Can we hear the sound of gas on graphene?

LOW-FREQUENCY ELECTRONIC NOISES IN CVD GRAPHENE GAS SENSORS

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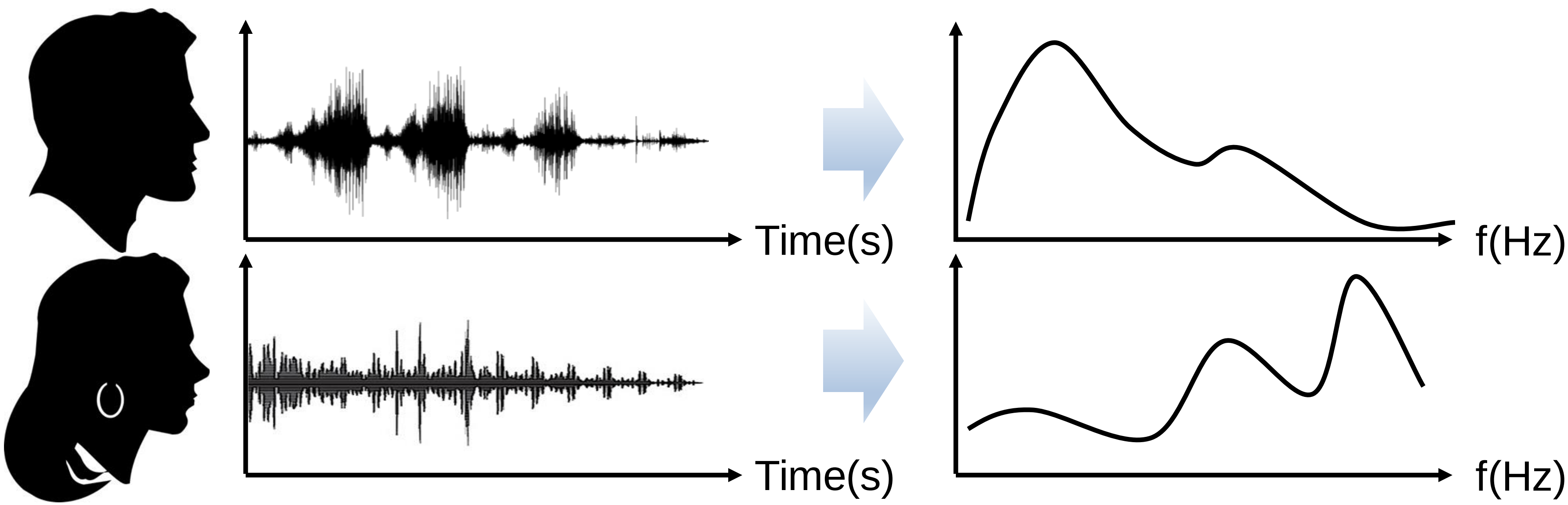
What factor make sound unique?



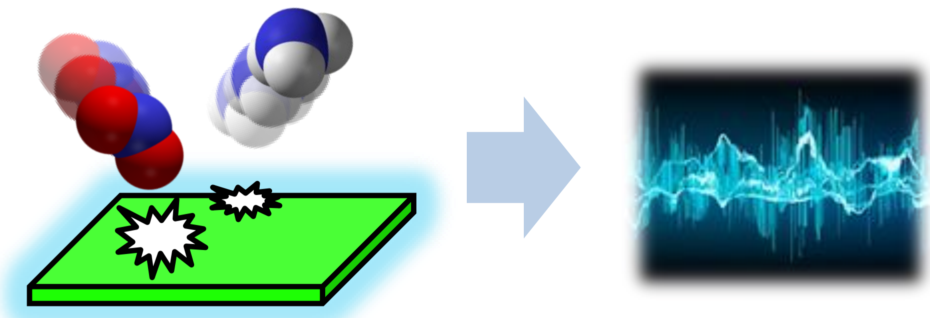
Difference in the frequency components -> **Selectivity**

Questions to be addressed

Human voice

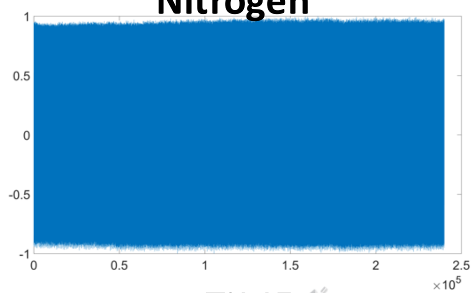
Mechanical Vibration → Ear-> Transducers

Gas molecule's "*voice*"

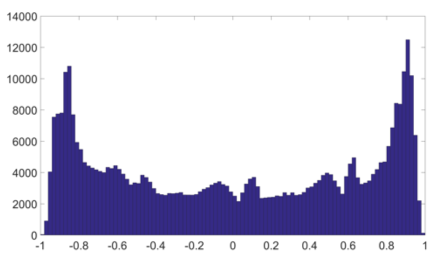


Physical quantities? → What kind of Transducers? → Electrical voice -> uniqueness?

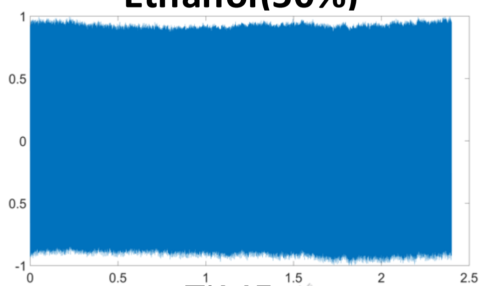
Nitrogen



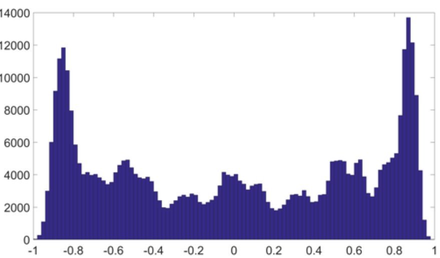
TIME



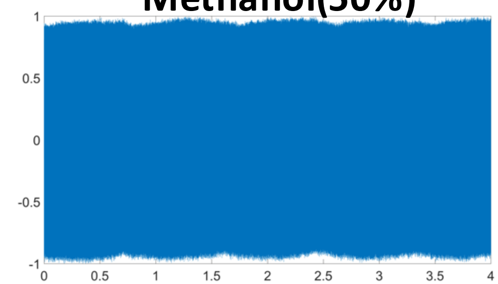
Ethanol(50%)



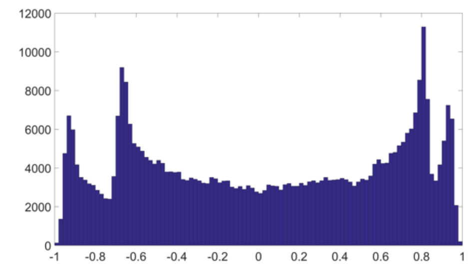
TIME



Methanol(50%)

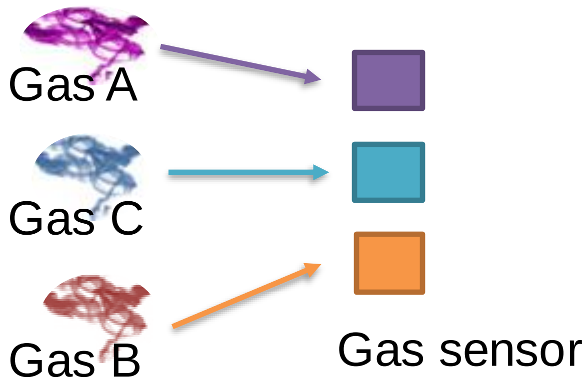


TIME



Frequency domain analysis in gas sensing

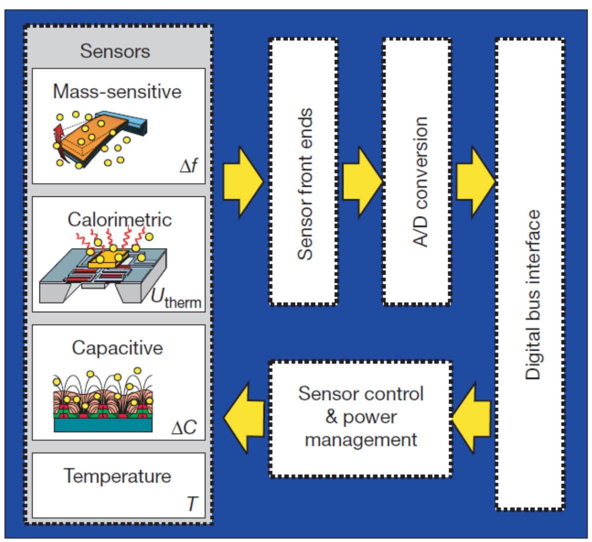
Functionalized array



Selectivity by different materials

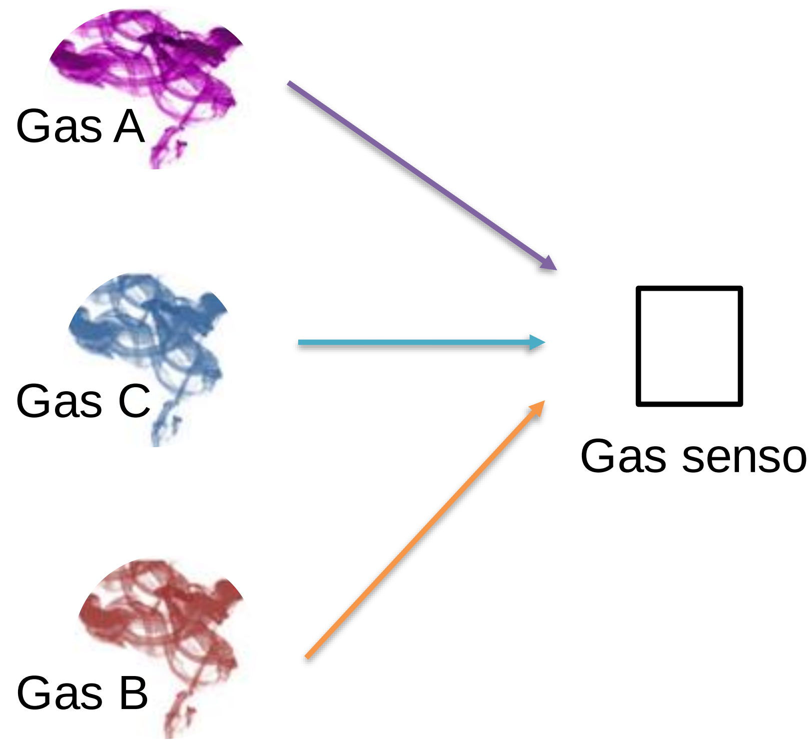
Pros: Working principle is valid

Cons: More process -> higher cost



[1]Hagleitner C, Hierlemann A, Lange D, et al. Smart single-chip gas sensor microsystem[J]. Nature, 2001, 414(6861): 293.

Single device



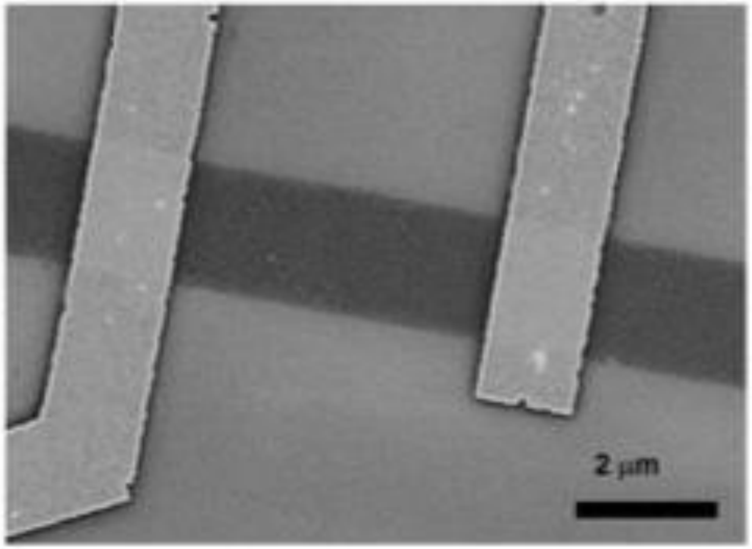
Selectivity by **frequency domain analysis**

Pros: Simple process, less expensive

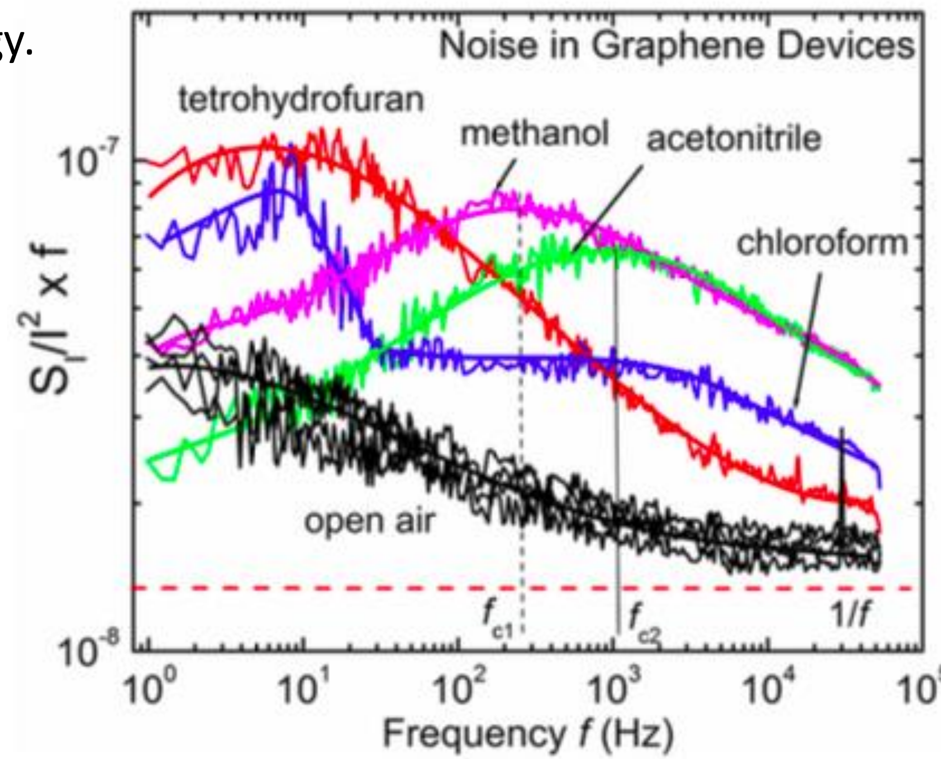
Cons: Complication of the analysis

Analysis in frequency domain with Graphene

[1] Balandin A A. Low-frequency 1/f noise in graphene devices[J]. Nature nanotechnology.



Mechanically exfoliated graphene - FET



- Mechanically exfoliated graphene – Transducers
- Characteristic bulges – Uniqueness

-> The mechanism behind the bulge is unclear

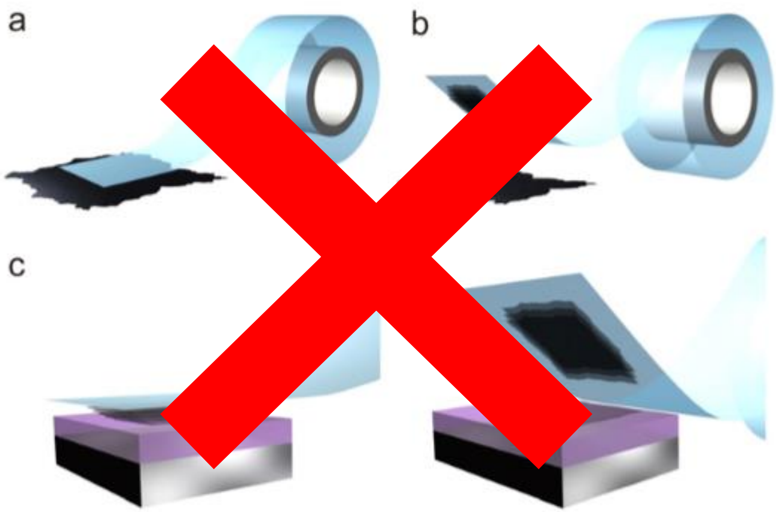
-> Mechanical exfoliation is not scalable

[1] Rumyantsev, Sergey, et al. "Selective gas sensing with a single pristine graphene transistor." *Nano letters* 12.5 (2012): 2294-2298.

Motivation

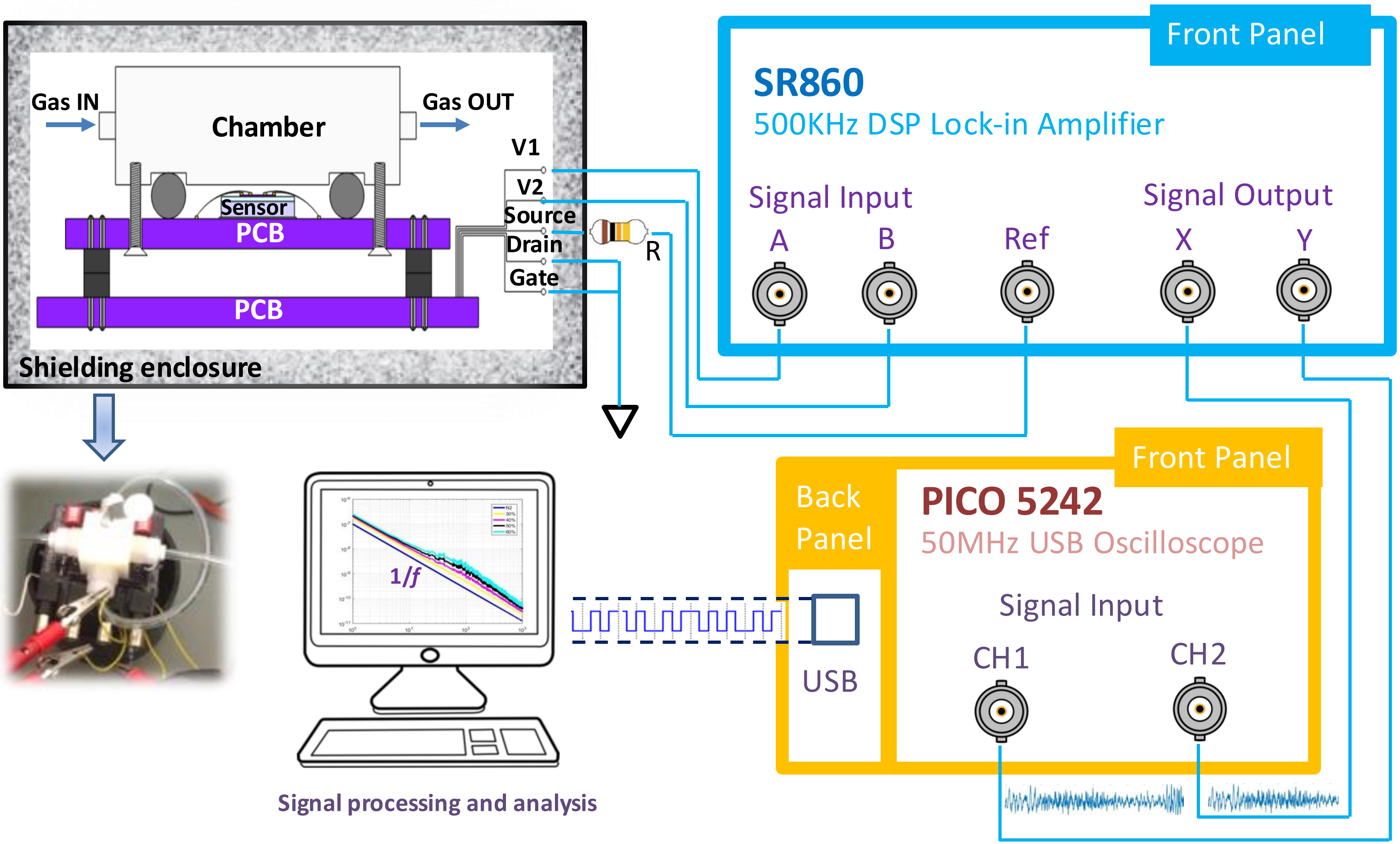
1) Understand the **mechanisms behind the characteristic bulges** in the power spectral density (PSD) through simulation

2) Demonstrate the analysis in the frequency domain by using **CVD graphene** in order to explore the possibilities for commercial applications



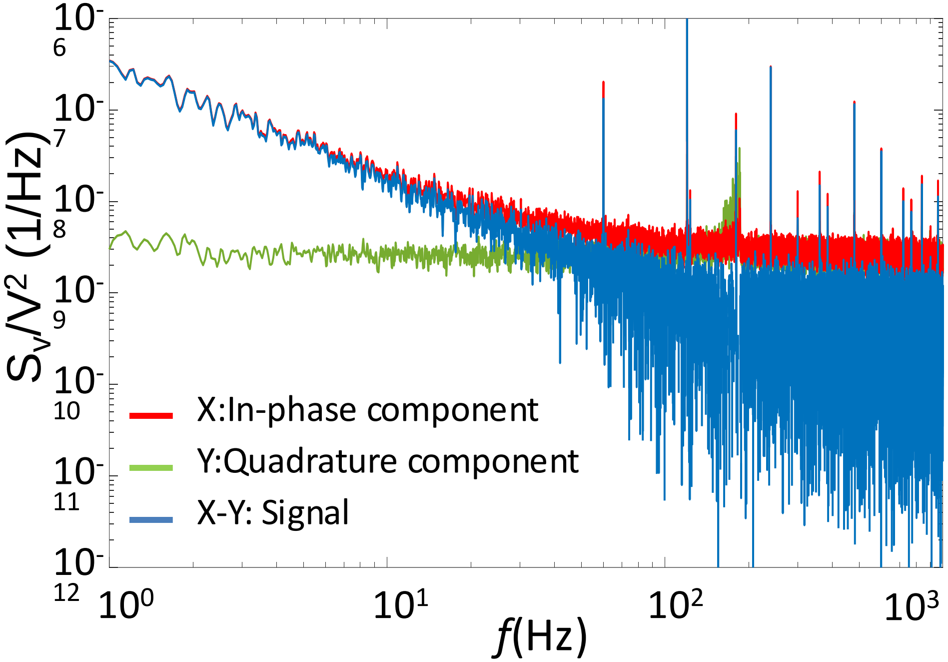
K S Novoselov, et al., Phys. Scr. 2012

Experimental setup

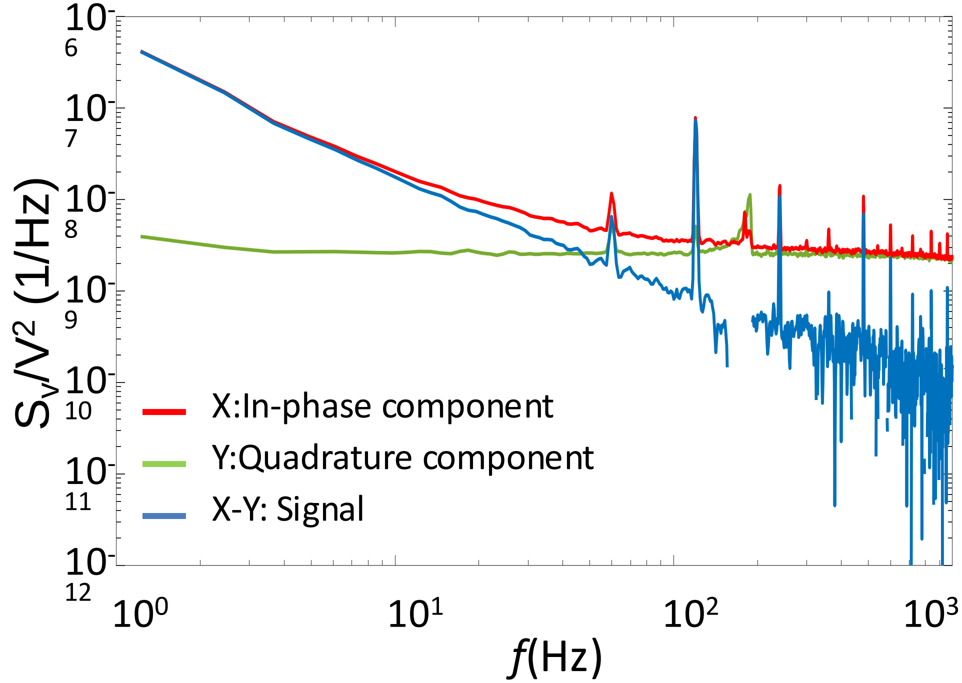


Experiment result

Before signal processing



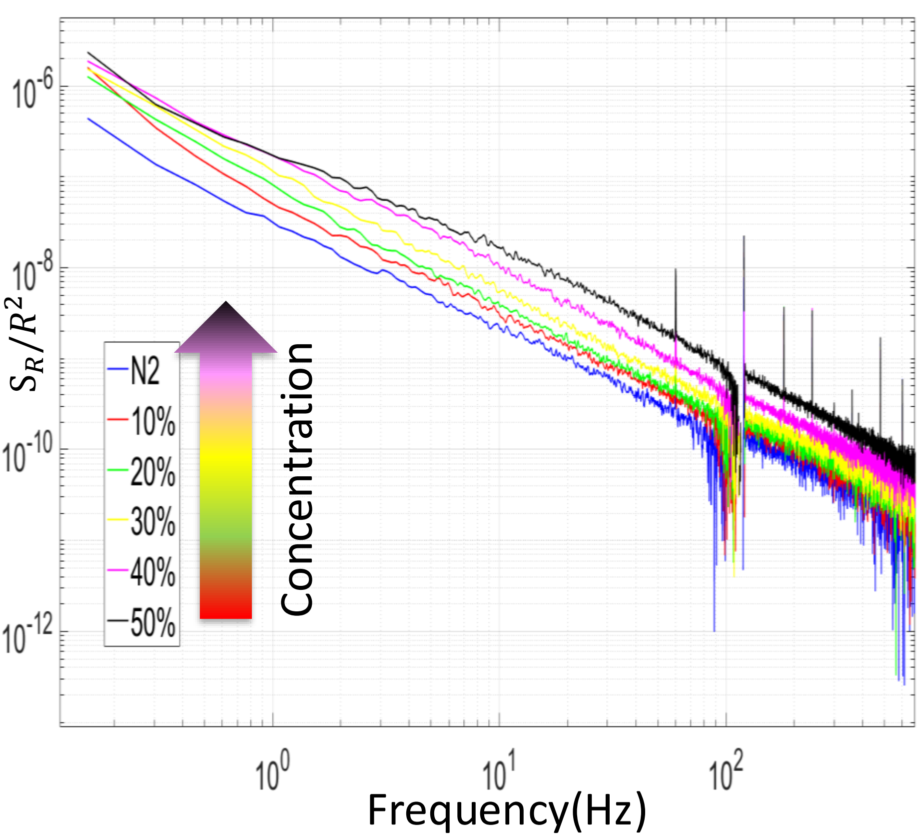
After signal processing



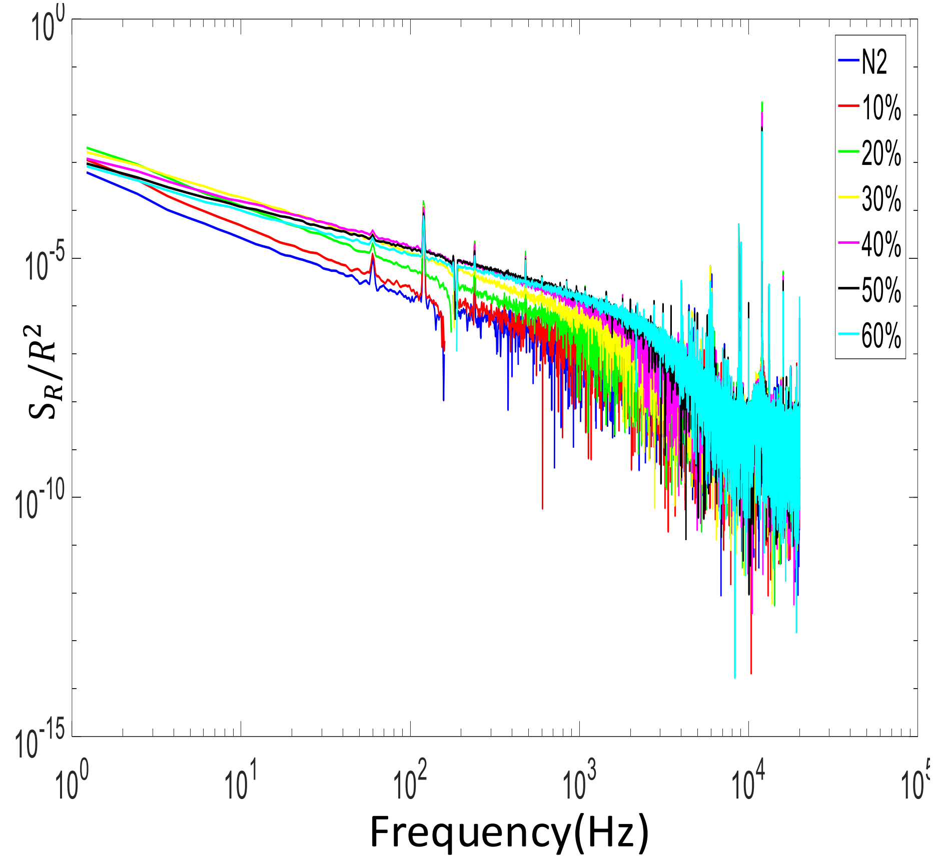
- ✓ Smooth 1/f noise was obtained through signal processing (Low-pass filter)

Experiment Result

Graphene Noise in **Ethanol**



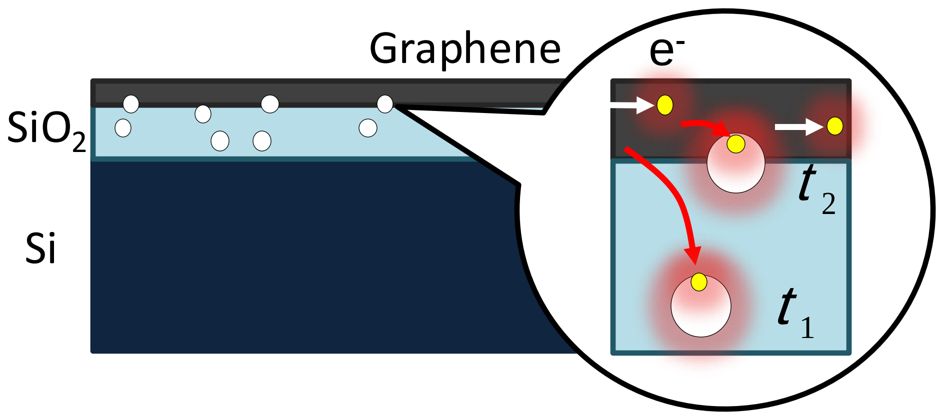
Graphene Noise in **Methanol**



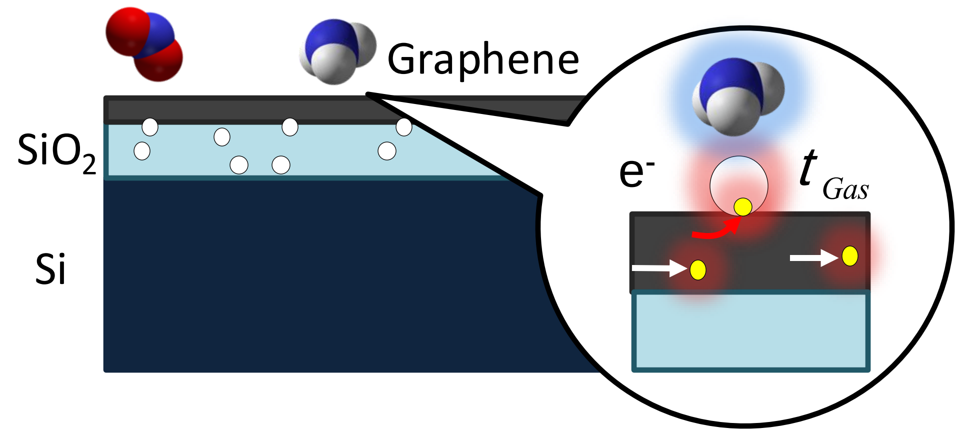
Gas sensing was demonstrated and the increase in 1/f noise was observed.

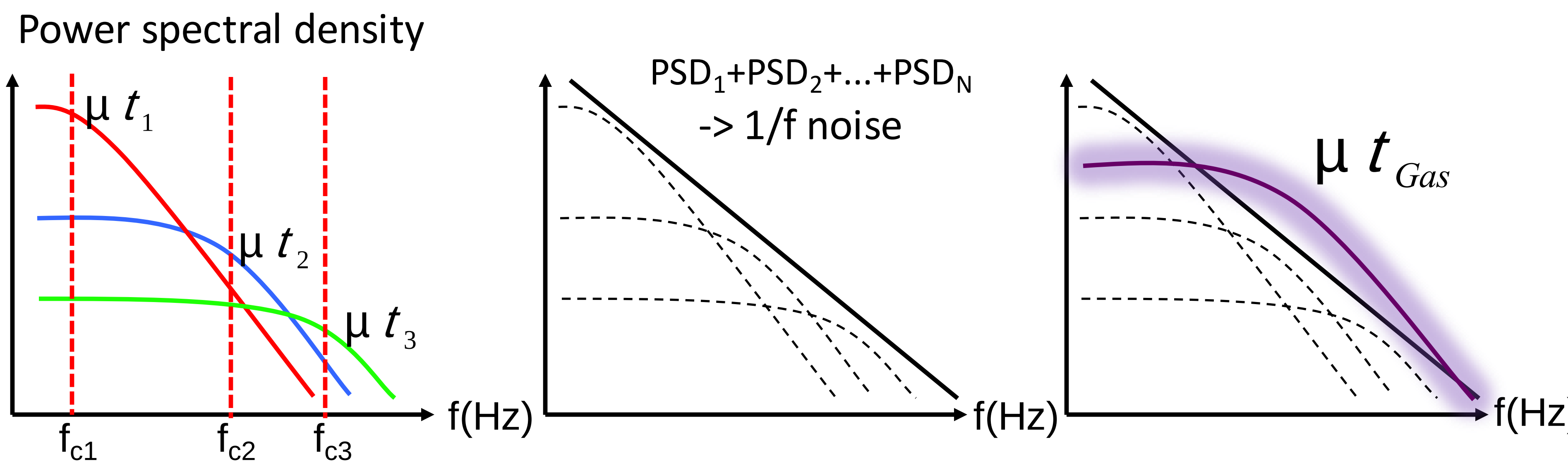
Hypothesis

Intrinsic trap states



Extrinsic trap states





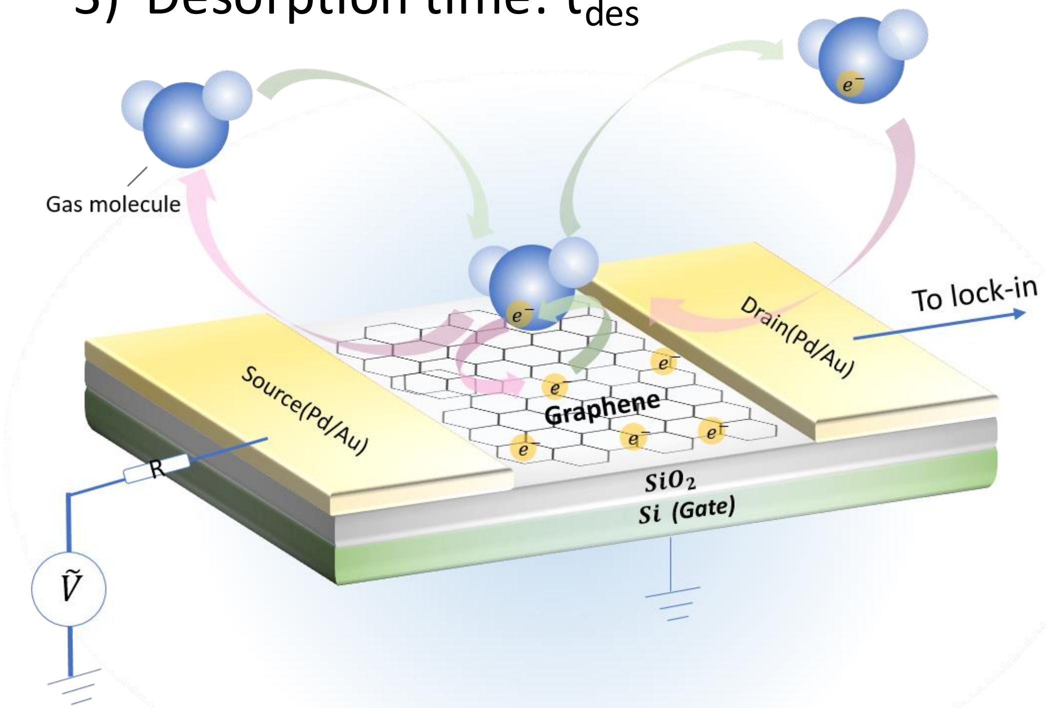
The bulges reflect time constants associated with trap states

Simulation model

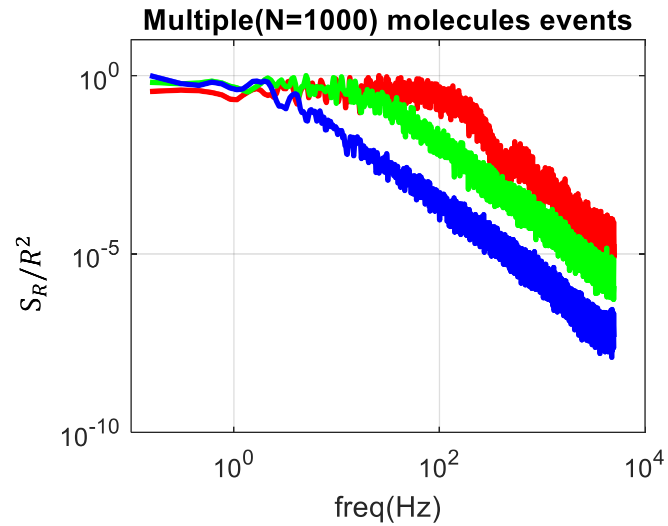
Assumption

Fluctuations in the electrical current are associated with:

1) Adsorption time: τ_{ads}
2) Life time: τ_{life}
3) Desorption time: τ_{des}



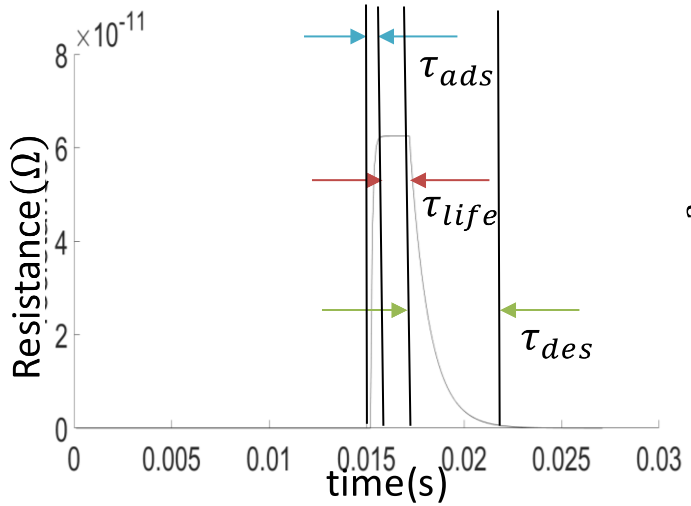
Parameter	S	Value (s)
Adsorption	τ_{ads}	10^{-3}
Desorption	τ_{des}	**10^{-2} , 10^{-1} ,10^{-0}**
Life	τ_{life}	10^{-3}

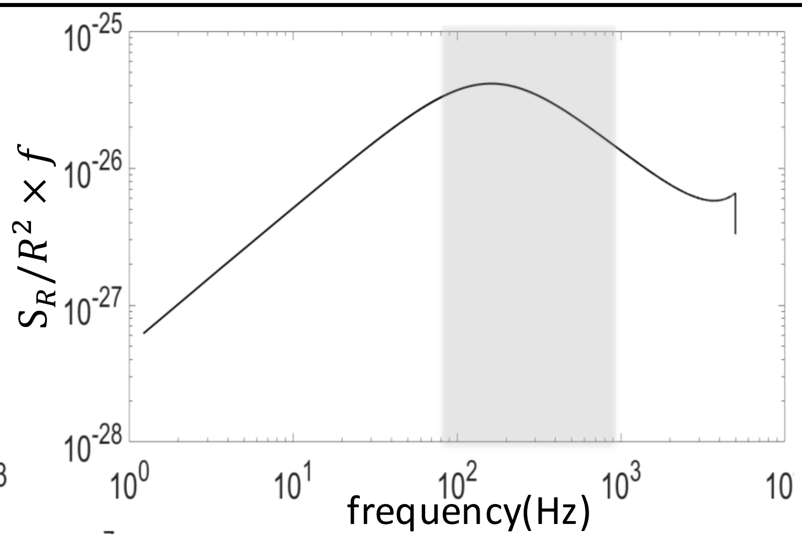


Simulate extrinsic fluctuations in the electrical current

The corner frequency is determined by the slowest event

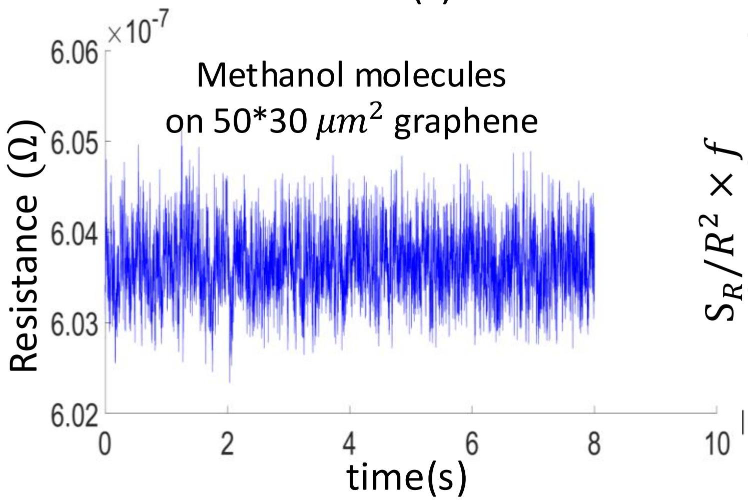
Equilibrium Noise Simulation

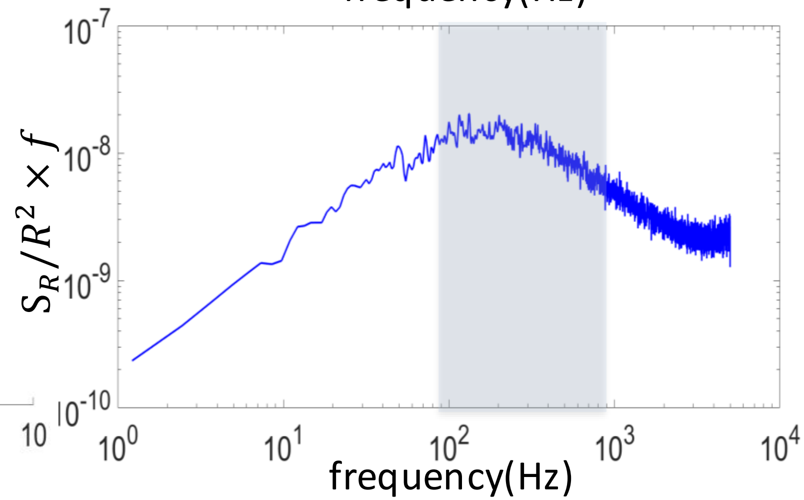




$$\tau_{\mathrm{Des}} = \nu^{-1} e^{\frac{E_D+Q}{RT}}$$

[1] Balandin, A.A. Nature nanotechnology





Langmuir Equation

$$\rho_{\mathrm{surface}} = \rho_{gas} \times e^{\frac{E_b}{k_b T}}$$

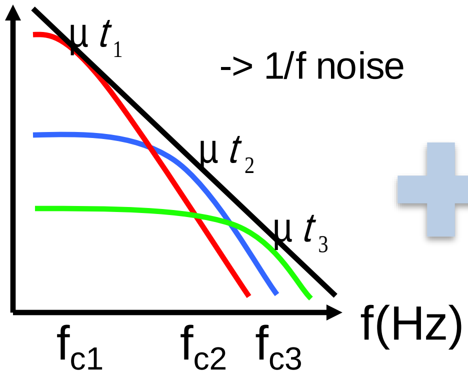
$$N = \theta N_0$$

[2]Romero, Hugo E., et al. *Nanotechnology*

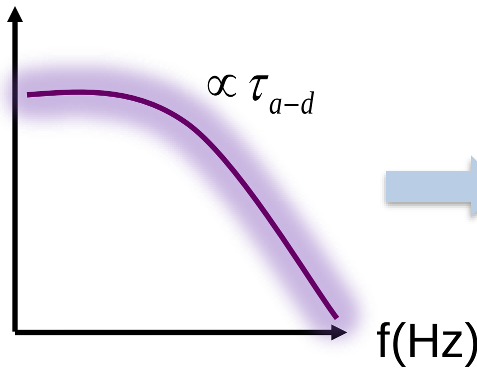
- ✓ The time constants associated with each charge transfer event can cause characteristic bulges in the PSDs

-> Possible mechanism for the bulge was proposed

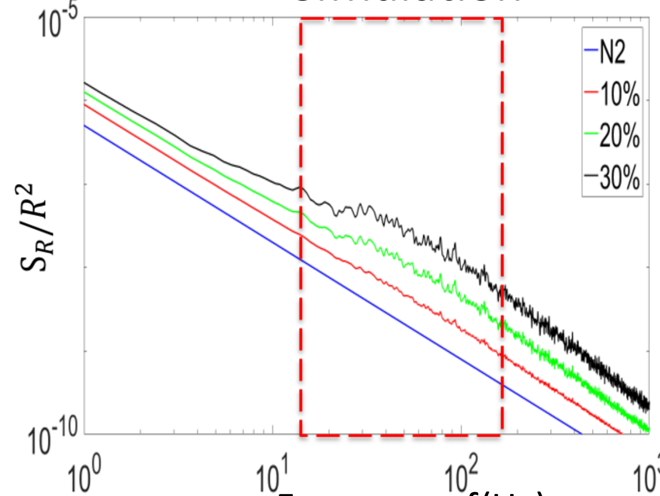
Simulation Result



McWhorter Model for 1/f noise



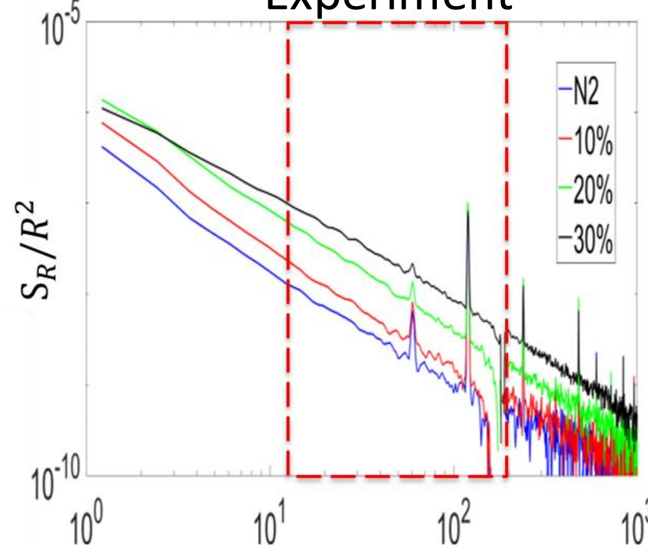
Simulation



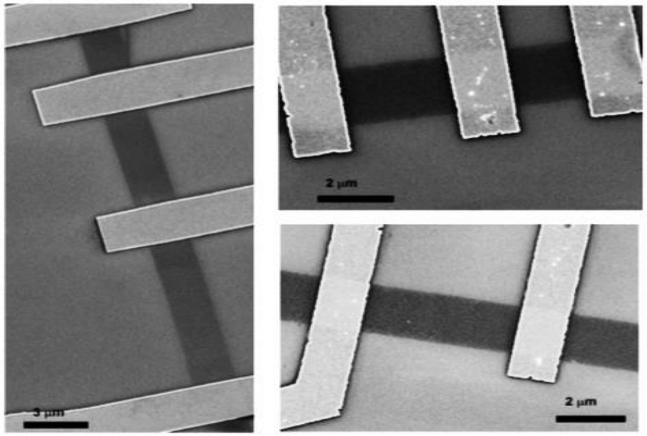
✓ Charge transfer in CVD graphene make the noise level change.

1/f noise level changed for different concentrations but with no characteristic bulge

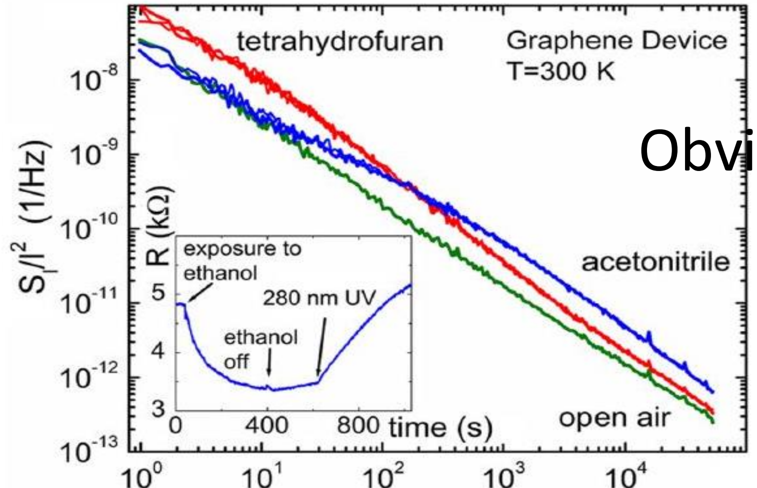
Experiment



Difference between graphenes



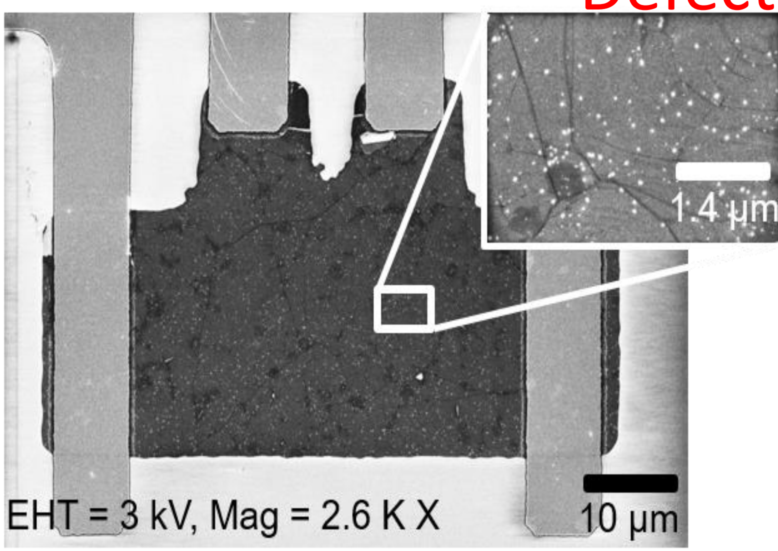
pristine graphene



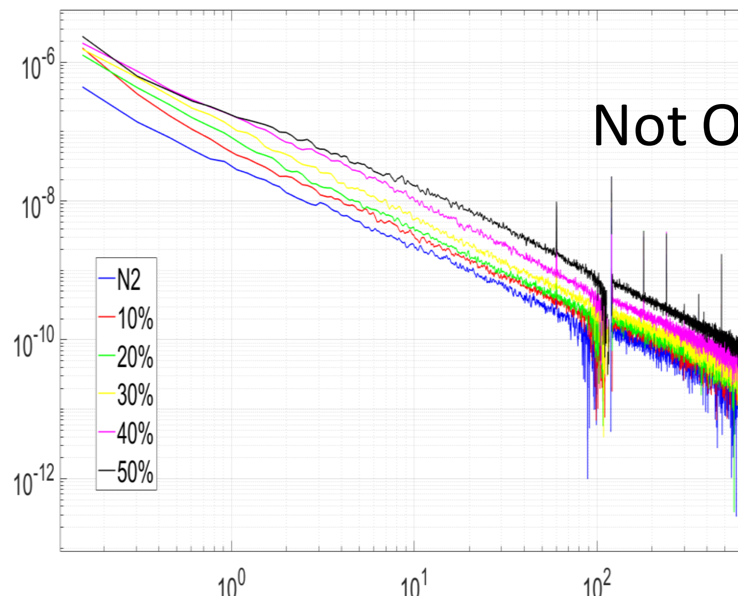
Frequency f(Hz)

Obvious bulge

Defects



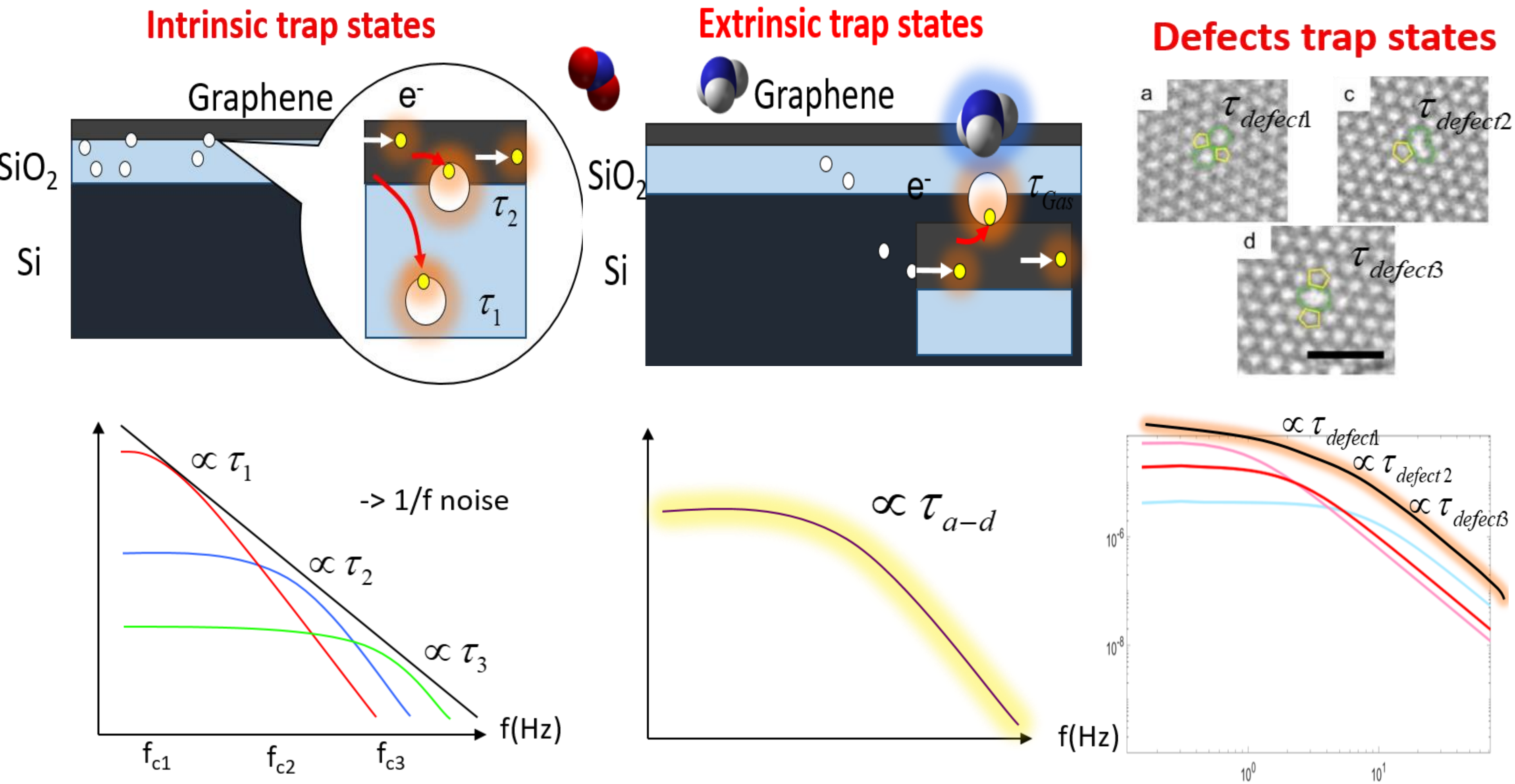
CVD graphene



Frequency f(Hz)

Not Obvious

Consist of noise in CVD graphene

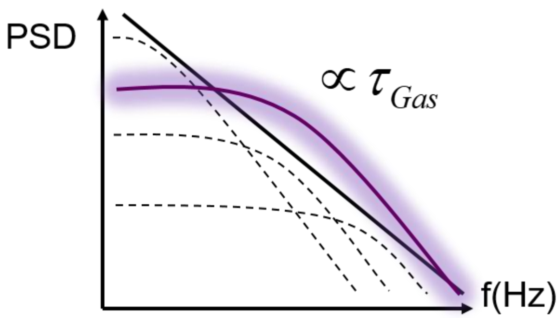


Defects in CVD graphene cause another bulge in low frequency range

[1]Vicarelli L, Heerema S J, Dekker C, et al. Controlling defects in graphene for optimizing the electrical properties of graphene nanodevices[J]. ACS nano

Hypothesis of indistinctive bulge

Pristine graphene

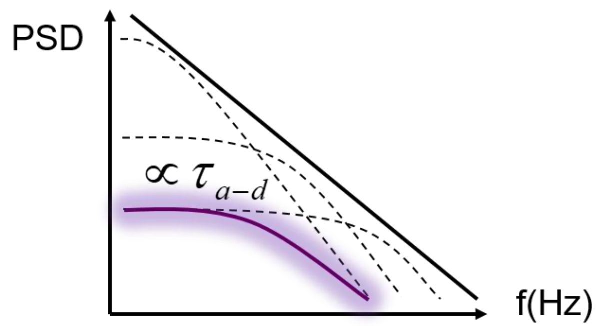


Pristine graphene noise

✓ Obvious bulge

CVD graphene

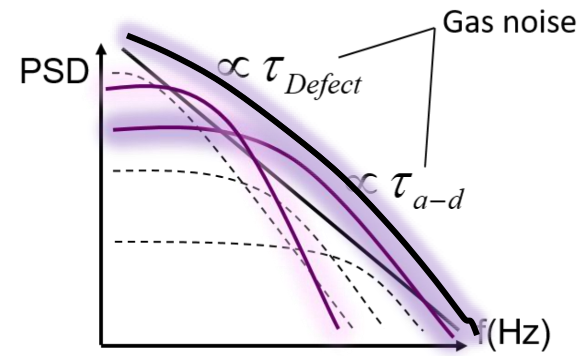
Previous hypothesis



Overwhelming gas noise

✓ Indistinctive bulge

× Move with concentration



Add defect noise

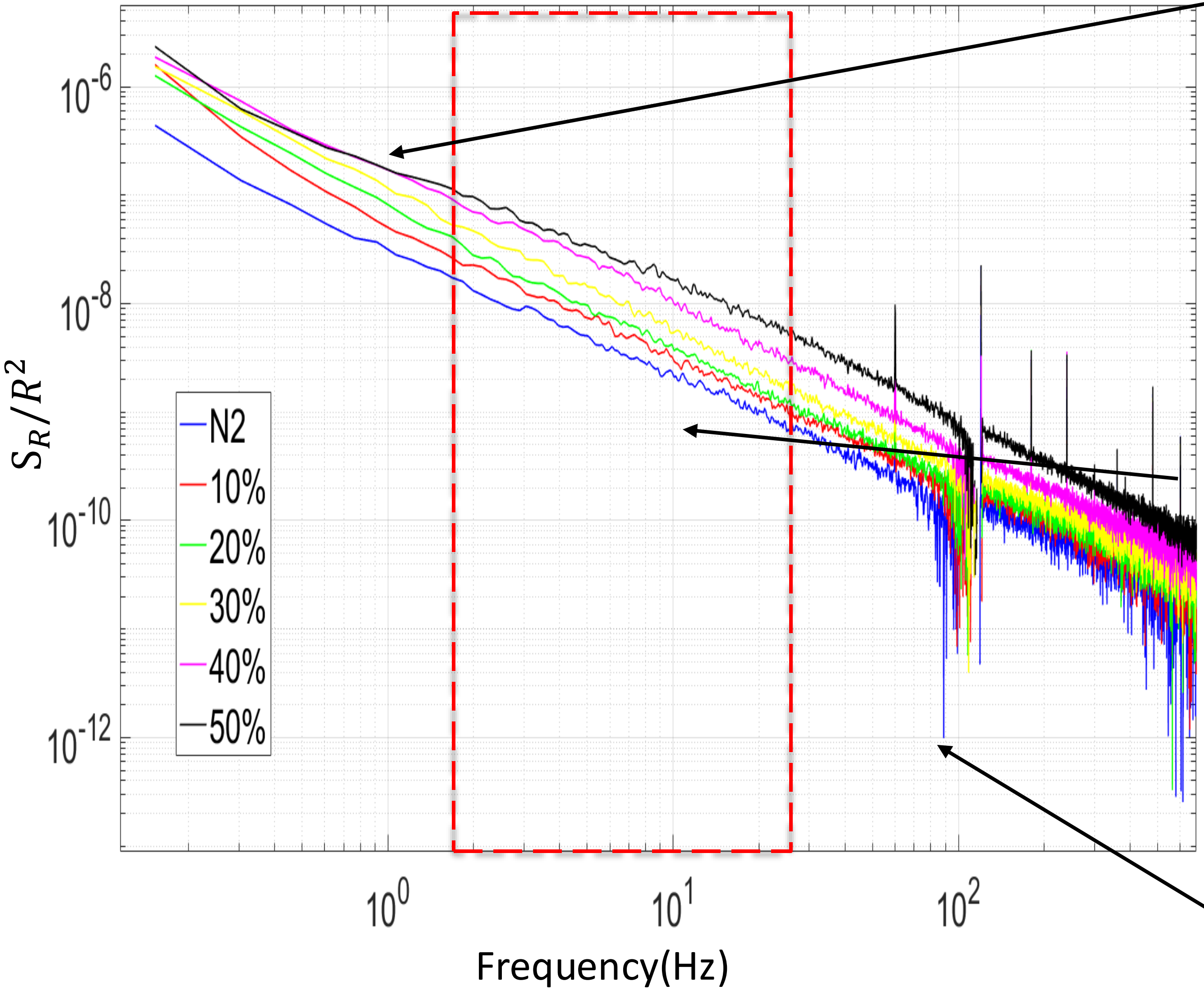
✓ Indistinctive bulge

✓ Move with concentration

✓ Defects on graphene make the bulge not so obvious

-> Possible mechanism for the indistinctive bulge was proposed

Preliminary results



Defect noise

$\tau \uparrow \rightarrow slow$

$\downarrow$

Long time for reaction & stable status

Charge transfer bulges

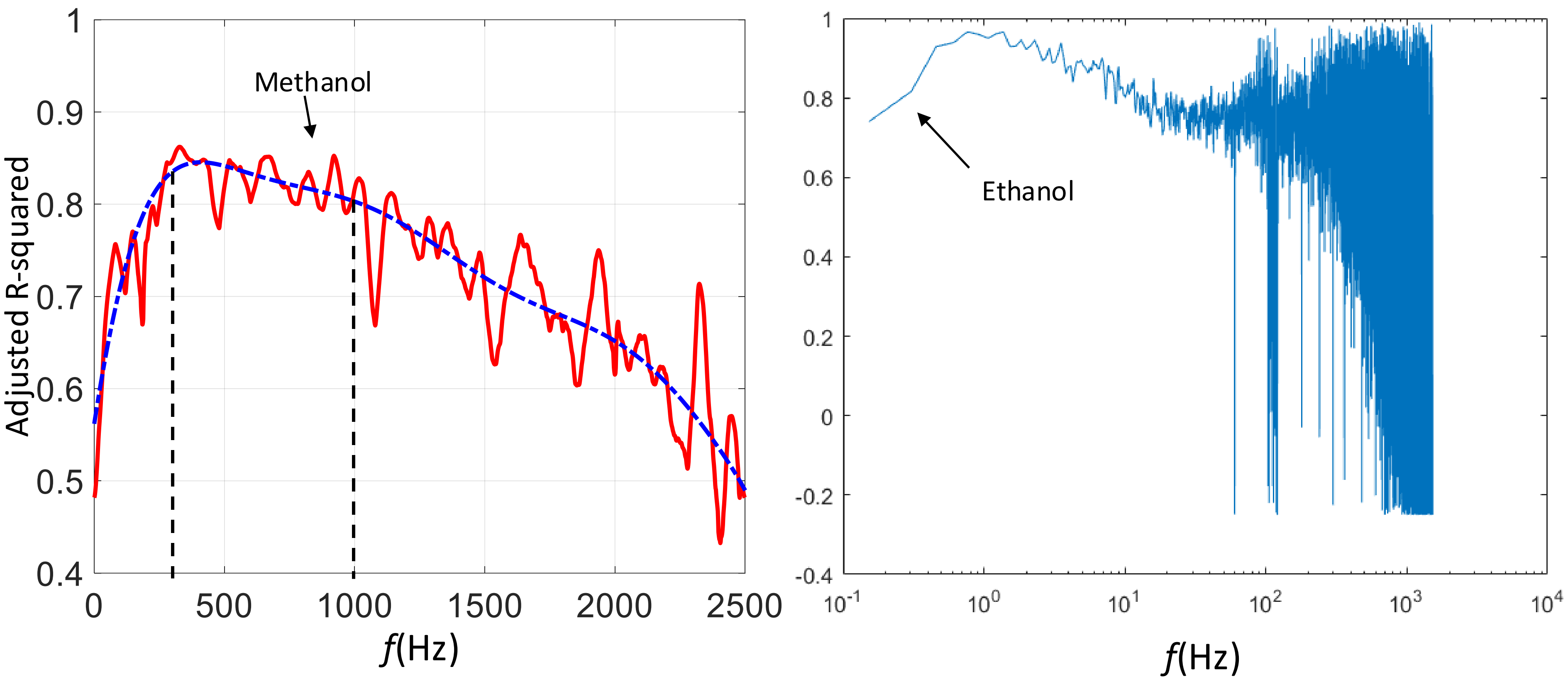
$\tau \downarrow \rightarrow fast$

$\downarrow$

Short time for reaction & stable status

White noise

R-square-adjusted Measurement



Using R-Square-Adjusted to measure the linearity of the noise at each frequency

The most linear frequency range fit the bulge frequency range

Method & Algorithm

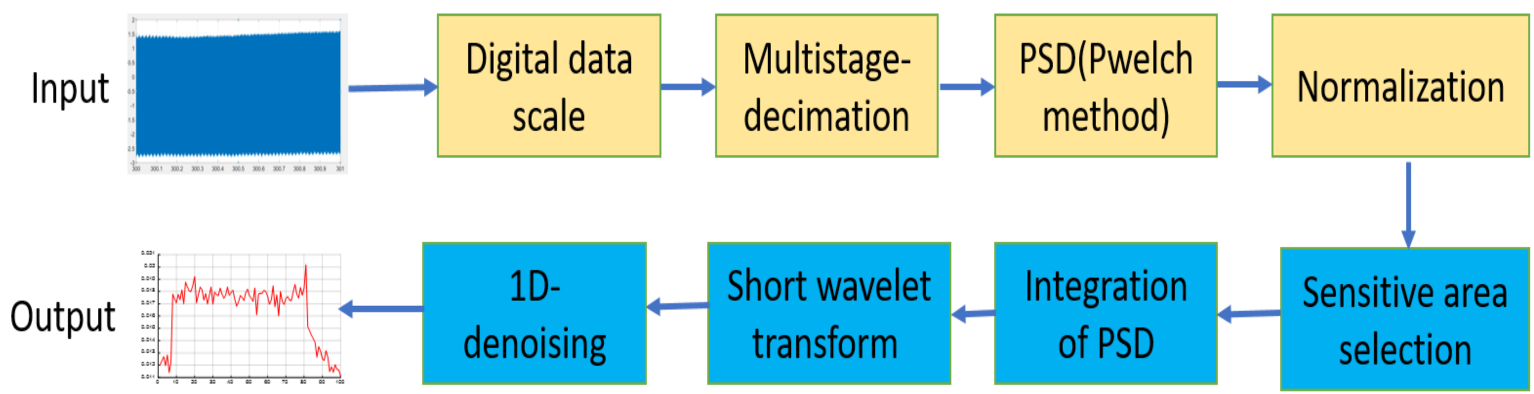
Method

Frequency domain:	Low frequency	Median frequency	High frequency

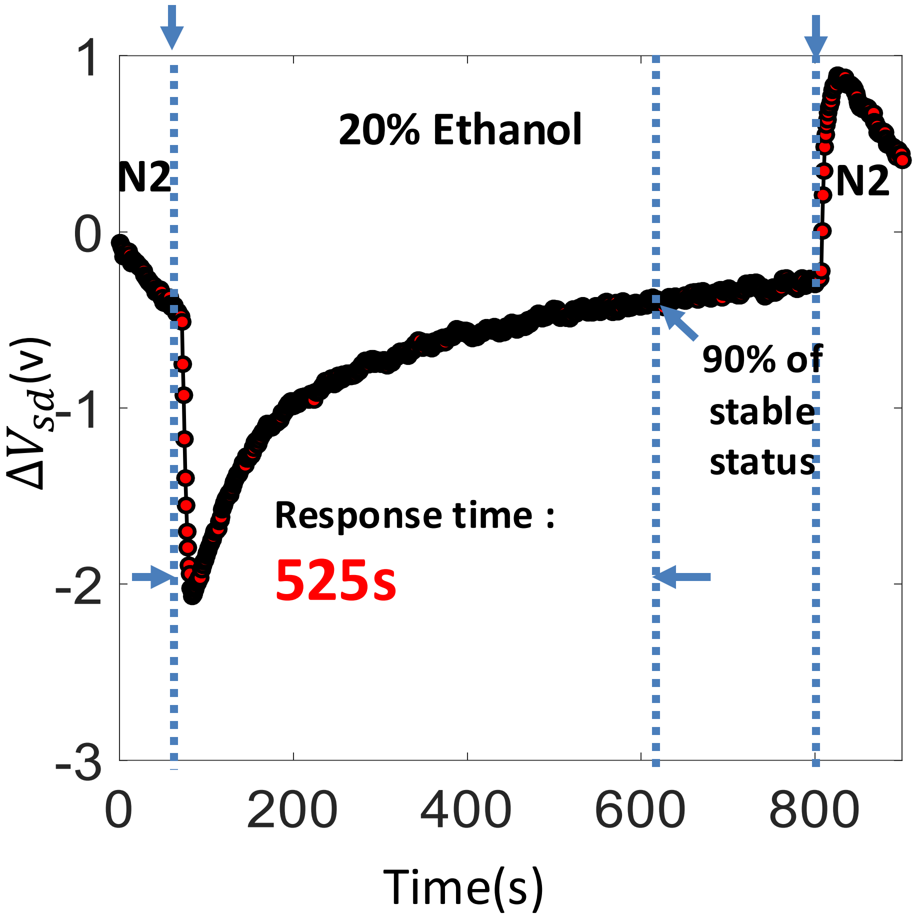
$$E_{eff}(t) = \frac{1}{V^2}\int_{f_1}^{f_2} S_{V_1}(f)df + \frac{1}{V^2}\int_{f_2}^{f_3} S_{V_2}(f)df + \frac{1}{V^2}\int_{f_3}^{f_4} S_{V_3}(f)df$$

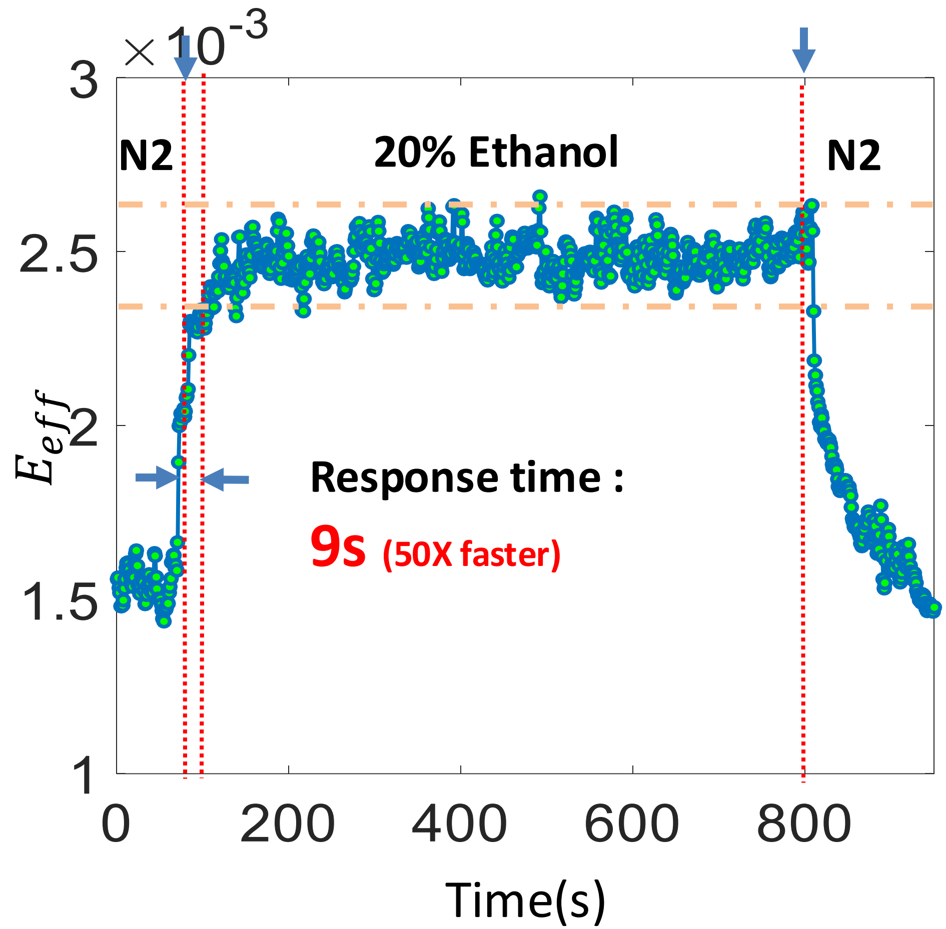
Sensitivity region:	Lower sensitivity for gas because of traps in CVD graphene	Most sensitive frequency domain for gas sensing	White noise floor(thermal noise or shot noise)

Algorithm



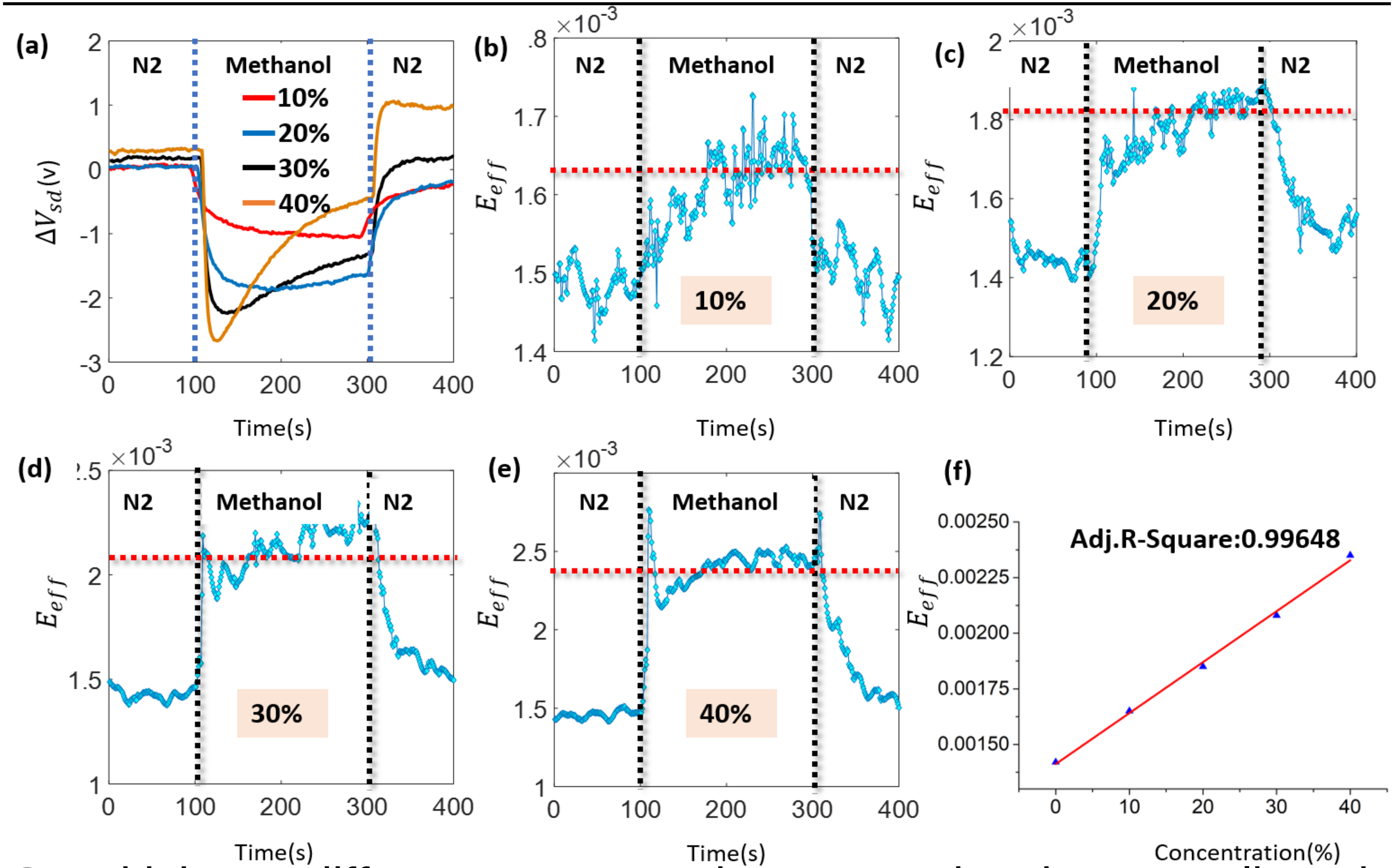
Fast response





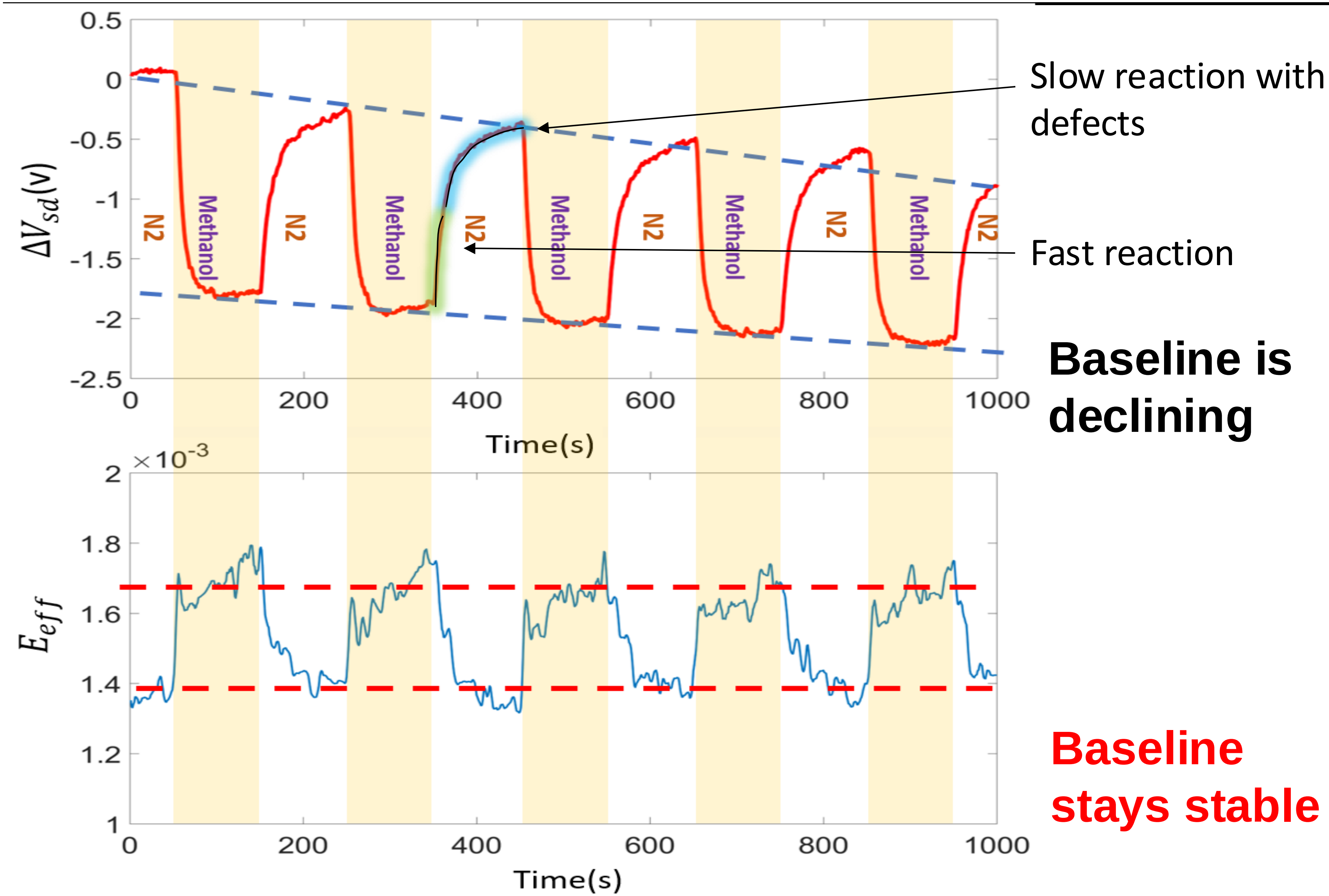
Response time in frequency domain is 50X faster than in time domain

Sensitivity & Linearity



Sensitivity to different concentrations vary, showing great linearity.

Stable baseline & Low drift



Baseline is declining

Baseline stays stable

Conclusion

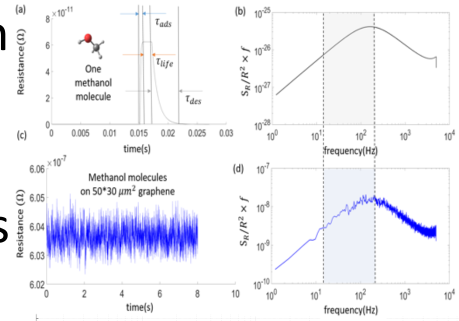
1) Simulation results show that the charge transfer events can cause characteristic bulges in the PSD.

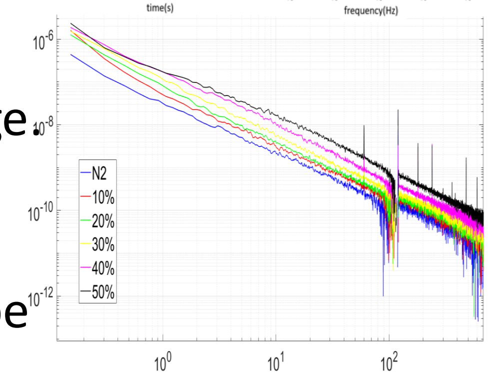
2) Gas sensing was demonstrated and the increase in noise was observed, but with no characteristic bulges.

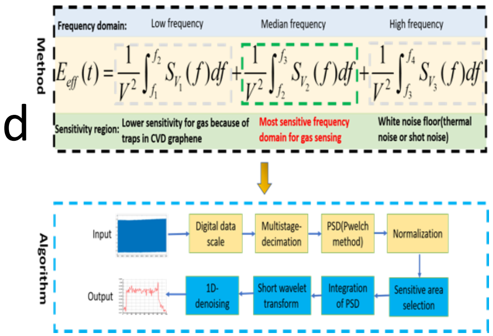
3) Charge transfer in CVD graphene make the noise level change. Defects in CVD graphene make the bulge not obvious.

4) The most sensitive frequency domain of noise can be obtained.

5) Using most sensitive frequency range to get good performances.







Future vision

-> Selective gas sensing in frequency domain might be achieved by improving the signal analysis method (adjusted R square) of CVD graphene.

-> More kinds of gas to do experiment to improve the repeatability and reliability.

-> Using machine learning or embedded system to develop a kind of gas sensor system.

Acknowledgement

Liwei Lin

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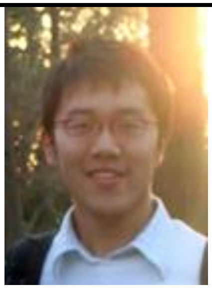

Huiliang Liu

Thank you!