# Low-frequency noise mechanism in GaN/AlN 2D electron and hole gases: experiment and theory

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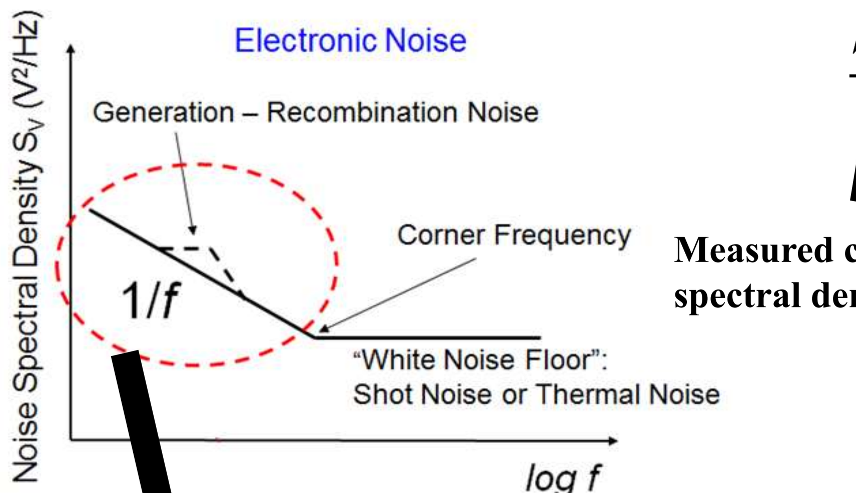
## Low-frequency noise in III-V electronics

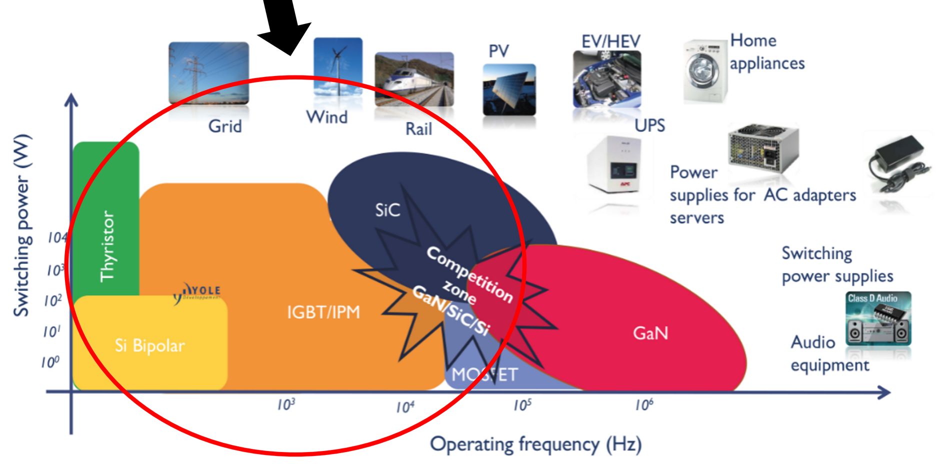



$$\frac{S_I(f)}{I^2} = \frac{S_\mu(f)}{\mu^2} = \frac{\alpha_H}{fN}$$

Measured current power spectral density

Number of particles

Material dependence

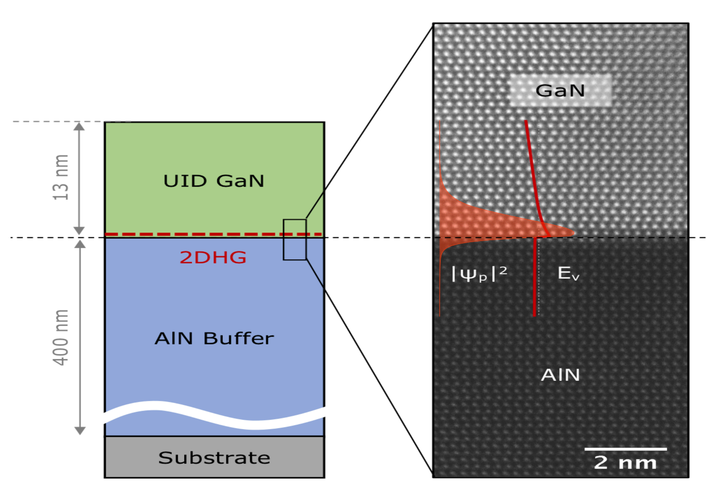



Noise power spectrum [PSD] (over frequency) used to quantify noise response of channel. 'Flicker noise' (< 1 MHz) has a 1/f dependence on frequency.

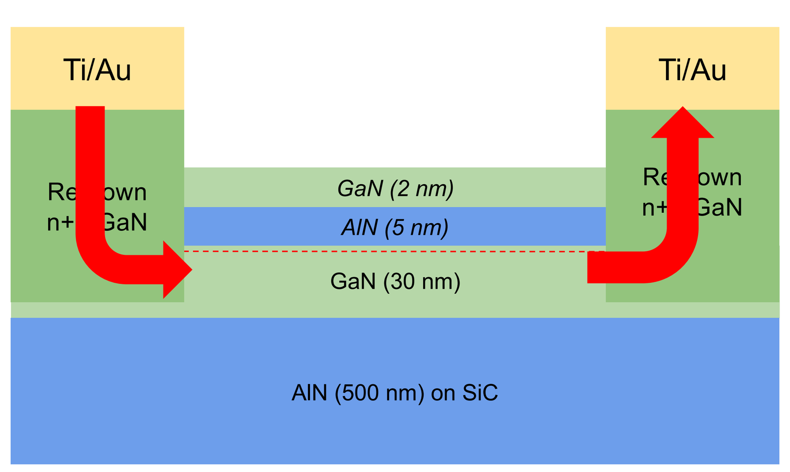
Seek to minimize noise.

- Operating frequencies differ based on application
- Most applications operate < MHz ➔ 1/f regime
- Need to minimize noise in GaN/AlN 2DHG/2DEG channel for high-speed communication application

**GaN/AlN 2D channel devices: complementary hole and electron transport allow for similar noise physics. Noise is dominant at contacts and source-drain channel of transistors.**



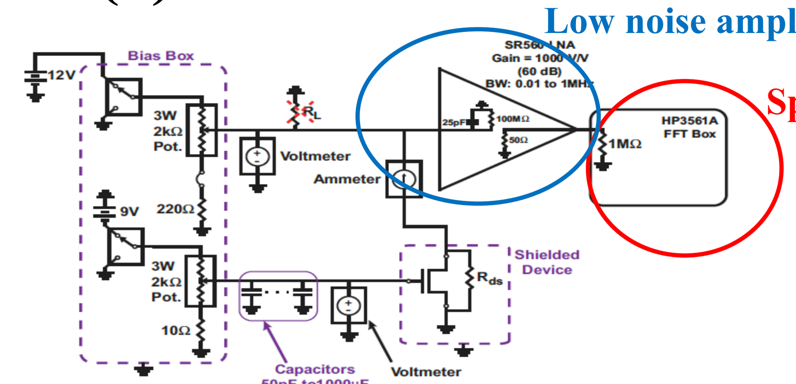

2DHG- pFET




2DEG- HEMT

## Experiment: measuring low-frequency noise in 2DEG/2DHG channels and devices

### (1) Noise measurement setup

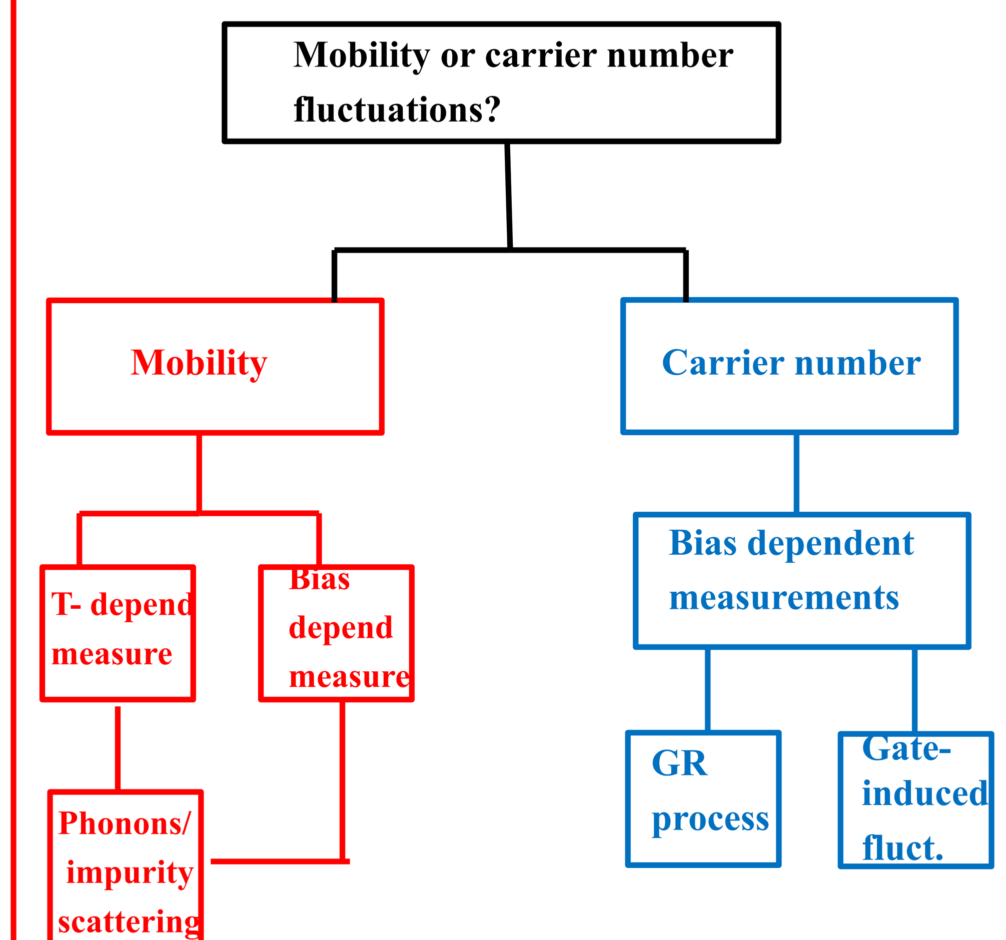



- **Spectrum analyzer** is used to measure voltage noise spectrum
- Low pass filters + **LNA** critical for noise filtering
- Devices are biased at source-drain before and after inversion. $V_g$ modulates 2DEG/2DHG density

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

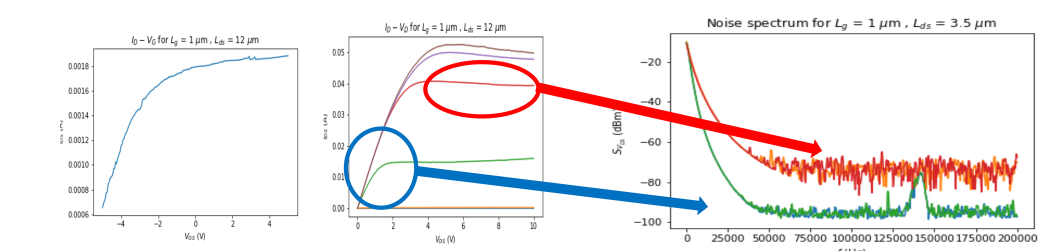
**Goal: density dependent noise ➔ number fluctuation**

### (2) Identity degrees of freedom



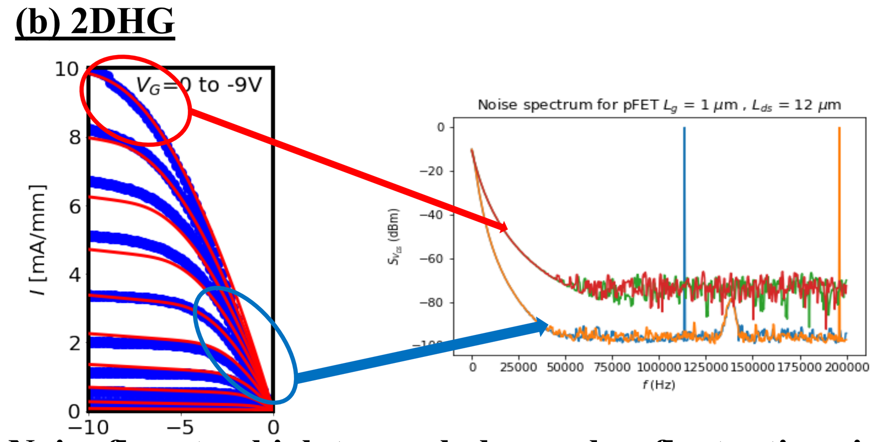

### (3) Measure gate-dependence

(a) 2DEG



Noise outcome in linear and saturation regime suggests ➔ more robust to small fluctuations at high bias. Noise floor too high to see number fluctuation noise dependence.

(b) 2DHG




Noise floor too high to see hole number fluctuations in *p*-channel device. Frequency regime below 1 MHz still suggests mobility fluctuations are are present .

## Theory: predicting low-frequency noise in 2DEG/2DHG channels and devices

### (1) Identify dominant noise mechanism

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

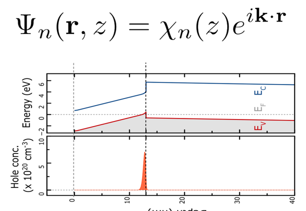
**Goal: temperature dependent noise ➔ mobility fluctuation**

(a) Determine electronic structure of noise channel

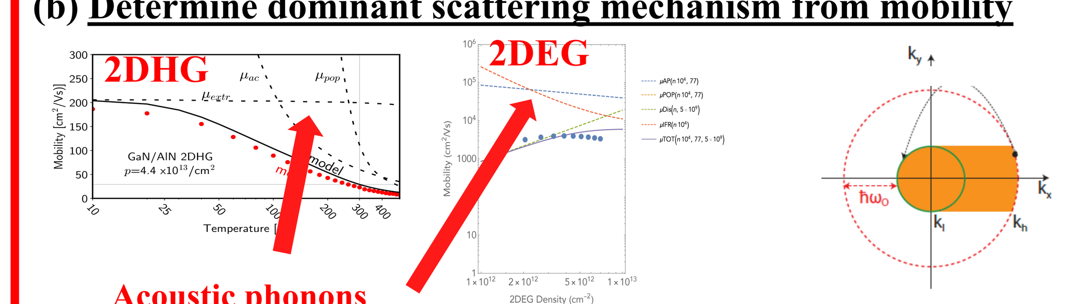
Determine wavefunctions/band structure :

- k . p, DFT, Schrodinger-Poisson

$$\Psi_n(\mathbf{r}, z) = \chi_n(z) e^{i\mathbf{k}\cdot\mathbf{r}}$$



(b) Determine dominant scattering mechanism from mobility




Acoustic phonons

Strong acoustic phonon interactions seen in mobilities of 2DEG/2DHG motivates use of the mechanisms in noise simulations

### (2) Run Monte Carlo algorithm

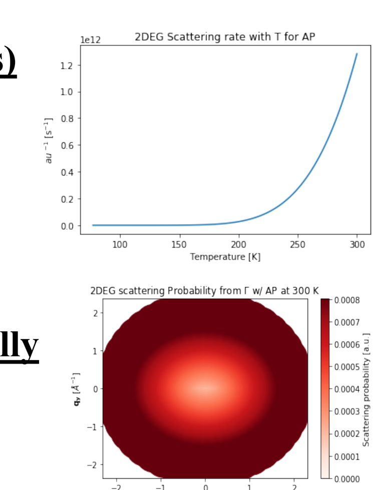
- Let k evolve with drift and diffusion:
  - drift step = deterministic ($k = k_0 + \frac{eE\delta t}{\hbar}$)
  - diffusion step = stochastic

(a) Determine rate for a single noise process (acoustic phonons)

$$\tau^{-1}_{c,\mathbf{k}_i,\mathbf{k}_j} = \frac{2\pi}{\hbar}|\langle\psi_{\mathbf{k}_i}|\hat{W}(\mathbf{r})|\psi_{\mathbf{k}_j}\rangle|^2\delta(\epsilon_{c,\mathbf{k}_i} - \epsilon_{c,\mathbf{k}_j} + \hbar\omega_{\mathbf{q}})$$

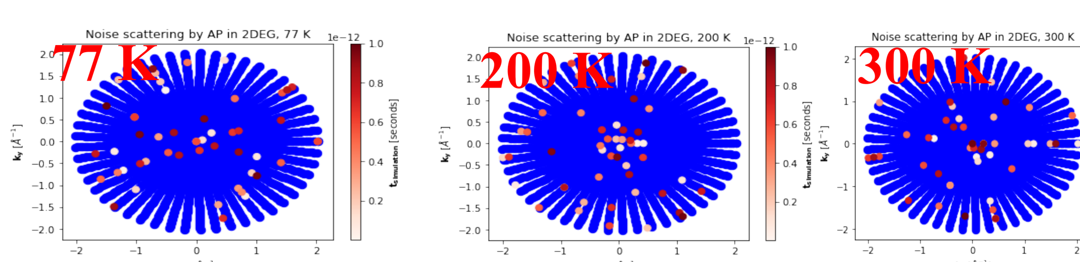
Noise mechanism coupling: needs wavefunctions

Enforce energy conservation



(b) Determine probability of diffusion and evolve k stochastically

$$\mathcal{P}(|\mathbf{k}_i\rangle \rightarrow |\mathbf{k}_i\rangle) = \frac{\tau^{-1}_{c,\mathbf{k}_i,\mathbf{k}_j}}{\sum_{i,j}\tau^{-1}_{c,\mathbf{k}_i,\mathbf{k}_j}}$$




Evolution over 1 ps in 2DEG w/AP ➔ T dependent!

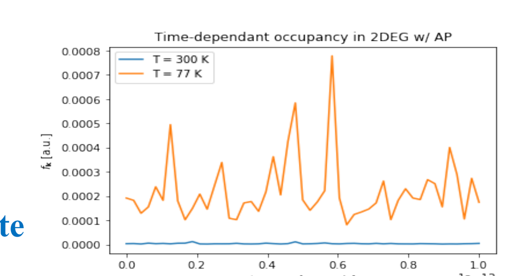
### (3) Extract noise spectrum

(a) Compute occupation function over every timestep

$$f_{\mathbf{k}} \approx f_{0,\mathbf{k}} + e\tau_{c,\mathbf{k}}\frac{\partial f_{0,\mathbf{k}}}{\partial \mu}\mathbf{v}_{g,\mathbf{k}}\cdot\mathbf{E}$$

Evolved occupation

Stochastic evolution stored in rate



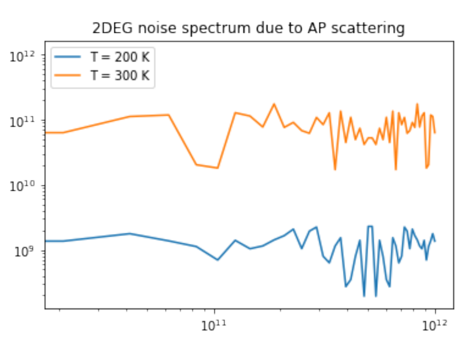

(b) FT of occupation autocorrelation function gives PSD

$$C_I(t) = q\sum_{\mathbf{k}}|v_{g,\mathbf{k}}|^2\langle\delta f_{\mathbf{k}}\delta f_{\mathbf{k}}(0)\rangle$$

Occupation autocorrelation

Current autocorrelation

FT of autocorrelation gives us the noise spectral density for specific noise mechanism. Current PSD can be plotted against experimental measurements.




## Acknowledgments

I would like to acknowledge Samuel Bader and Reet Chauduri for access to *p*-channel device and access to the PyNitride source code for simulations. I thank Menyoung Lee for fruitful discussion in theory implementation. Measurements would not have been possible without access to facilities at CCMR and the CNF.

## Future work

- Perform small signal analysis to identify the cause of unusually high noise floor in measurements and temperature dependent noise measurements
- Use MC implementation on AlN/GaN 2DHG heterostructure ➔ perform full ensemble calculations to capture degenerate physics
- Identify ways to suppress noise mechanisms experimentally by suppressing phonon scattering events