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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!
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”

Basics of Electronic Noise – Fluctuations are Everywhere


Thermal: $S_V = 4k_B T R$
Shot: $S_I = 2e <I>$
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.

Mathematical Background for Noise Studies

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

$S(f) = \frac{L_t}{T \to \infty} \left( \frac{1}{2T} \right) \left| \int_{-T}^{T} dt \, X(t) \, e^{-ij2\pi ft} \right|^2 \quad (1)$

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

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

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

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

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

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

$F(\tau) \sim \tau^{-\alpha}$ would give $S(f) \sim f^{-2+\alpha} \quad (5)$

Superposition of Lorentzians can give approximately $1/f$ spectrum.
Early Models of 1/f Noise – Schottky and Surdin Models

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


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

Surdin: $g(\tau)d\tau = d\tau/\tau \ln(\tau_h/\tau_i)$. 
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 $0.5 \leq \gamma \leq 1.5$) power spectra at low frequencies $f$ have been observed in physics, technology, biology, astrophysics, geophysics, economics, psychology, language and music.


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:

$$R = \frac{L}{\rho S} = \frac{1}{\sigma S} = \frac{1}{en\mu} \frac{L}{S}$$
Persistent Questions for 1/f Noise in Metals and Semiconductors

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

\[ R = \frac{L}{S} = \frac{1}{\sigma S} = \frac{1}{en\mu S} \]

- 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).\(^{10}\)


- Low-frequency limit; etc.
McWhorter Model for 1/f Noise in Semiconductors

- 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

\[ I \sim qN\mu \]

\[ \delta I \sim q(\delta N)\mu + qN(\delta \mu) \]

McWhorter’s model:

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

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

Series of levels:

\[ \tau_1 \quad \tau_2 \quad \tau_3 \quad \tau_4 \quad \tau_5 \]
Experimentally Established Characteristics of 1/f Noise


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 \(2 \times 10^{-3}\) 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.


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:
\[ S_1 = 4k_B T/R \]

Shot noise:
\[ S_1 = 2e<I> \]

G-R noise:
\[ S_1 \sim 1/(1+(2\pi f \tau)^2) \]

Flicker 1/f noise:
\[ S_1 \sim I^2/f \]

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 $T (\sim 1/f)$

→ 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
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.

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Part II: 1/f Noise in Graphene

Low-frequency 1/f noise in graphene devices

A. 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.

The First 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

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
Fabrication of Test Structures with Van der Waals Materials


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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 \( \mu \text{m}^2 \)
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.

Features of Electronic Noise in Graphene

\[ A = \frac{1}{N} \sum_{m=1}^{N} f_m S_{I_m} / I_m^2 \]

In some graphene devices, V-shape becomes M-shape at larger biases

\[ S_I/I^2 = 10^{-9} \text{ to } 10^{-7} \text{ Hz}^{-1} \text{ at } f=10 \text{ Hz or } A = 10^{-9} - 10^{-7} \]

\[ (S_I/I^2)L \times W = 10^{-8} - 10^{-7} \text{ } \mu\text{m}^2/\text{Hz} \]

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Thickness-Graded Few-Layer Graphene 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.

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 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: $\Delta E_F = -0.23$ eV and $\Delta E_F = 0.25$ eV were reported for Ti and Au contacts to graphene.

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.

Mobility in BN-Graphene-BN HFETs

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

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

\[
R_{\text{EFF}} = \frac{R_{DS} - R_C}{1 - \sigma_0 (R_{DS} - R_C)}
\]

\[
\mu_{\text{FE}} = \frac{g_{m0}}{C_G(V_{DS} - lR_C) W} L_G
\]

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

The charge carrier mobility in the range from ~30000 to ~36000 cm²/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 $V_G$. Note that $V_G=-7.75 \, V$ corresponds to the Dirac point.


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

<table>
<thead>
<tr>
<th>$V_G$ (V)</th>
<th>-60</th>
<th>-30</th>
<th>-10</th>
<th>-8</th>
<th>-5</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>30</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (device A)</td>
<td>1.16</td>
<td>1.04</td>
<td>0.96</td>
<td>1.19</td>
<td>0.95</td>
<td>1.16</td>
<td>0.97</td>
<td>1.12</td>
<td>1.12</td>
<td>1.20</td>
</tr>
<tr>
<td>$\gamma$ (device B)</td>
<td>1.27</td>
<td>0.84</td>
<td>0.95</td>
<td>1.04</td>
<td>1.02</td>
<td>1.02</td>
<td>0.96</td>
<td>0.94</td>
<td>1.04</td>
<td>1.05</td>
</tr>
</tbody>
</table>
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).

Parameter to Characterize Noise Level in 2D Devices

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

$$\beta = \left( \frac{S_f}{I^2} \right) (W \times L)$$

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

Noise in MoS$_2$ Thin Film Transistors – McWhorter Model Description

Here $S_{RC}/R_{CH}^2$ 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.

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.

Comparison of 1/f Noise Level in Graphene and MoS\textsubscript{2} FETs

The normalized noise spectral density in “thick” MoS\textsubscript{2} FETs is of the same level as that in graphene FETs.

MoS\textsubscript{2} FETs with “thick” channels (15–18 could be described by the McWhorter model.

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 IV: 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

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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.

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:

$$\frac{S_I}{I^2} = \frac{\lambda kTN_t}{fAVn^2}$$

$N_t$ is the concentration of the traps near the $E_F$ responsible for noise
$A$ is the gate area
$n$ is the carriers concentrations
$\lambda$ is the tunneling constant


$N_t$ is not the total concentration of traps!

Reduction in $N_t$ after irradiation? – possible but unlikely

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

$$S_N(\omega) = 4\delta N^2 \int_{\tau_1}^{\tau_2} g(\tau_N) \frac{\tau_N}{1+(\omega \tau_N)^2} d\tau_N$$
Possible Mechanisms of the 1/f Noise in Graphene

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

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

- \( N_t^\mu \) is concentration of the scattering centers contributing to 1/f noise
- \( l_0 \) is MFP of the charge carriers
- \( \zeta \) is the probability for a scattering center to be in the state with the cross-section \( \sigma_1 \)

\( N_t^\mu \) 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: \( S/I^2 (\sim l_0^2) \)

Reduced mobility results in reduced MFP

In graphene \( \mu \) is limited by the scattering from charged defects even at RT


Independent Confirmation:

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.

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


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

Part IV: Low-Frequency Current Fluctuations as the Signal

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


→ 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


Look for G-R bulges, which can be informative → sensor selectivity
Lorentzian Features in the Noise Spectrum of Graphene under Gas Exposure

- 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/P₀, where P during the experiment and P₀ is the saturated vapor pressure
- Measurements performed at Vᵢ=0 V (“hole” region of graphene I-V)

Superposition of a Lorentzian noise with defined relaxation time on a 1/f noise results in a bulge with specific frequency

\[ S \propto \frac{1}{1 + (\omega \tau)^2} \]
Selective and Sensitive Detection of Vapor and Gases with Graphene FTEs


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.

Comparison of MoS_2 FET Sensors with Graphene FET Sensors


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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).

$\rightarrow$ 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


The gas MoS$_2$ TF-FET sensors can work even with h-BN capping

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: $S/I^2 = 10^{-9}$ 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