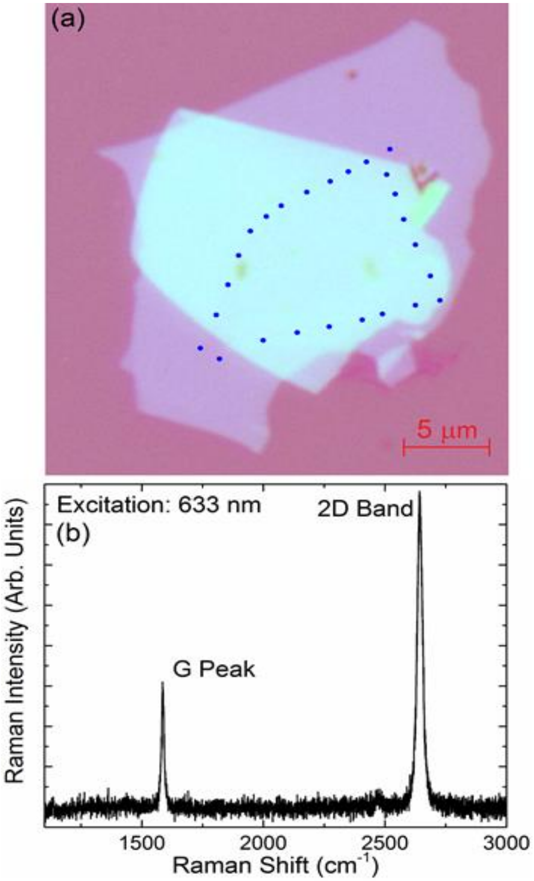
Graphene thickness-graded transistors with high electron mobility and low1/f noise

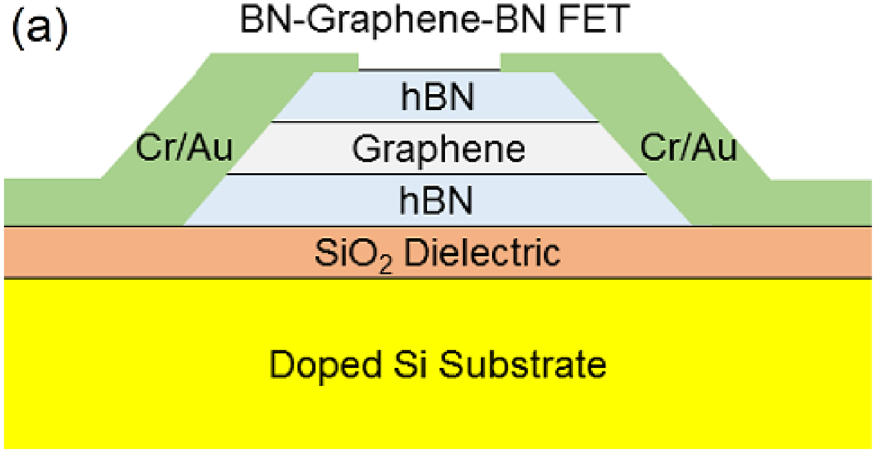
The same amount of the charge, transferred owing to the metal contact doping, leads to a smaller local Fermi level shift in BLG devices than in SLG devices owing to the difference in the electron DOS.

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).

Fabrication of BN-Graphene-BN Heterostructures



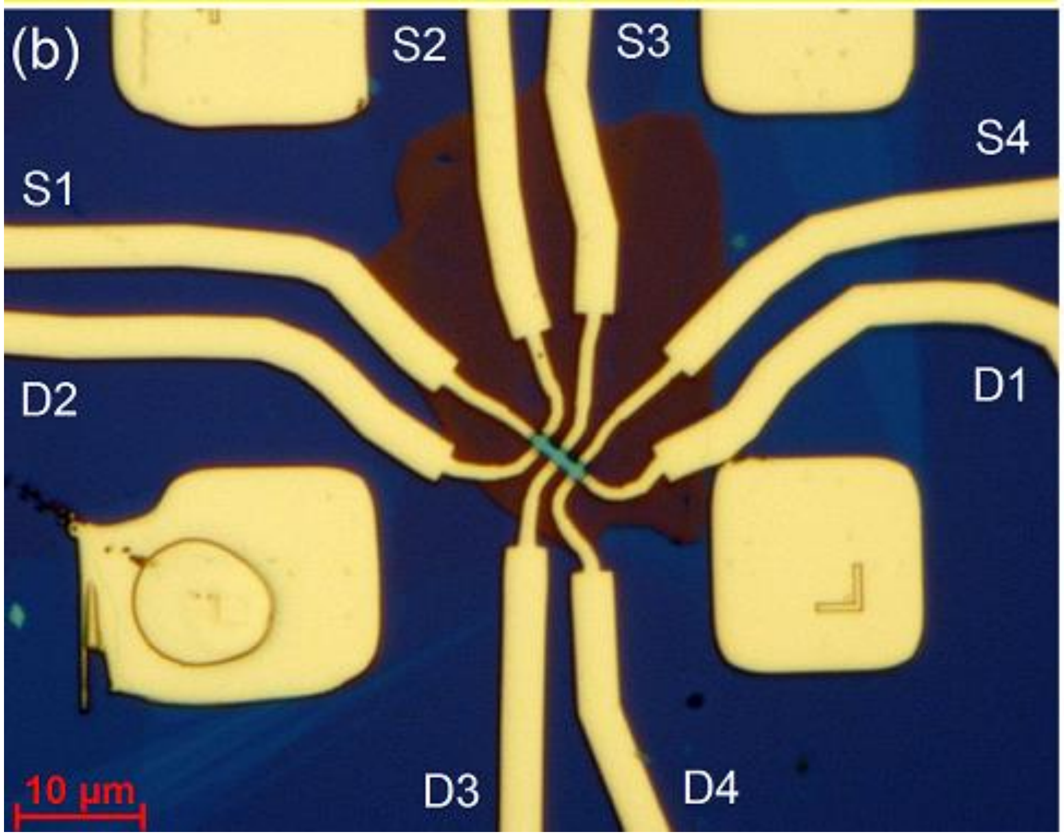


→ Dry transfer method

→ Use of viscoelastic stamps adhered to glass slides as transparent stamps for layer transfer

→ The “1D contact” technology

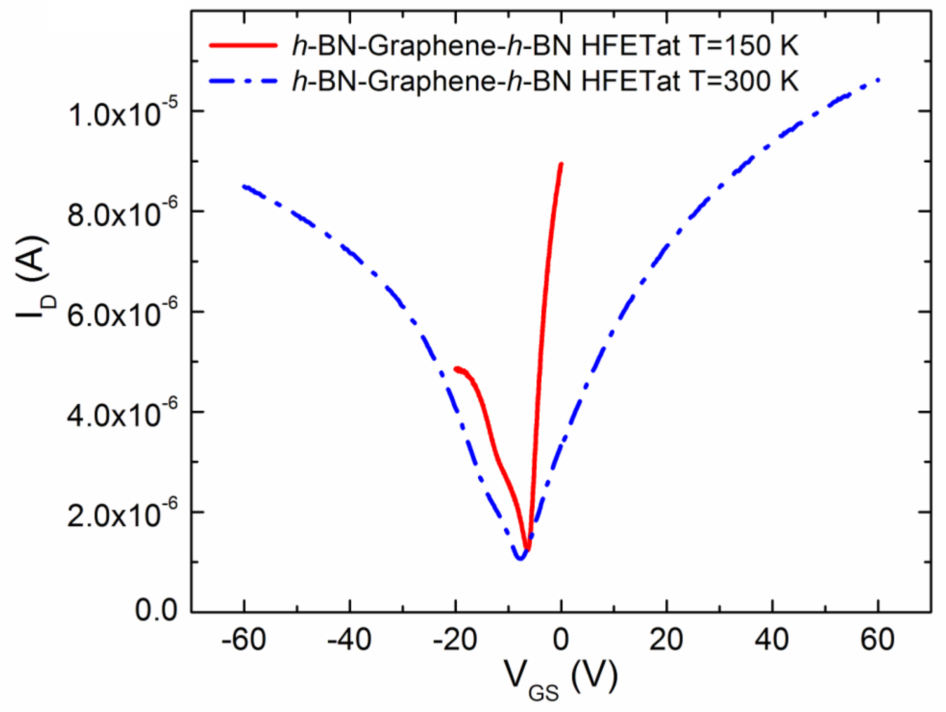
BN-Graphene-BN Heterostructure FET



Optical microscopy image of a representative graphene encapsulated HFET. The source and drain contacts of the device are denoted with S and D symbols, respectively.

M. A. Stolyarov, G. Liu, S. L. Rumyantsev, M. Shur and A. A. Balandin, "Suppression of 1/f noise in near-ballistic h-BN-graphene-h-BN heterostructure fieldeffect transistors," Applied Physics Letters, 107, 023106 (2015).

Mobility in BN-Graphene-BN HFETs



M. A. Stolyarov, G. Liu, S. L. Rumyantsev, M. Shur and A. A. Balandin, Suppression of 1/f noise in near-ballistic h-BN-graphene-h-BN heterostructure fieldeffect transistors, Appl. Phys. Lett., 107, 023106 (2015).

Current – voltage transfer characteristics of h-BN-G-h-BN HFETs. The source-drain voltage is 10 mV.

$$\mu_{EFF} = \frac{L_G}{R_{EFF}C_G(V_{GS} - V_D)W}$$

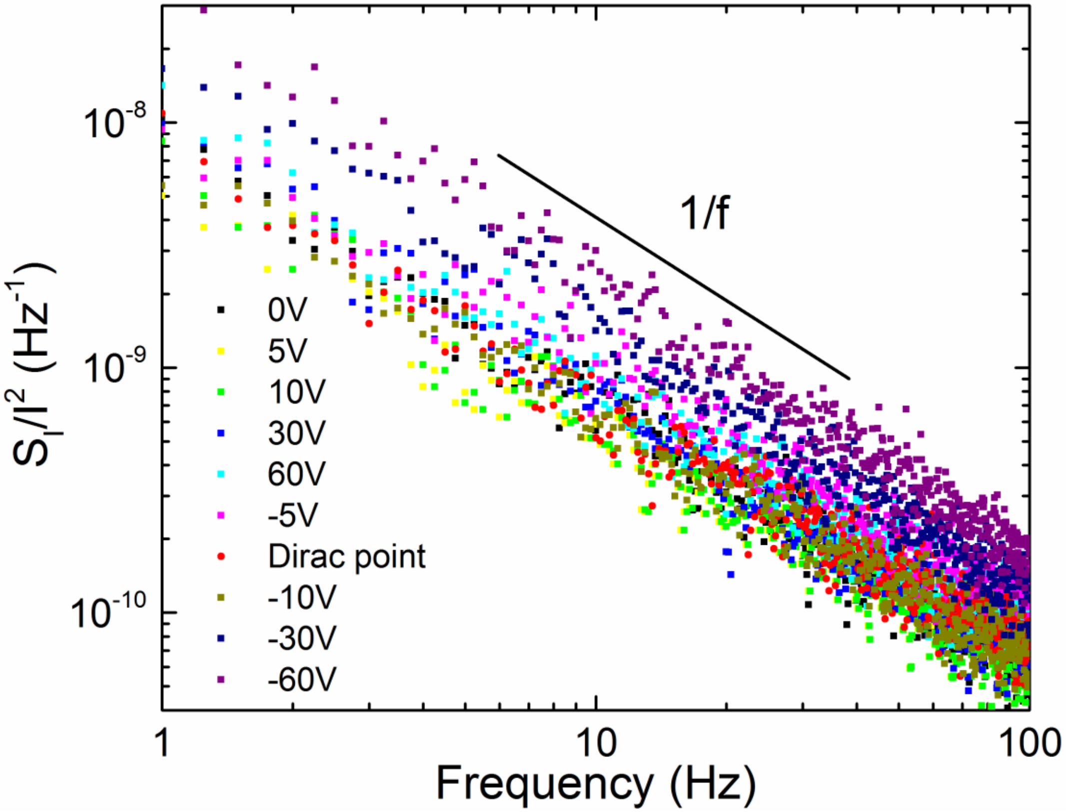
$$R_{EFF} = \frac{R_{DS} - R_C}{1 - \sigma_0(R_{DS} - R_C)}$$

$$\mu_{FE} = \frac{g_{m0}}{C_G(V_{DS} - IR_C)}\frac{L_G}{W}$$

$$g_{m0} \approx g_m\left(1 + \frac{R_C}{R_{EFF}} + R_C\sigma_0\right)$$

The charge carrier mobility in the range from ~30000 to ~36000 cm^2/Vs at room temperature.

Low-Frequency Noise in BN-Graphene-BN HFETs



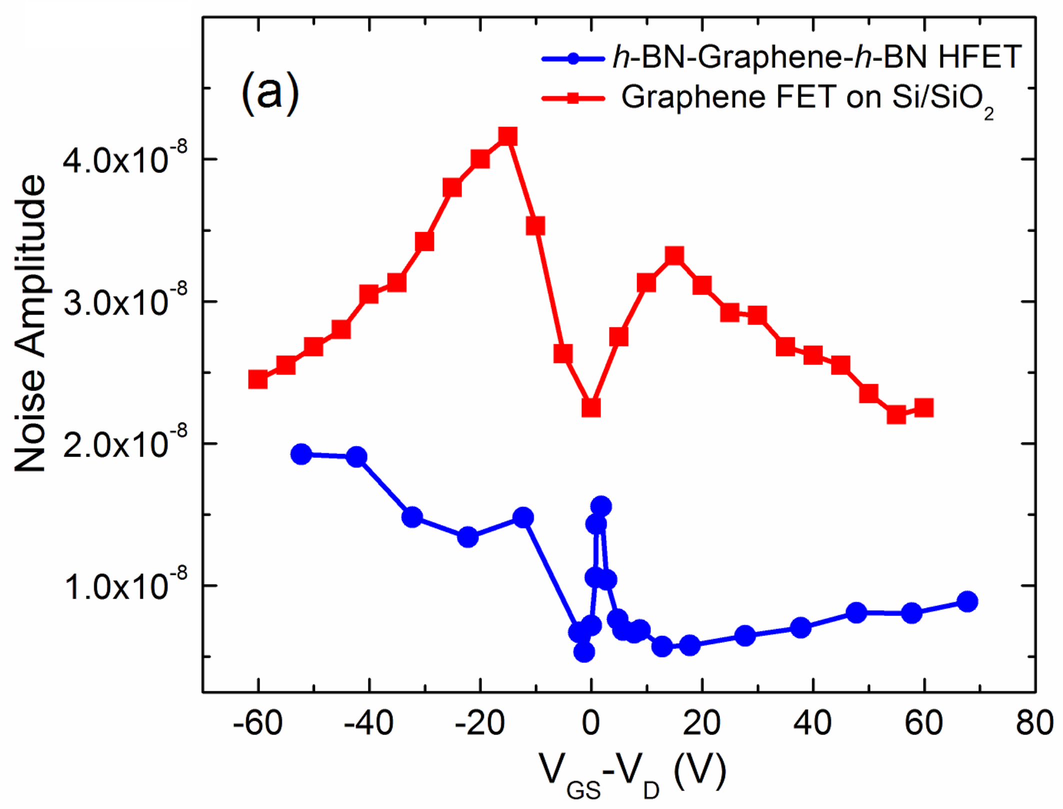
Normalized noise spectrum density in h-BN-G-h-BN HFET as a function of frequency for several values of the back-gate bias VG. Note that V_G=-7.75 V corresponds to the Dirac point.

M. A. Stolyarov, G. Liu, S. L. Rumyantsev, M. Shur and A. A. Balandin, "Suppression of 1/f noise in near-ballistic h-BN-graphene-h-BN heterostructure fieldeffect transistors," Applied Physics Letters, 107, 023106 (2015).

$S \sim 1/f^{\gamma}$

V_G (V)	-60	-30	-10	-8	-5	0	5	10	30	60
γ (device A)	1.16	1.04	0.96	1.19	0.95	1.16	0.97	1.12	1.12	1.20
γ (device B)	1.27	0.84	0.95	1.04	1.02	1.02	0.96	0.94	1.04	1.05

Comparison of the Noise Level in BN-Graphene-BN HFETs

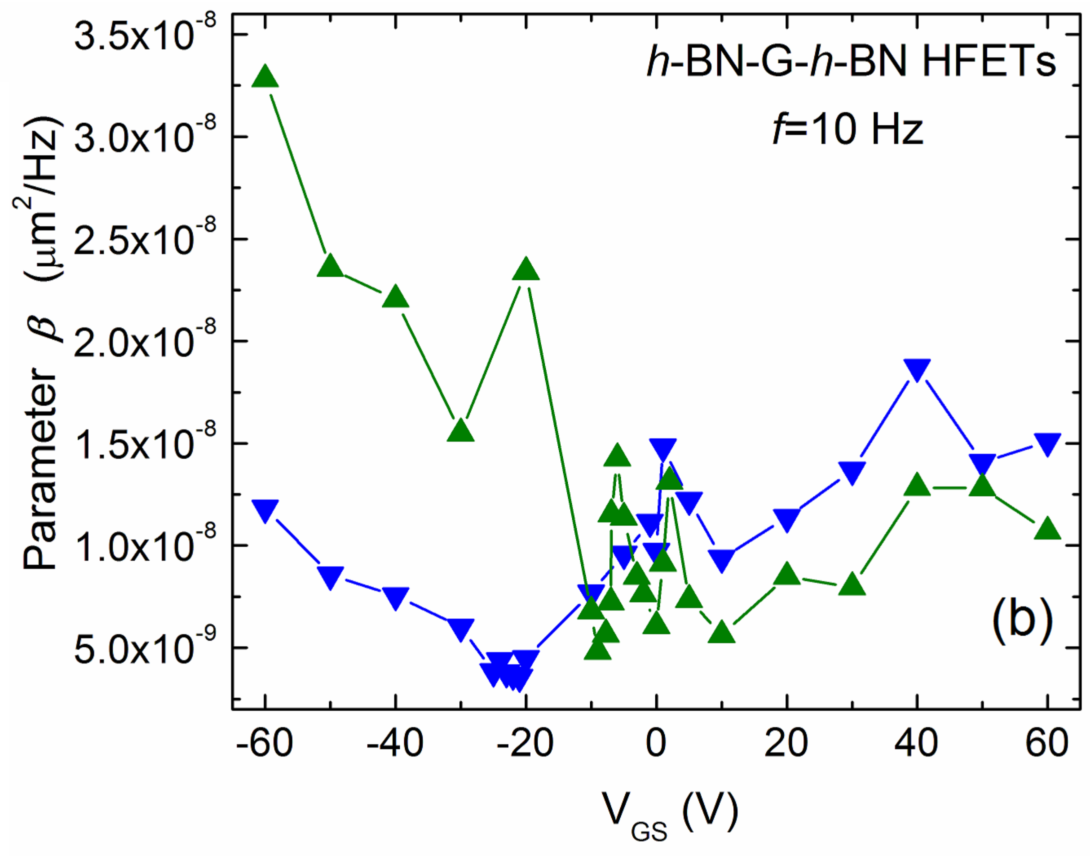


Noise amplitude as a function of the gate bias with respect to the Dirac point, V_{GS}-V_D for h-BN-G-h-BN HFET.

The data for conventional non-encapsulated graphene FET on Si/SiO$_2$ wafer is after G.Y. Xu, et al., Nano Letters, 10, 3312 (2010).

M. A. Stolyarov, G. Liu, S. L. Rumyantsev, M. Shur and A. A. Balandin, Suppression of 1/f noise in near-ballistic h-BN-graphene-h-BN heterostructure field-effect transistors, Appl. Phys. Lett., 107, 023106 (2015).

Parameter to Characterize Noise Level in 2D Devices



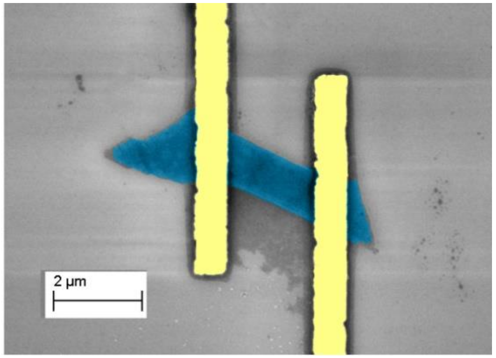
Parameter β, which defines 1/f noise level in 2D channels plotted as a function of gate bias for two representative devices.

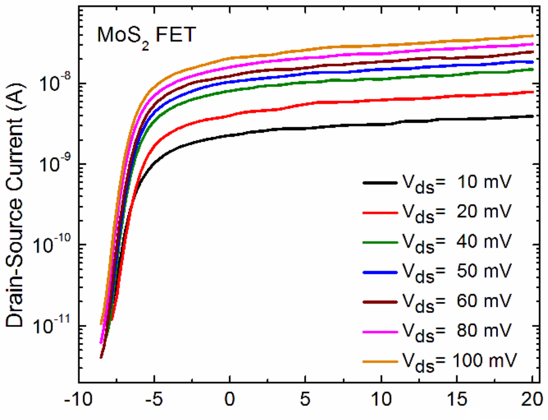
$$\beta = (S_I/I^2)(W\times L)$$

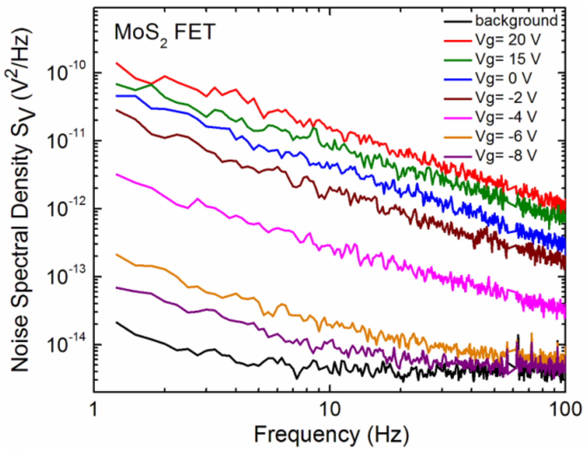
$$\alpha_H = \frac{S_I}{I^2} f N$$

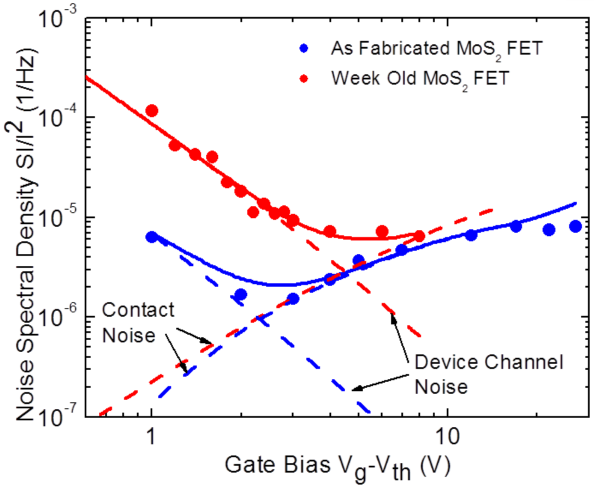
M. A. Stolyarov, G. Liu, S. L. Rumyantsev, M. Shur and A. A. Balandin, Suppression of 1/f noise in near-ballistic h-BN-graphene-h-BN heterostructure field-effect transistors, Appl. Phys. Lett., 107, 023106 (2015).

Noise in MoS_2 Thin Film Transistors – McWhorter Model Description







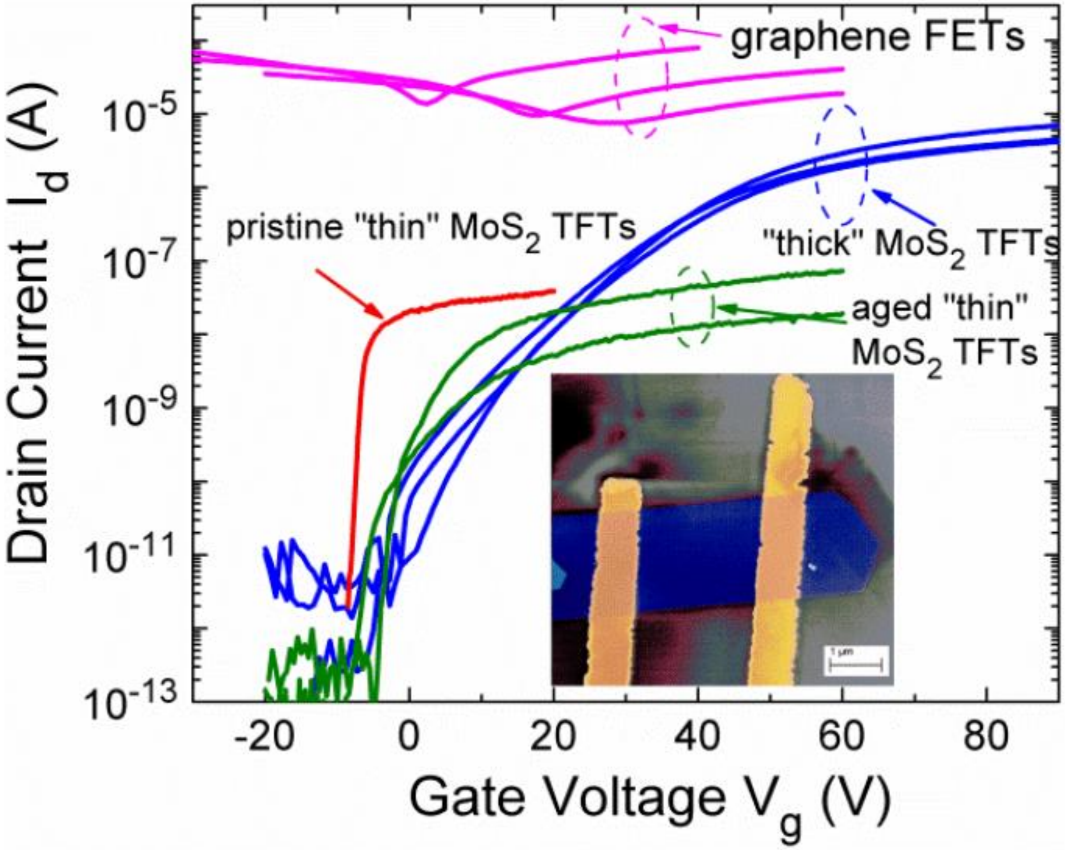


$$\frac{S_I}{I_{ds}^2} = \frac{S_{RCH}}{R_{CH}^2}\frac{R_{CH}^2}{\left(R_{CH}+R_C\right)^2} + \frac{S_{RC}}{R_C^2}\frac{R_C^2}{\left(R_{CH}+R_C\right)^2}$$

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, Appl. Phys. Lett., **104**, 153104 (2014).

Comparison of Current-Voltage Characteristics in Graphene and MoS_2 FETs

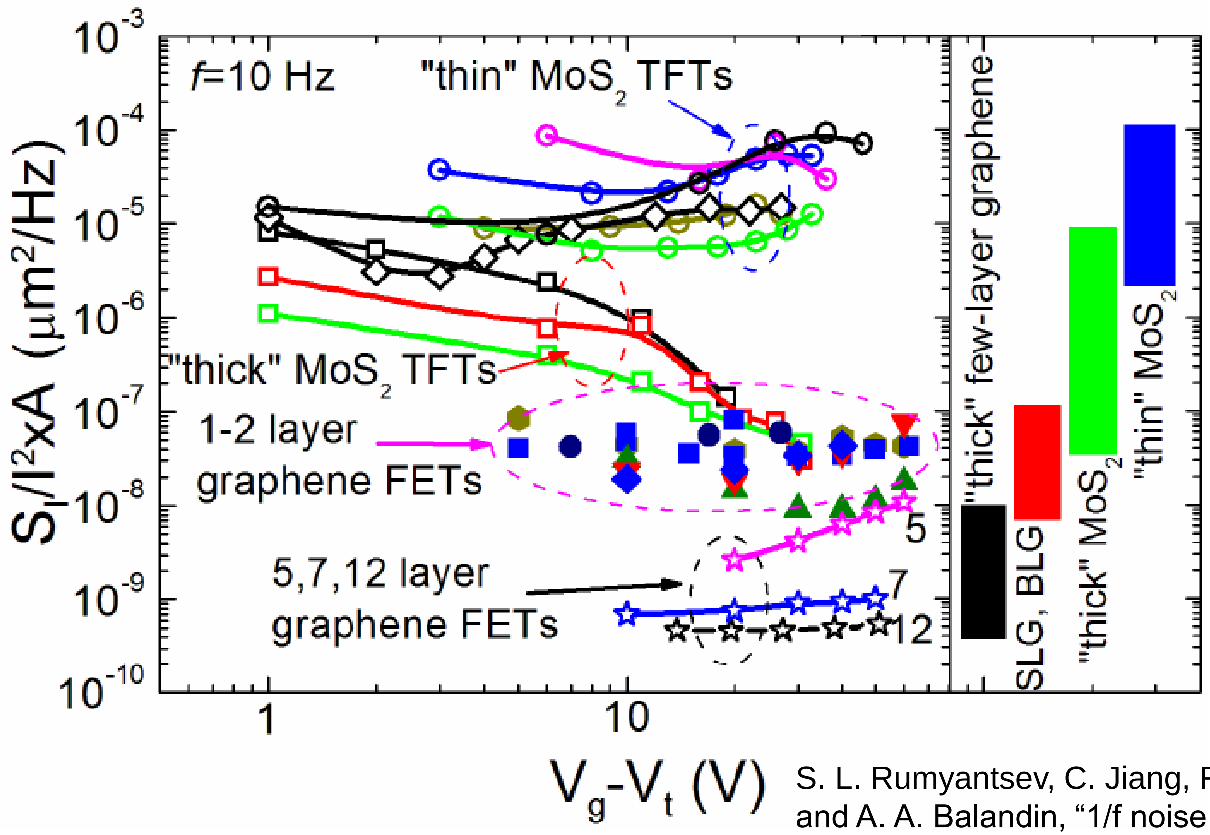


→ MoS_2 TF-FETs) with thin (2–3 atomic layers) and thick (15–18 atomic layers) channels.

→ The “thick” MoS_2 channels have advantages of the higher mobility and lower noise level.

S. L. Rumyantsev, C. Jiang, R. Samnakay, M. S. Shur, and A. A. Balandin, “1/f noise characteristics of MoS2 thin-film transistors: comparison of single and multilayer structures,” IEEE Electron Device Lett., 36, 517 (2015).

Comparison of 1/f Noise Level in Graphene and MoS_2 FETs



The normalized noise spectral density in “thick” MoS_2 FETS is of the same level as that in graphene FETs.

MoS_2 FETs with “thick” channels (15–18 could be described by the McWhorter model.

S. L. Rumyantsev, C. Jiang, R. Samnakay, M. S. Shur, and A. A. Balandin, “1/f noise characteristics of MoS2 thin-film transistors: comparison of single and multilayer structures,” IEEE Electron Device Lett., 36, 517 (2015).

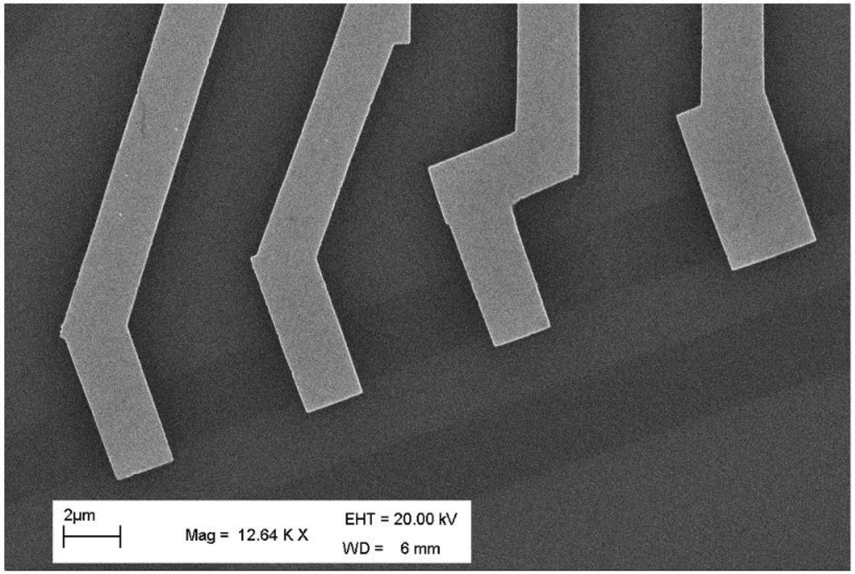
Investigation of 1/*f* Noise in Graphene Devices under Irradiation

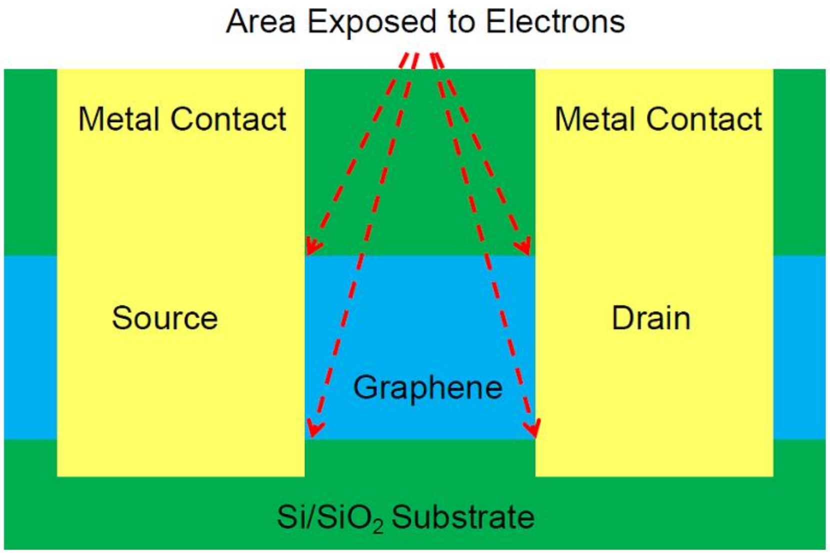
Goal

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

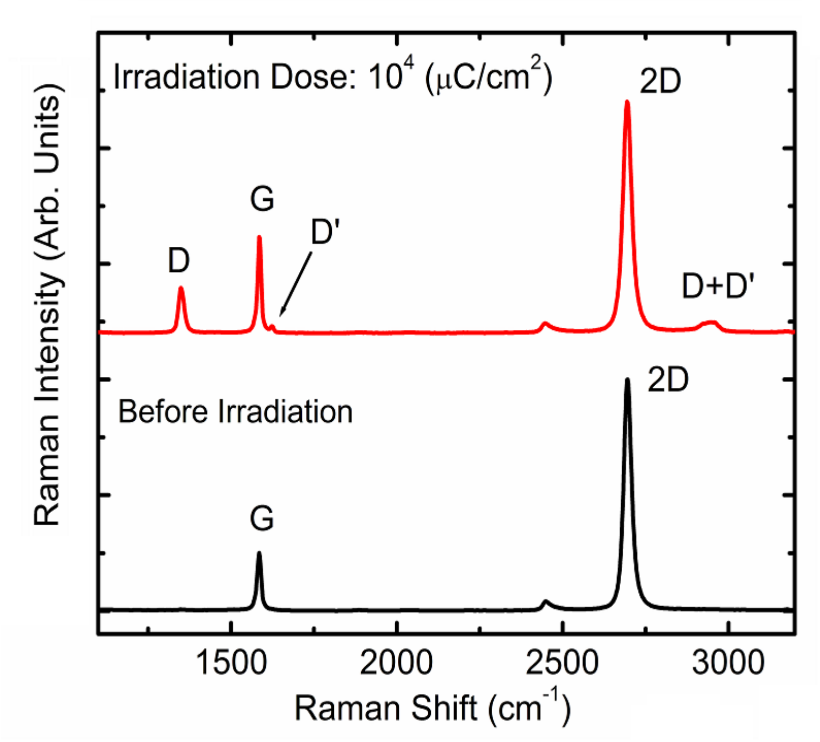
Methodology

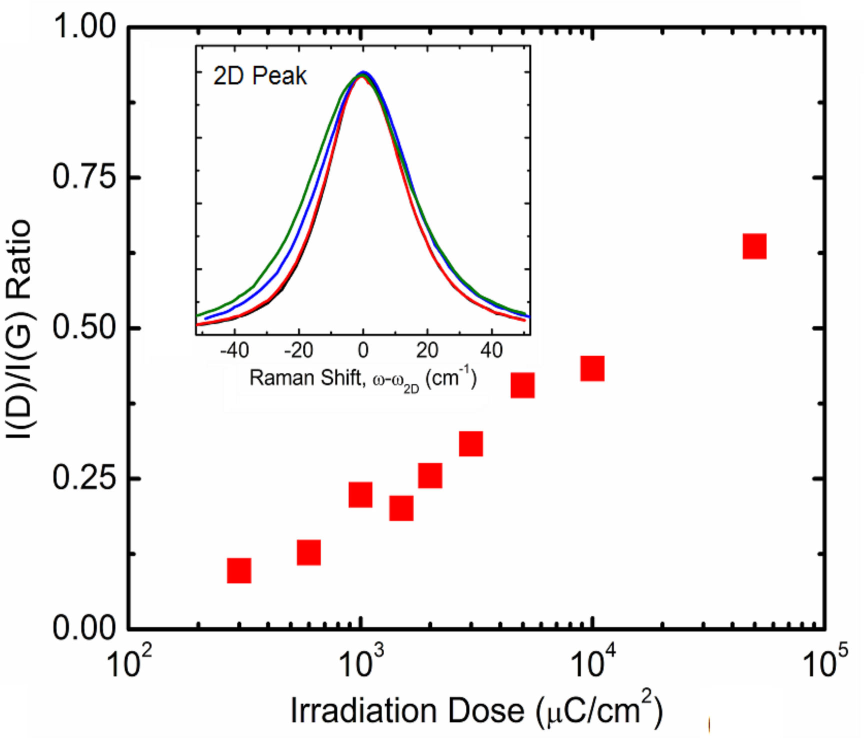
Step I: Raman of pristine graphene
Step II: IV characteristics and noise measurements
Step III: E-beam irradiation of the device
Step III: Raman of the irradiated device
Step IV: IV characteristics and noise measurements





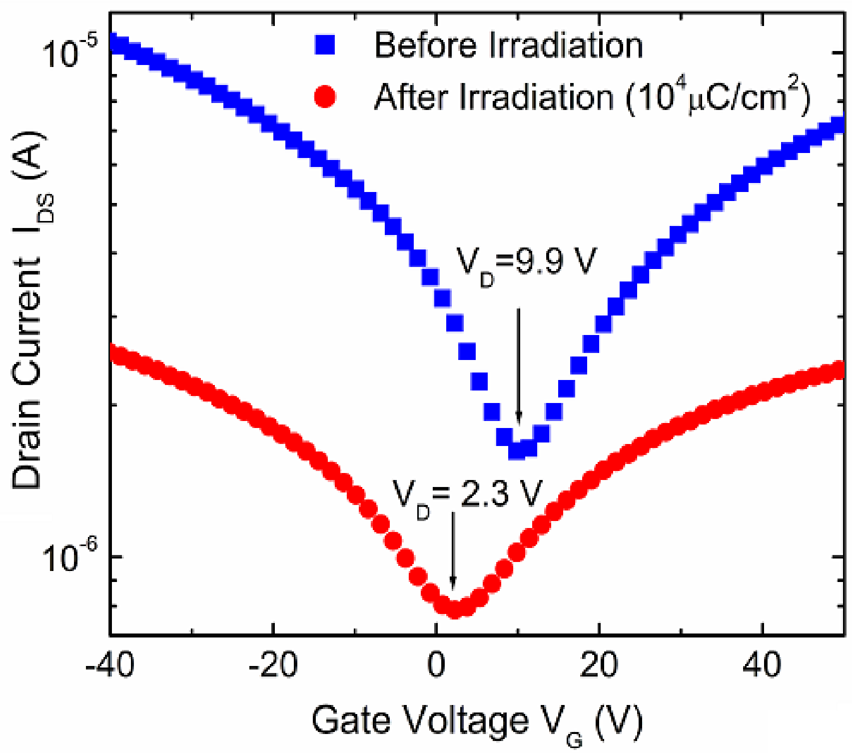
Introduction of Structural Defects to Graphene by Electron Beam Irradiation

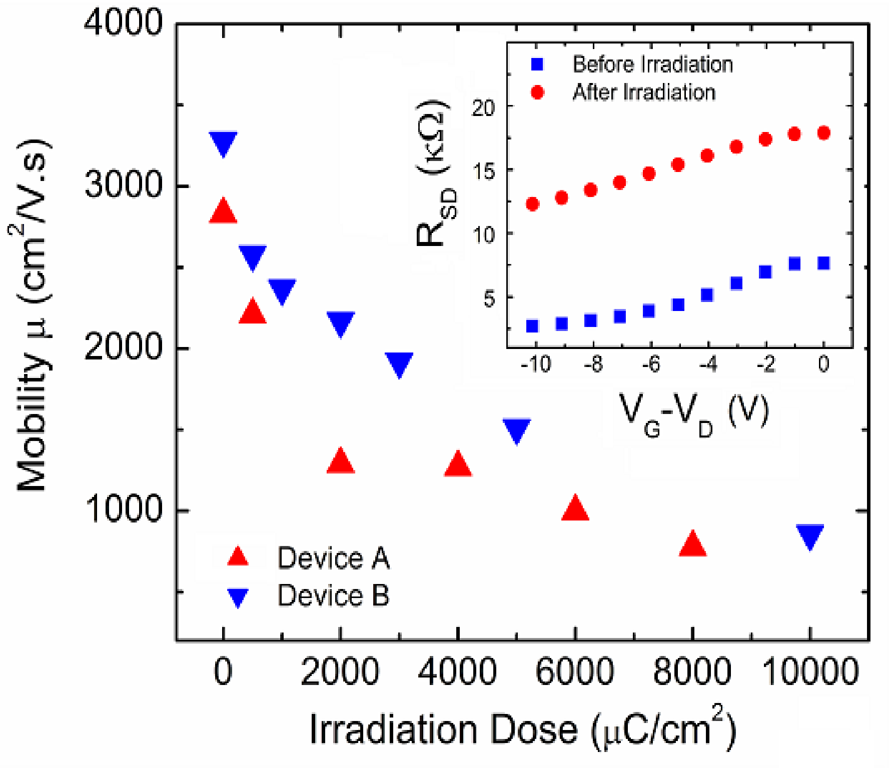




The electron energy was set to 20 keV in order to exclude the severe knock-on damage to the graphene crystal lattice, which starts at ~50 keV

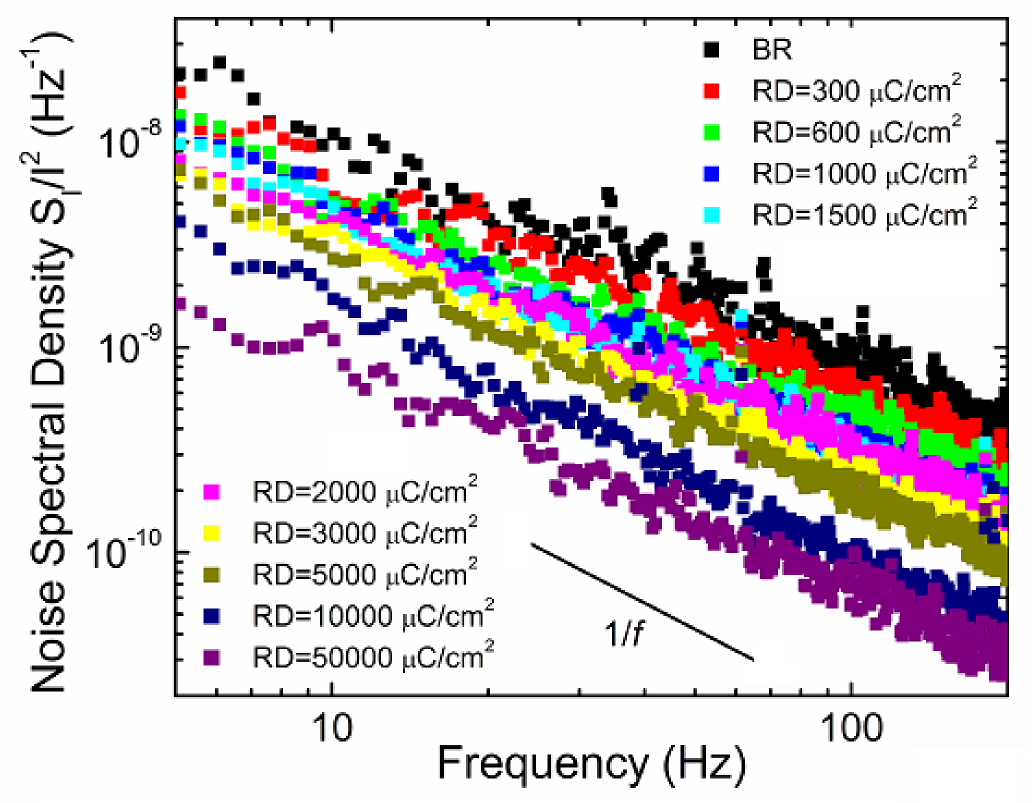
Electron Beam Irradiation Effects on Electronic Properties of Graphene





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



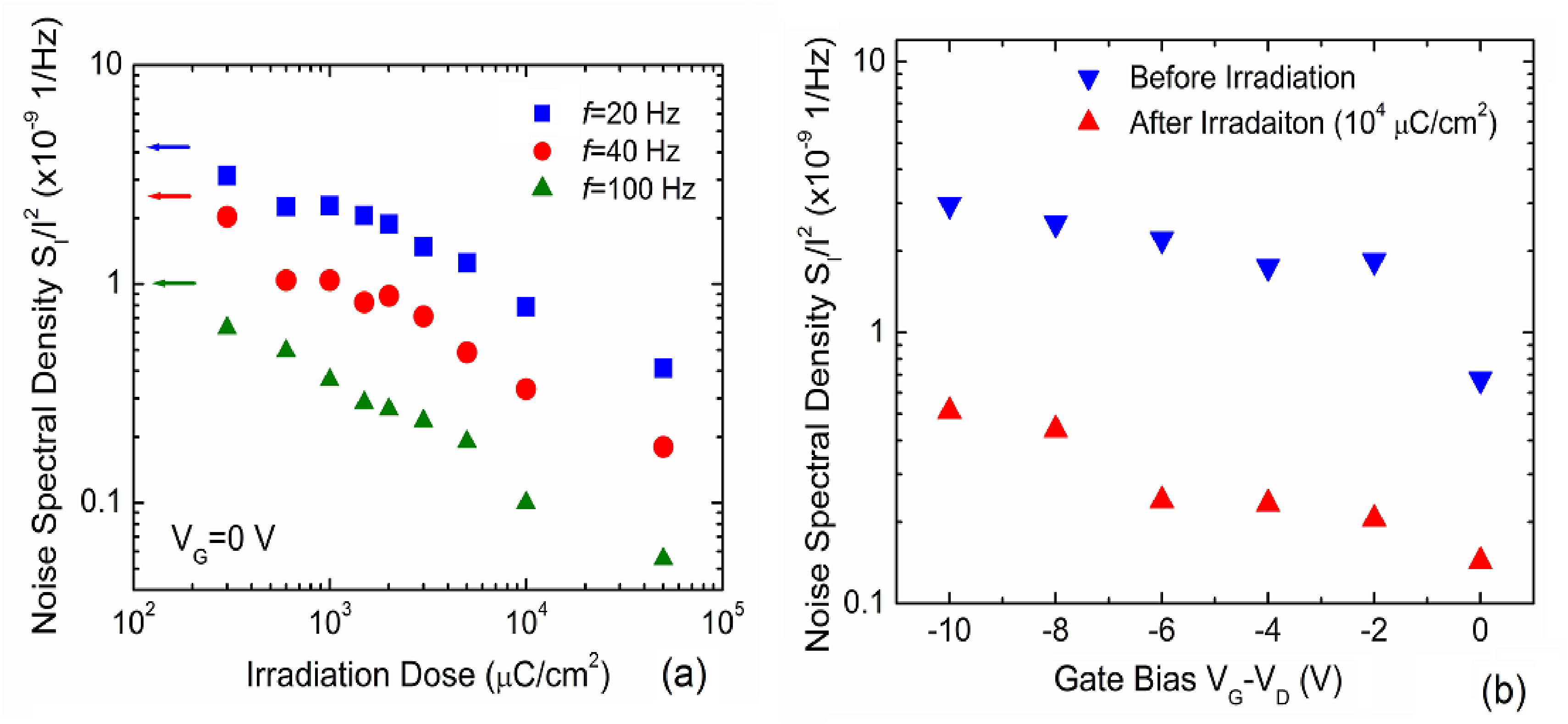
The noise was measured in the linear region of the drain bias keeping the source at a ground potential.

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 R_D 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

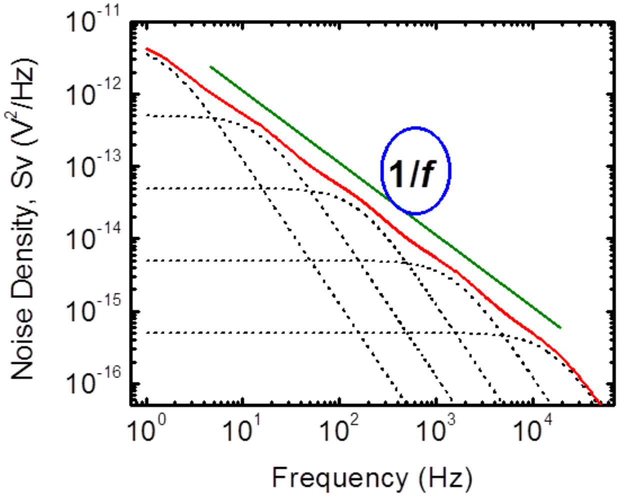
McWhorter model of the number of carriers fluctuations:

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

→ 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).



→ N_t is not the total concentration of traps!

→ Reduction in N_t after irradiation? – possible but unlikely

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

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

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
- → ς 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).

Independent Confirmation:

Ting Wu, et al., Low-frequency noise in irradiated graphene FETs, Appl. Phys. Lett. 113, 193502 (2018)

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

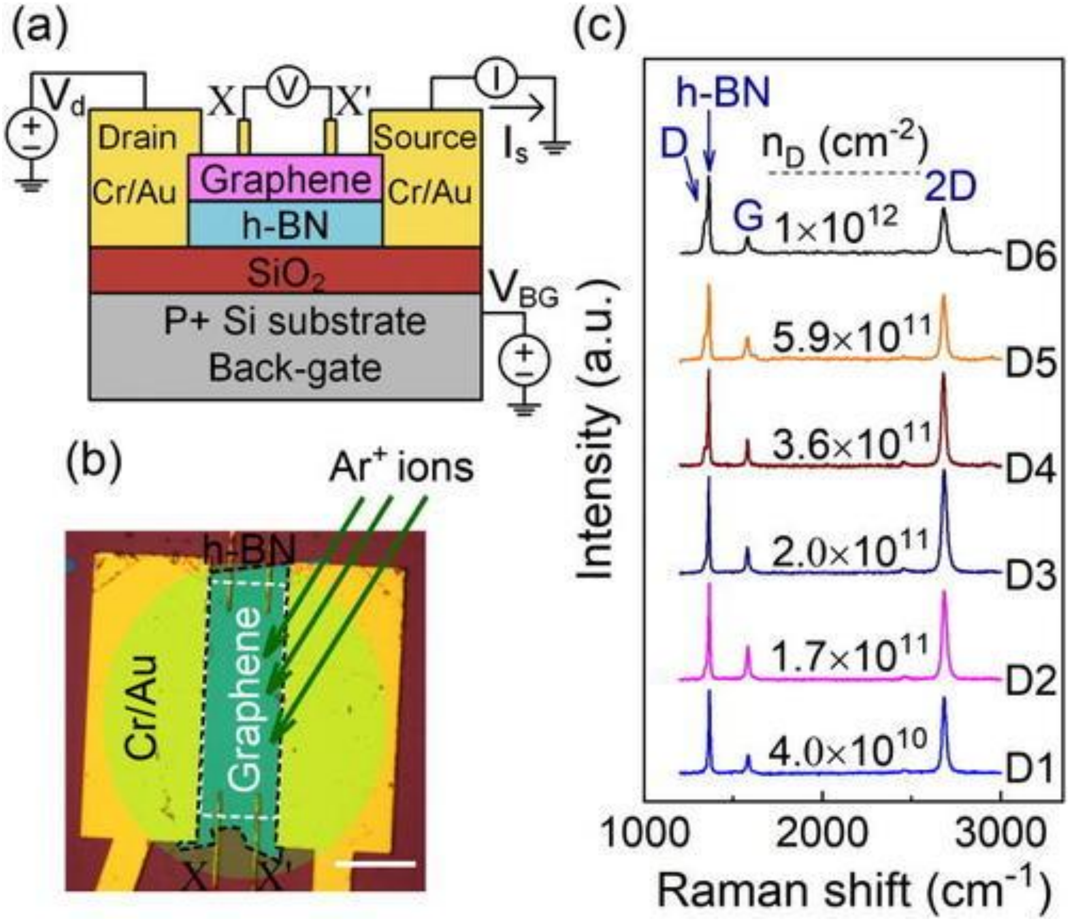
→ N_t that limit electron mobility increases

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

→ Reduced mobility results in reduced MFP

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

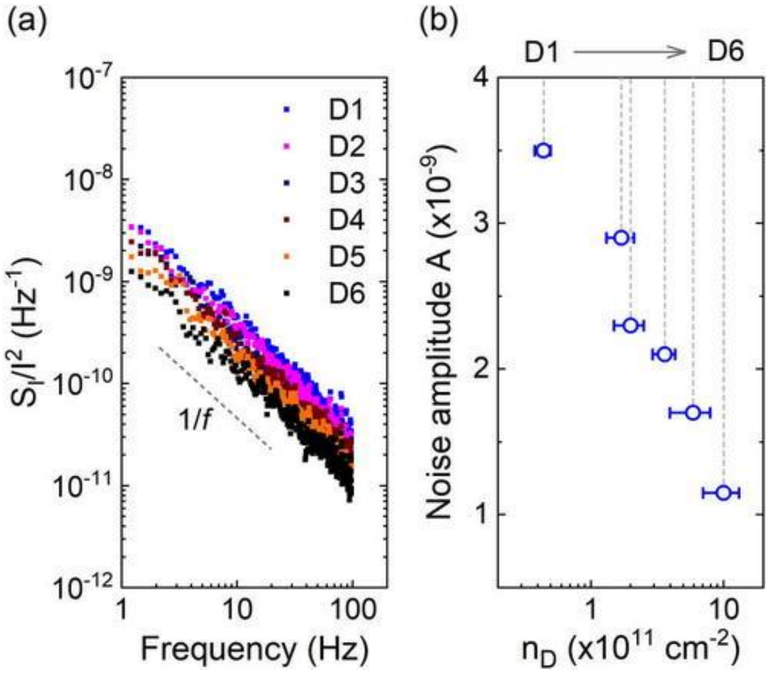
Independent Confirmation - Graphene FETs Irradiated with Argon Ions

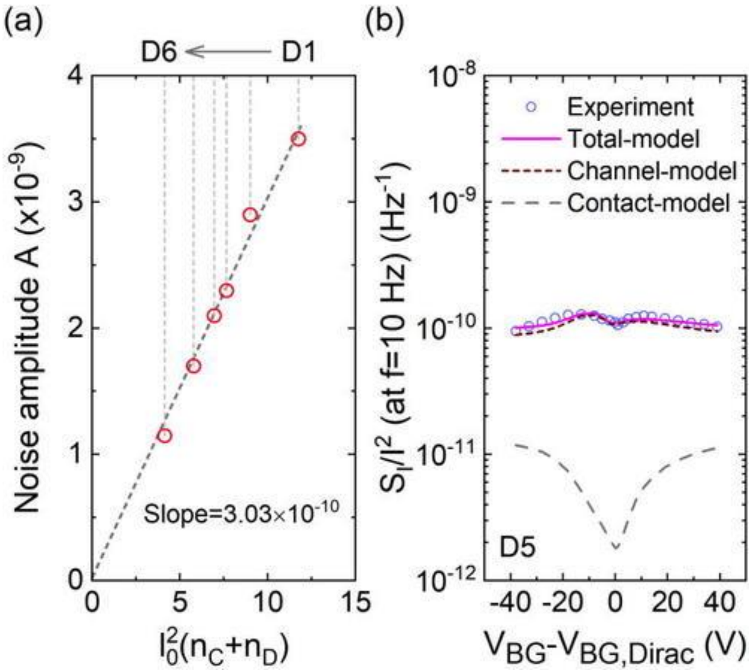


- → Bombarded a graphene FET with low-energy Ar ions at 90 eV.
- → This ion energy generates mostly single vacancies in graphene.
- → These defects add localized energy states at the Dirac point.
- → Each irradiation treatment increased the density of vacancy defects in the graphene FET.

Ting Wu, Abdullah Alharbi, Takashi Taniguchi, et al., Low-frequency noise in irradiated graphene FETs, Appl. Phys. Lett. 113, 193502 (2018).

Noise Characteristics in Graphene FETs Irradiated with Argon Ions



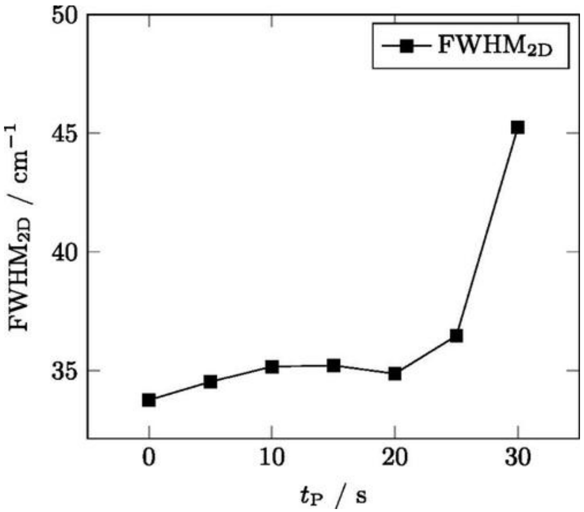


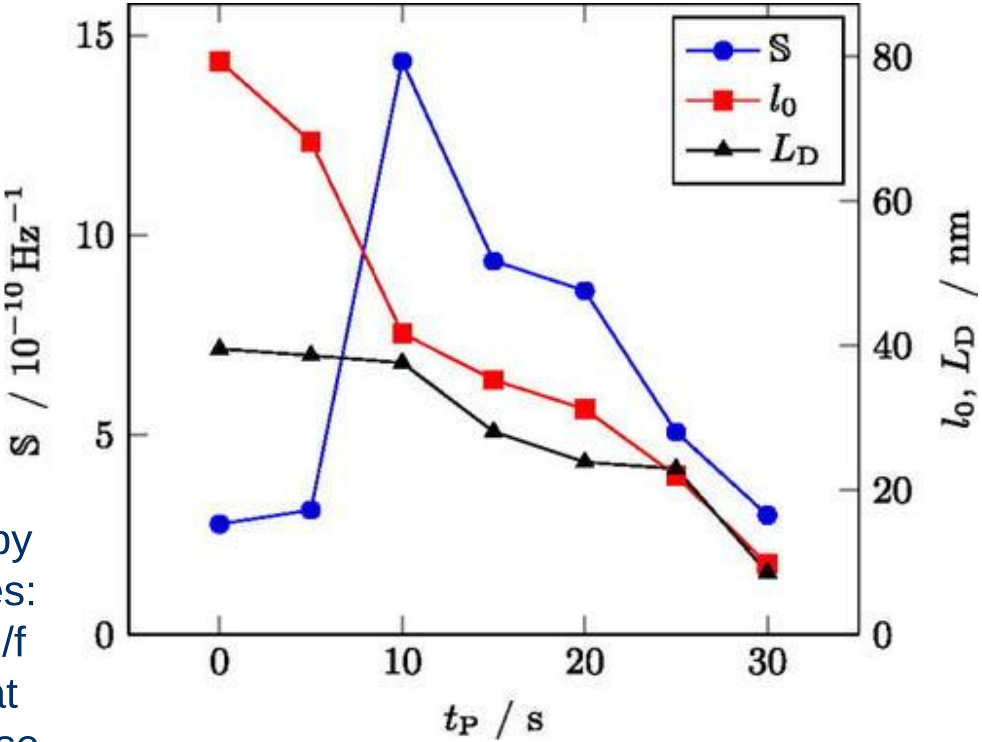
- → The noise amplitude decreases monotonically with the increasing density of vacancy defects.
- → The mobility fluctuation model can explain this observation.

Ting Wu, Abdullah Alharbi, Takashi Taniguchi, et al., Low-frequency noise in irradiated graphene FETs, Appl. Phys. Lett. 113, 193502 (2018).

Excellent agreement with our results reported in Appl. Phys. Lett., **102**, 153512 (2013).

Independent Study - 1/*f* Noise in Graphene with Defects





→ The increasing damage induced by oxygen plasma on graphene samples: at low doses, the magnitude of the 1/f noise increases with the dose; and at high doses, it decreases with the dose.

A. Cultrera, L. Callegaro, M. Marzano, M. Ortolano, and G. Amato, «Role of plasma-induced defects in the generation of 1/f noise in graphene, Appl. Phys. Lett. 112, 093504 (2018).

Part IV: Low-Frequency Current Fluctuations as the Signal

NANO LETTERS

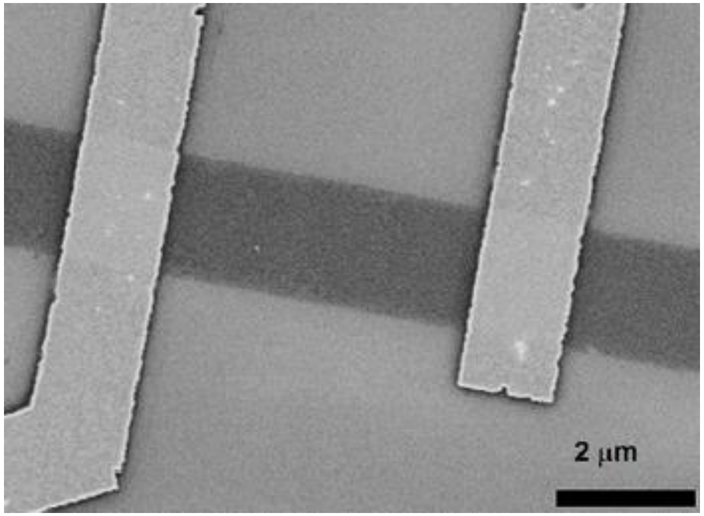
Letter

pubs.acs.org/NanoLett

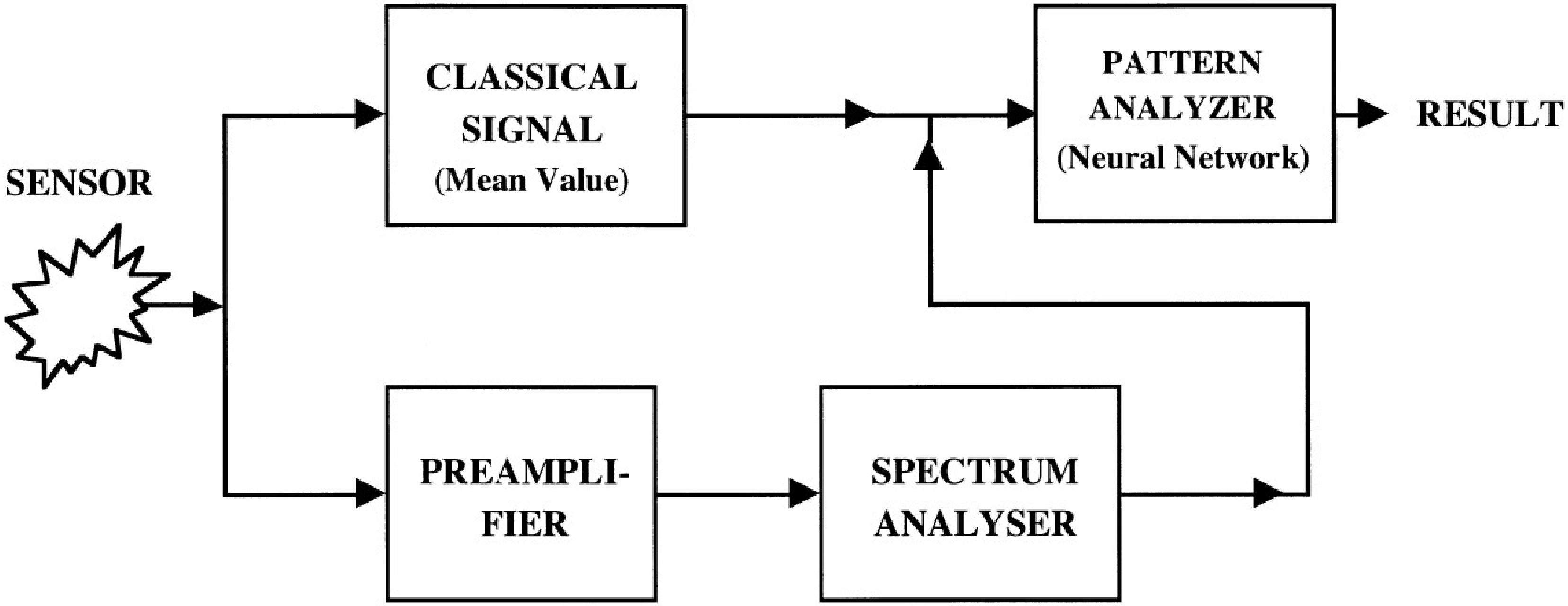
Selective Gas Sensing with a Single Pristine Graphene Transistor

Sergey Rumyantsev,[†,‡] Guanxiong Liu,[§] Michael S. Shur,[†] Radislav A. Potyrailo,[||] and Alexander A. Balandin*[,§,⊥]

- → Sensor sensitivity is often limited by the electronic noise.
- → Noise is usually the main limiting factors for the detector operation.
- → Electronic noise spectrum itself can be used as a sensing parameter increasing the sensor sensitivity and selectivity.



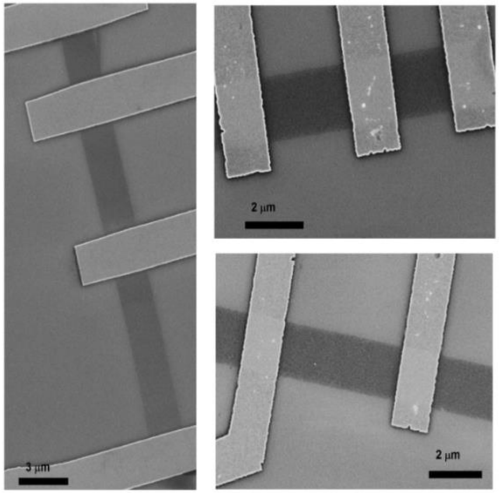
Noise as a Signal – Prior Demonstrations

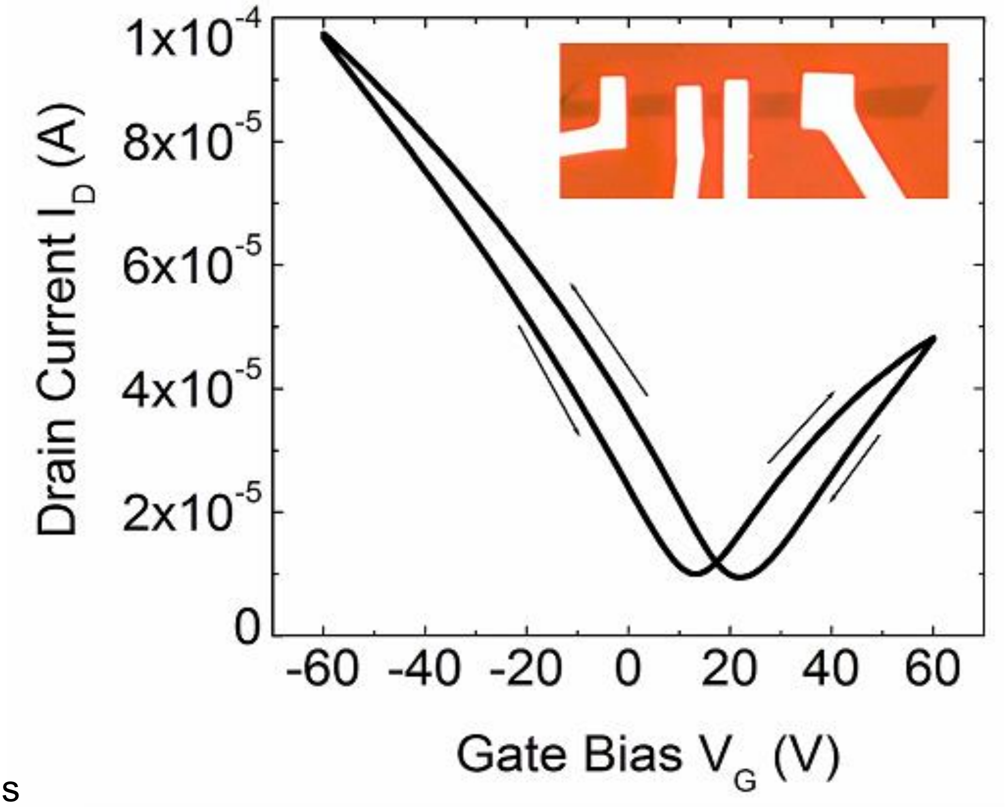


L.B. Kish, R. Vajtai, C.G. Granqvist, Extracting information from noise spectra of chemical sensors: single sensor electronic noses and tongues, Sensors and Actuators B 71 (2000) 55±59.

→ Change in the 1/f noise level used for signal processing

Graphene FETs as Sensors





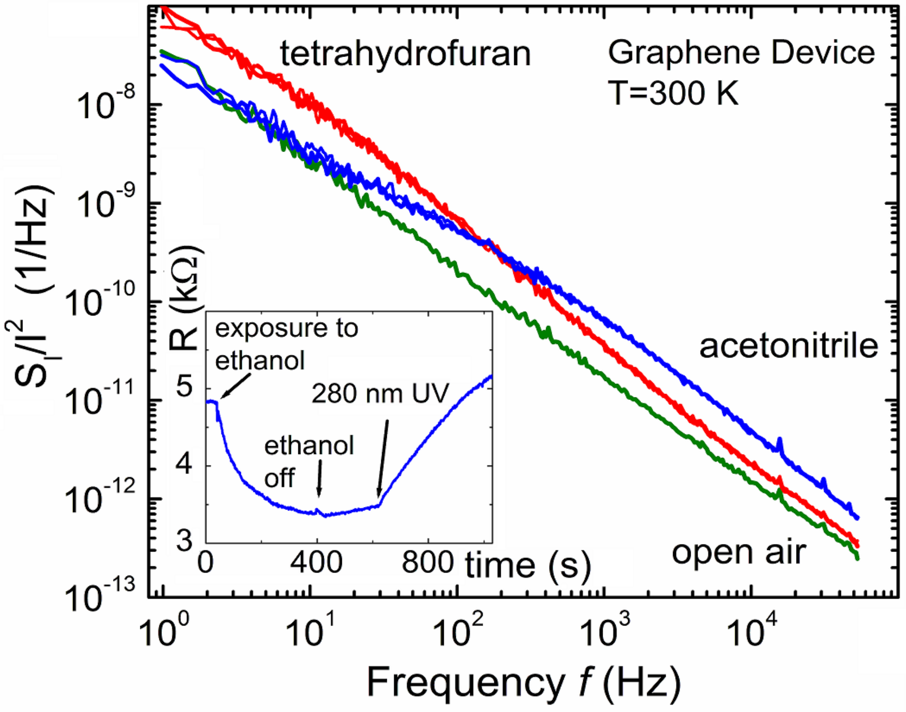
→High gas sensitivity (<1 ppb); Linear response to the gas concentration

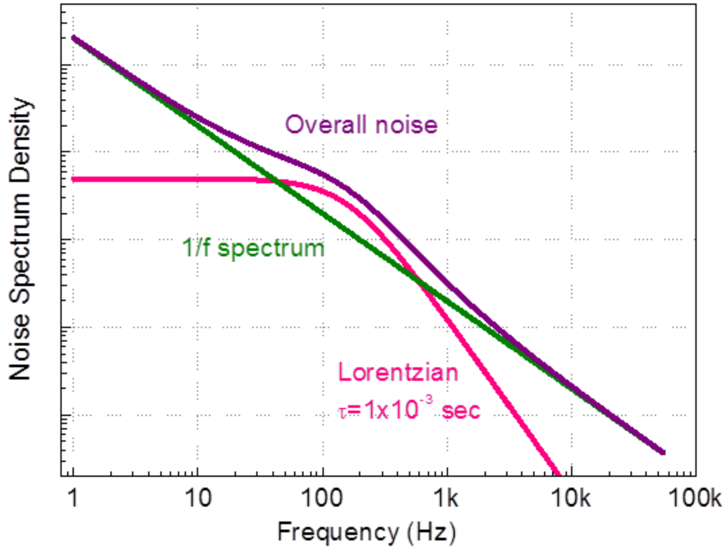
→ Sensing parameters: change in resistivity; shift in Dirac point voltage

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

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

Lorentzian Features in the Noise 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

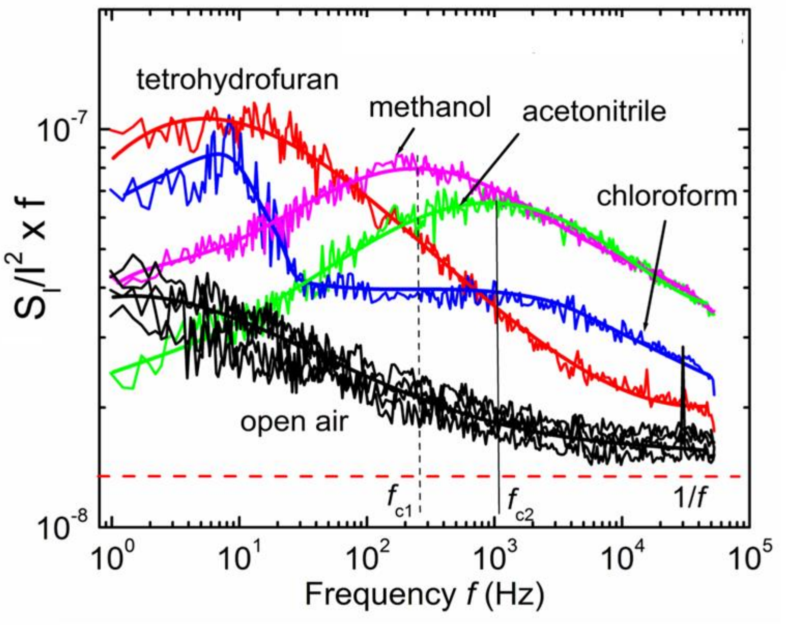
$$S \propto \frac{1}{1+(\omega\tau)^2}$$

→ 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)

Selective and Sensitive Detection of Vapor and Gases with Graphene FTEs



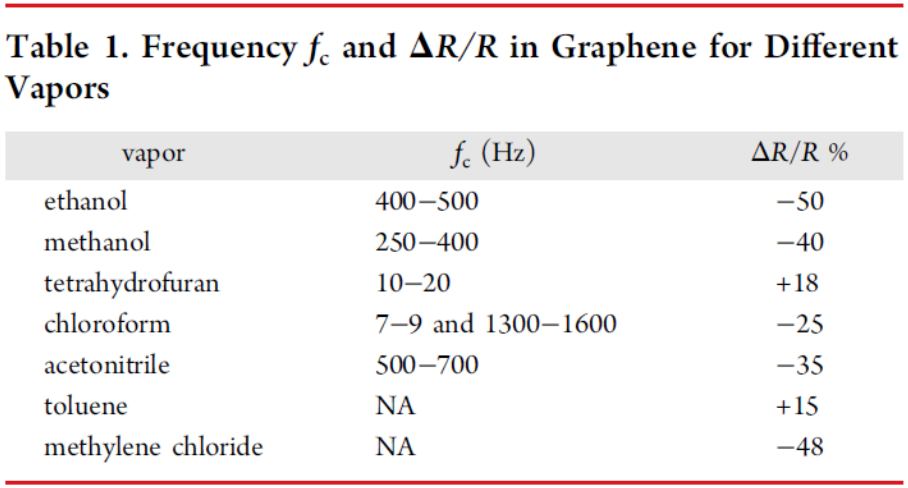


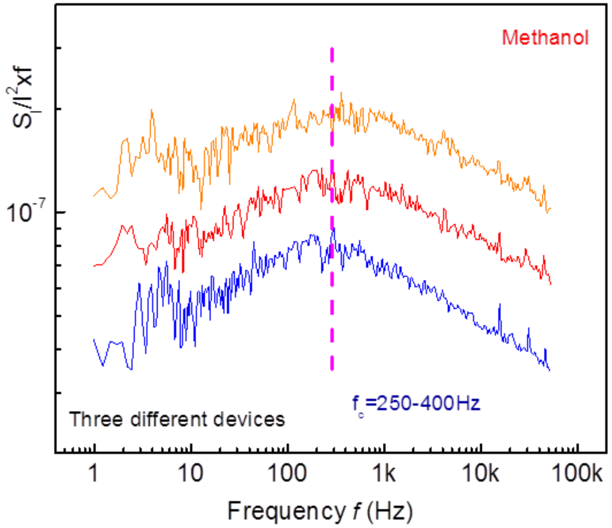
Table 1. Frequency f_c and $\Delta R/R$ in Graphene for Different Vapors

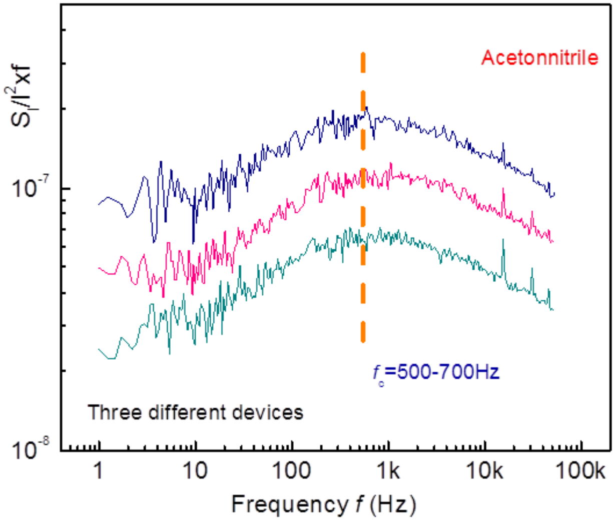
vapor	f_c (Hz)	$\Delta R/R$ %
ethanol	400−500	−50
methanol	250−400	−40
tetrahydrofuran	10−20	+18
chloroform	7−9 and 1300−1600	−25
acetonitrile	500−700	−35
toluene	NA	+15
methylene chloride	NA	−48

S. Rumyantsev, G. Liu, M. S. Shur, R. A. Potyrailo, and A. A. Balandin, “Selective gas sensing with a single pristine graphene transistor,” Nano Lett.,12, 2294 (2012).

S. Rumyantsev, G. Liu, M. S. Shur, R. A. Potyrailo, and A. A. Balandin, “Selective sensing of individual gases using graphene devices,” IEEE Sensors Journal, 13, 2818 (2013).

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

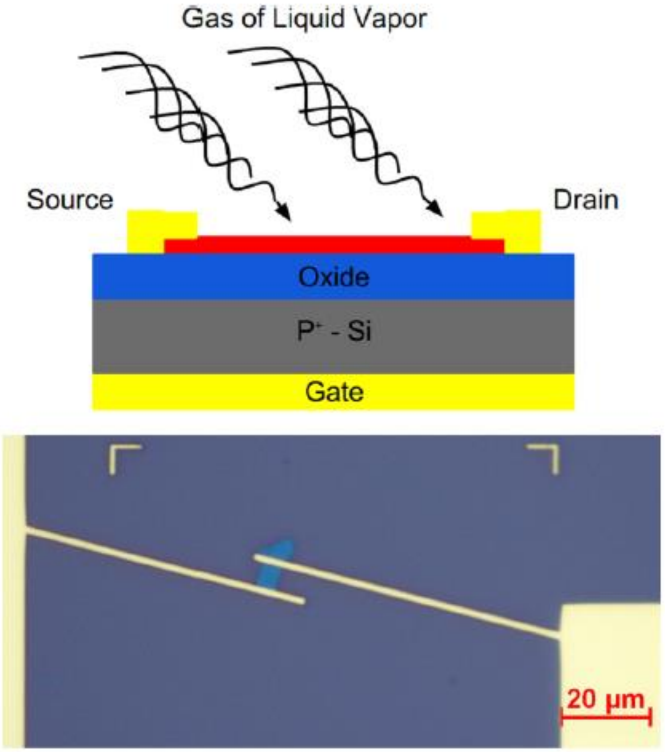


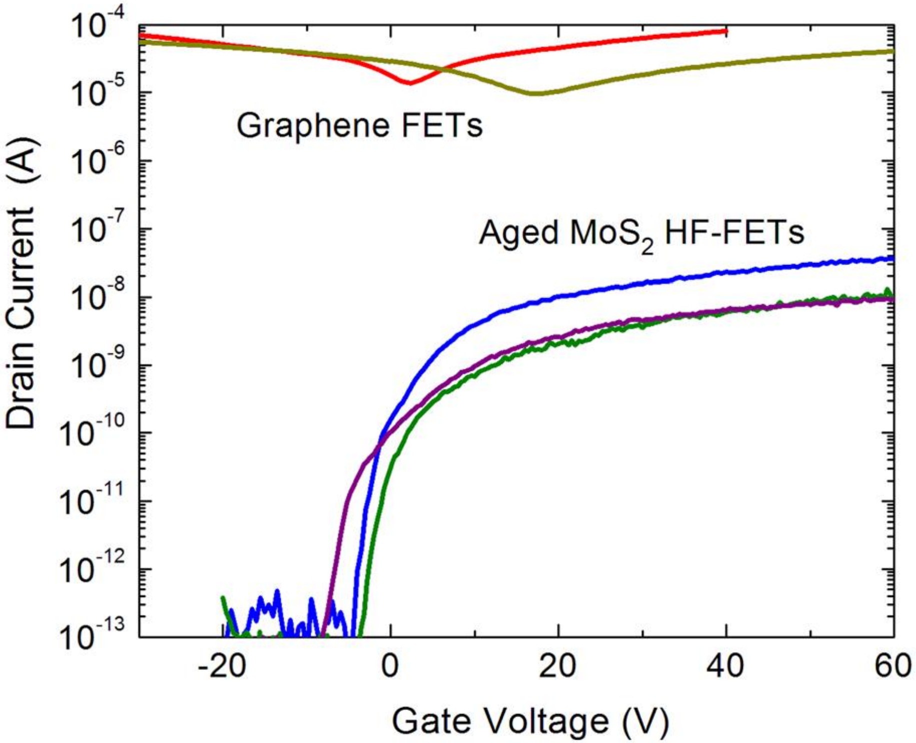


- → The characteristics frequency f_c of Lorentzian peaks with certain vapor gases is reproducible for different graphene devices
- → The gas molecules can create specific traps and scattering centers in graphene, which lead to either number of carriers fluctuation due to the fluctuations of traps occupancy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

S. Rumyantsev, G. Liu, M. S. Shur, R. A. Potyrailo, and A. A. Balandin, “Selective gas sensing with a single pristine graphene transistor,” Nano Lett.,12, 2294 (2012).

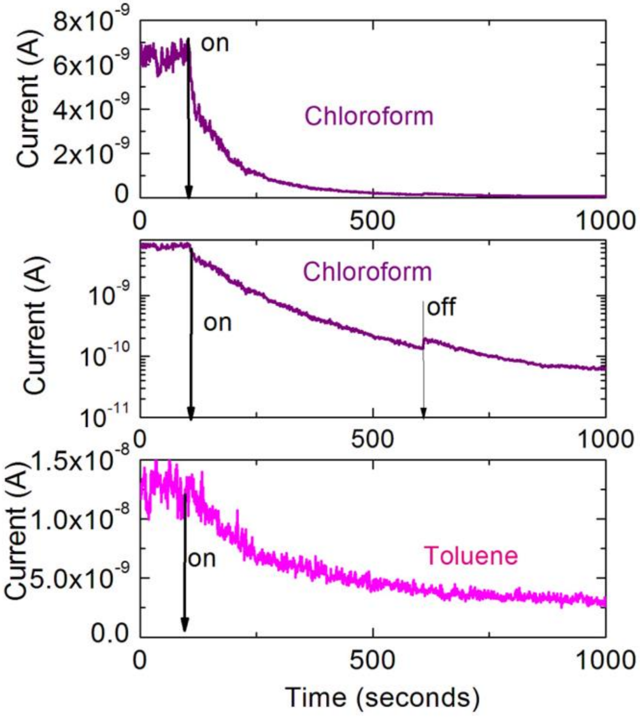
Comparison of MoS_2 FET Sensors with Graphene FET Sensors



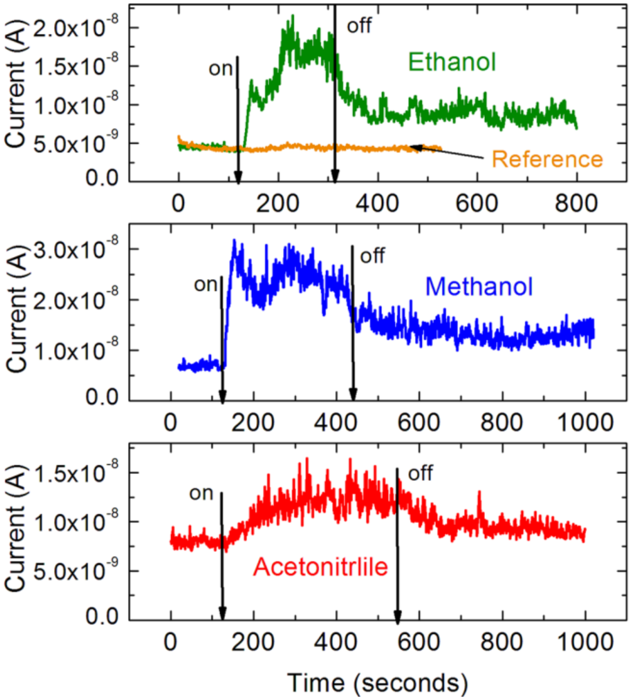


R. Samnakay, C. Jiang, S. L. Rumyantsev, M. S. Shur, and A. A. Balandin, “Selective chemical vapor sensing with few-layer MoS_2 thin-film transistors: comparison with graphene devices,” Appl. Phys. Lett., 106, 23115 (2015).

Resistive Sensing with MoS_2 FETs



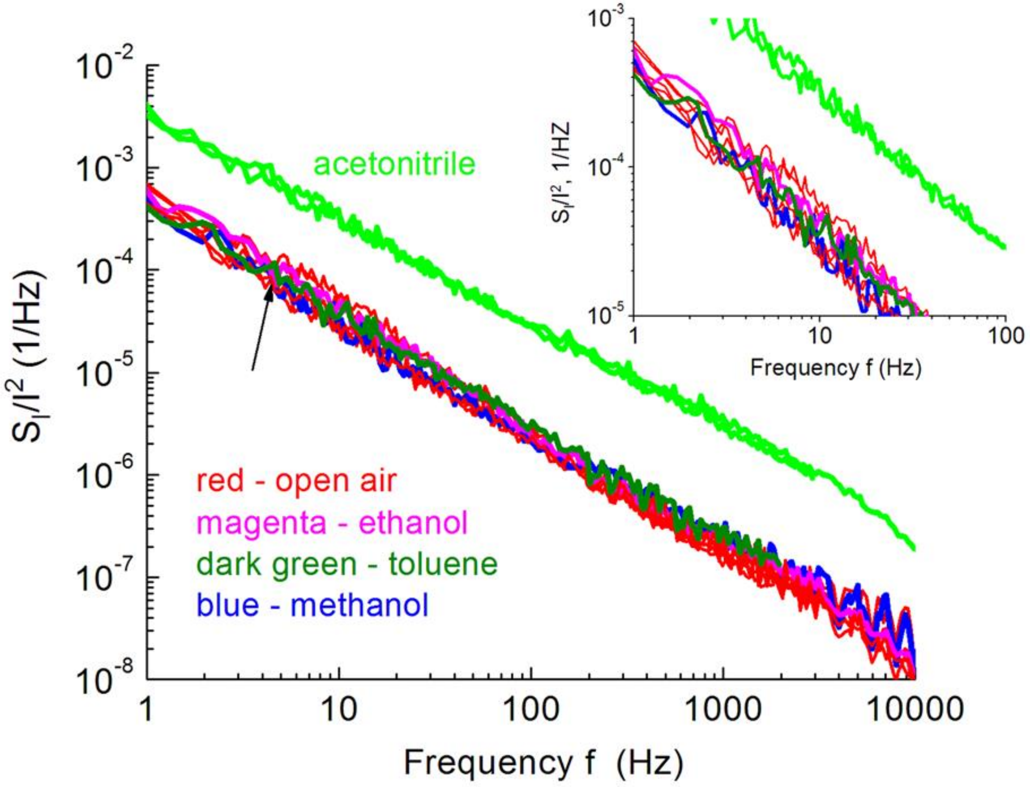
Non-polar solvents: chloroform (upper and middle panels) and toluene (lower panel).



Polar solvents: ethanol (upper panel), methanol (middle panel), and acetonitrile (lower panel).

→ The current can increase or decrease by more than two-orders of magnitude depending on the polarity of the analyte.

Sensing with Noise Works Differently in MoS_2 FETs than in Graphene FETs



R. Samnakay, C. Jiang, S. L. Rumyantsev, M. S. Shur, and A. A. Balandin, “Selective chemical vapor sensing with few-layer MoS_2 thin-film transistors: comparison with graphene devices,” Appl. Phys. Lett., 106, 23115 (2015).

The gas MoS2 TF-FET sensors can work even with h-BN capping

G. Liu, S. L. Rumyantsev, C. Jiang, M. S. Shur, and A. A. Balandin, “Selective gas sensing with h-BN capped MoS2 heterostructure thin-film transistors,” IEEE Electron device Lett., 36, 1202–1204, 2015.

Conclusions and Take Home Messages

- → Graphene and FLG constitute an interesting material platform to address fundamental questions in 1/f noise field
- → Noise reduction after irradiation can be explained by the mobility fluctuation models
- → Low-frequency fluctuations can be used for selective sensing with graphene
- → 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}

More to Come -- Next Lecture Topics

- →Part IV: Noise in 2D CDW Materials
  - →Noise spectroscopy of CDWs in 2D quantum materials
- →Part IV: 1D van der Waals Materials
  - → Going from 2D to 1D – again!

Acknowledgements