Cross-spectrum noise spectroscopy for characterization of deep-levels in nanoscale devices

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1. Abstract

Role of defects, whether present in bulk or at the interface, becomes increasingly important in nanoscale devices. Electrically-active defects in semiconductors often act as unintended generation-recombination centers, affecting the electrical and optical properties. Conventional methods to study deep levels, such as deep level transient spectroscopy and photo-induced current transient spectroscopy often becomes impractical for nanoscale devices.

In this poster we show the implementation of a powerful technique based on cross spectrum to study low-frequency noise(LFN) in nanoscale devices. The accurate measurements of the noise signal in low-current nanoscale devices such as field effect transistors (FETs) are extremely challenging because the device noise, which is proportional to the dc current, becomes comparable with the instrumental noise of the measurement setup. To overcome this issue, we implemented a LFN measurement method based on dual-channel cross-spectrum analysis technique. As a test bed we studied LFN in silicon nanowire (SiNW) field-effect transistors (FETs), correlated technique enabled sensitive noise measurement resulting in three orders of magnitude difference in power spectral density (PSD) as compared with conventional single-channel uncorrelated noise measurements.

Results indicated presence of electrically active deep-levels at 0.44 eV and 0.42eV for n-dope NWs grown using Au and Ni catalyst respectively. For the p-doped wires, the deep-levels were identified at 0.38 eV and 0.22 eV in NWs grown using Au and Ni catalyst. Other parameters like capture-cross section and deep level defect concentration were also estimated.

2. Theory

Low frequency noise or "spontaneous fluctuations" in current through semiconductors exists due to the stochastic nature of the conduction process.

Measuring noise power spectral density (PSD) of the dc current flowing through a semiconductor, one can estimate energy level, time-constants, and density of the generation-recombination (G-R) centers present in the sample. Typically for device exhibiting G-R noise, the PSD can be described by Lorentzian-behavior, i.e. $S_I = A/(1+(f/f_0)^2)$, where A is the low-frequency amplitude and f_0 is the characteristics frequency. G-R process is prominent at moderate temperatures with time-constant τ ($\tau=1/2\pi f_0$) which can be related to the trap energy-level and capture cross-section by the relationships:

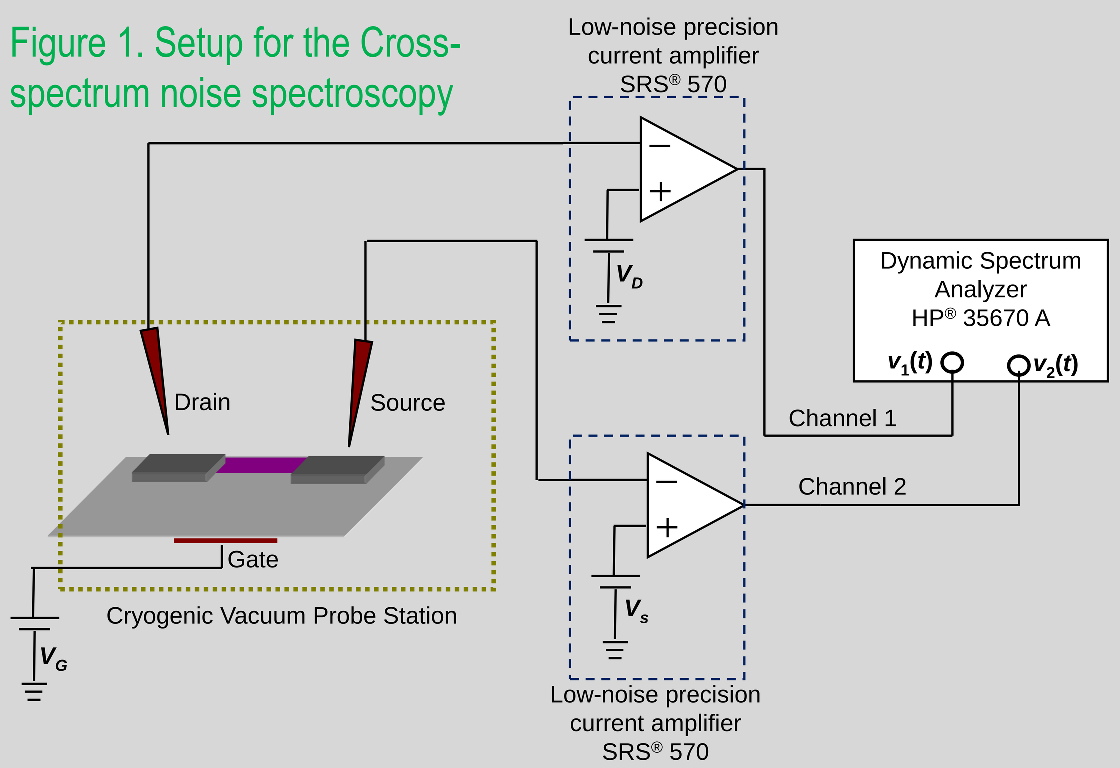
$$\ln(T^2\tau) \approx (\Delta E/k_BT)-\ln[(4k_B^2\sigma_n/gh^3)(6\pi^3 m_e^{1/2} m_h^{3/2})^{1/2}] \quad \text{------(1)}$$

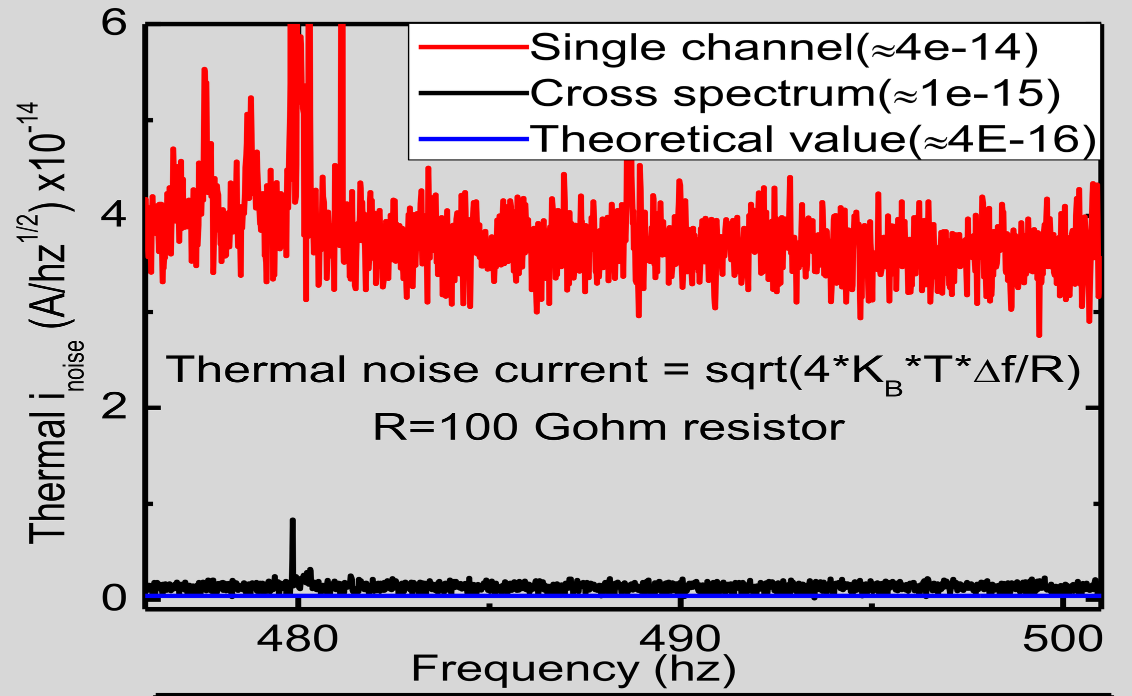
$$\ln(T^2\tau) \approx (\Delta E/k_BT)-\ln[(4k_B^2\sigma_p/gh^3)(6\pi^3 m_e^{3/2} m_h^{1/2})^{1/2}] \quad \text{------(2)}$$

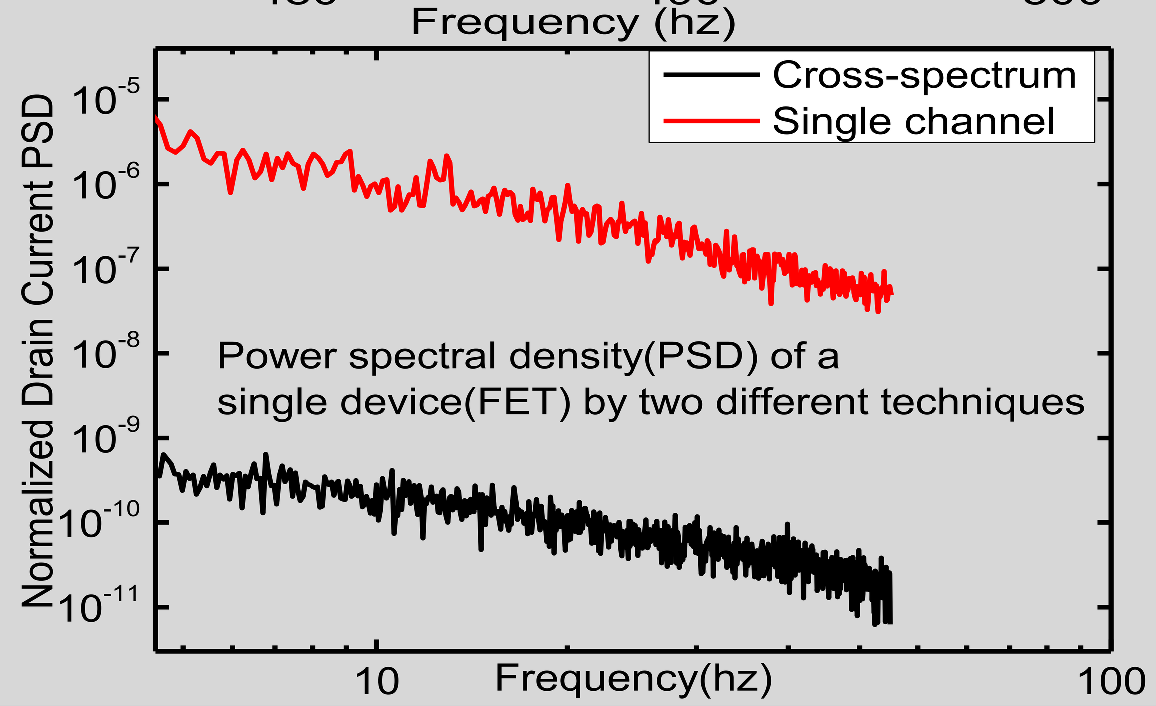
Where ΔE is the trap-energy, σ_n and σ_p are the electron and hole capture cross-sections, respectively, g is the degeneracy factor, T is the temperature and m_e and m_h are the electron and hole masses, respectively. From the slope of the plot of $\ln(T^2\tau)$ vs. $1/k_BT$ we can extract the energy position of the trap-level, and the intercept will give us the capture cross sections. It should be noted that often degeneracy values are not accurately known and hence may affect the capture cross-sections and trap density calculations.

3. Noise measurement setup

Figure 1. Setup for the Cross-spectrum noise spectroscopy







4. Working principle of cross-spectrum technique

In time-domain, the cross-correlation of two signals is defined as:

$$Rv_1v_2(\tau) = \lim_{T\to\infty} \int v_1(t)\, v_2(t+\tau)dt \quad \text{--------(3)}$$

In frequency-domain the equivalent cross-power spectrum of the two-signals is expressed as:

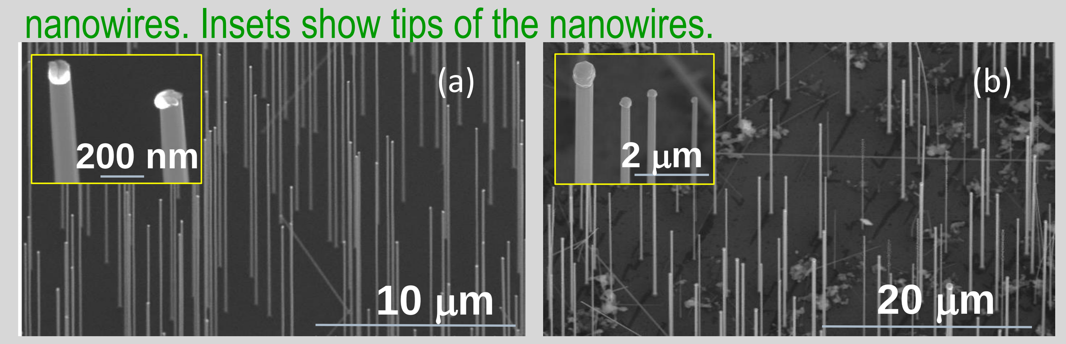
$$Gv_1v_2(f) = Sv_1(f)S^*v_2(f) \quad \text{--------(4)}$$

Where $v_1(t) = c_1(t) + s(t)$ and $v_2(t) = c_2(t) + s(t)$. s(t) is the correlated component, mostly the device-under-test (DUT) noise and $c_1(t)$ and $c_2(t)$ being the uncorrelated noise from channel 1 and 2 respectively due to amplifier circuits and analyzer front-end circuits. By taking only the real part of $Gv_1v_2(f)$ we minimize the uncorrelated noise power and therefore improve the standard deviation of the fluctuations around the DUT power density value at the output of the instrument.

5. Fabrication of devices for LFN measurements

The new method was applied to probe deep levels in Si nanowires (SiNWs) grown by the vapor-liquid-solid (VLS) mechanism using Au and Ni catalysts. Metal catalysts employed in the VLS growth are known to be the sources of unintentional deep level impurities.

Figure 2. Bird's-eye view SEM images of (a) Au- and (b) Ni-catalyzed Si nanowires. Insets show tips of the nanowires.



Au-catalyzed SiNWs were grown at 900 °C for 10 min. Average diameter of these NWs is about 130 nm. Ni-catalyzed SiNWs were grown at 1000 °C for 5 min. Diameters of these NWs varied between 100 nm and 600 nm

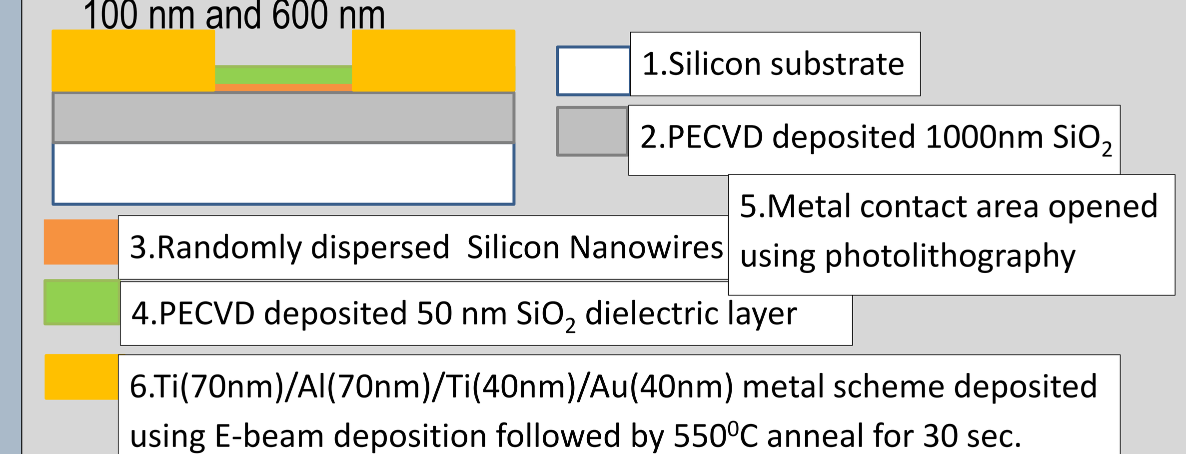


Figure 3. FET Fabrication process flow

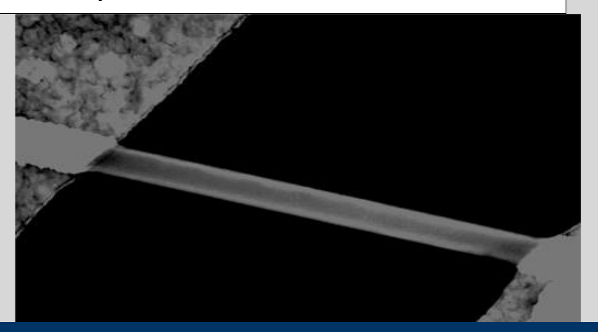
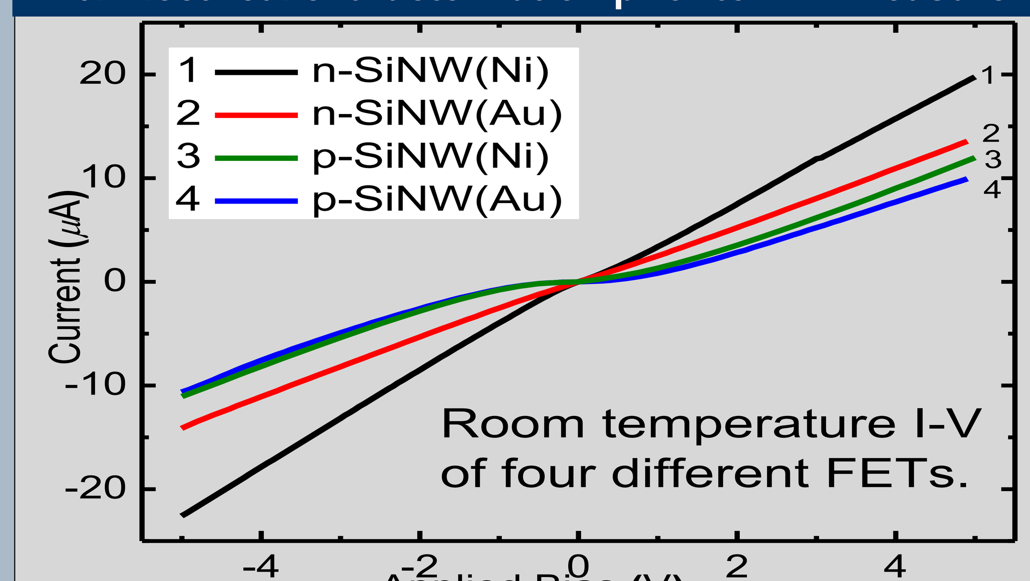
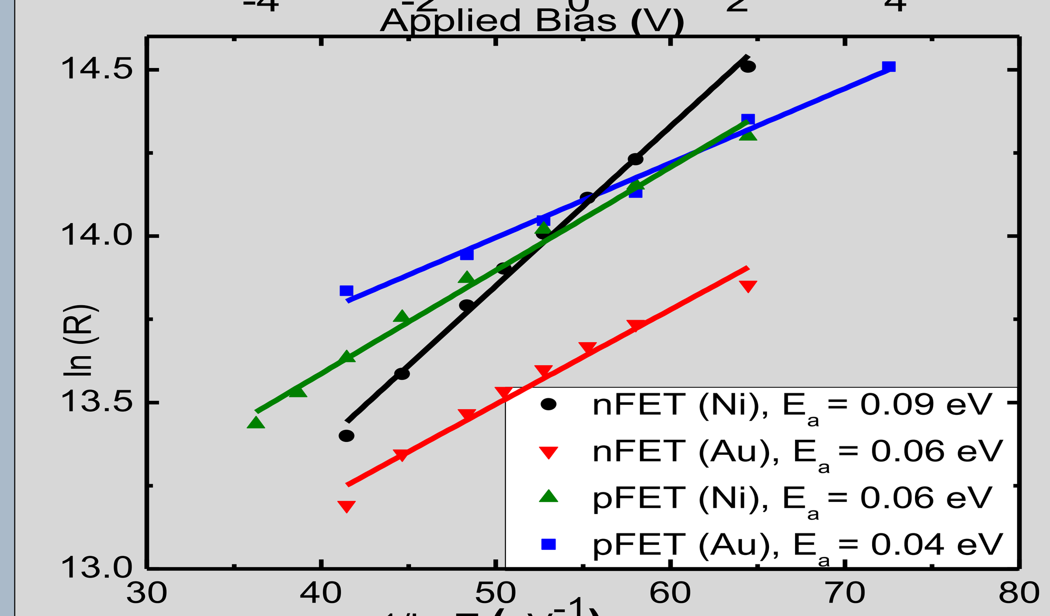


Figure 4. SEM image of a fabricated SiNW FET

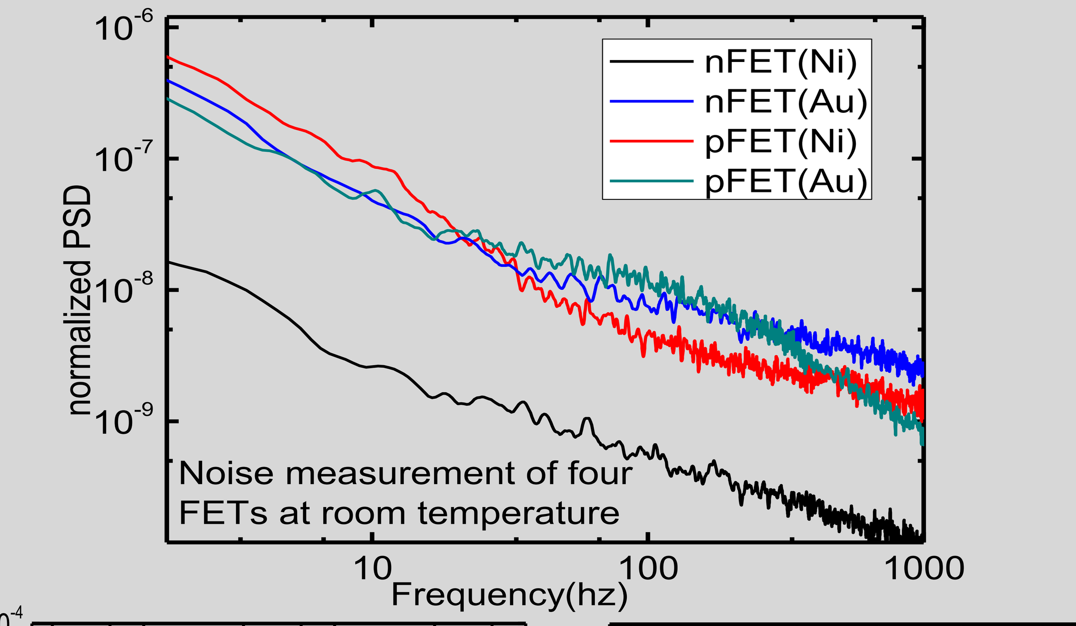
6. Electrical characterization prior to LFN measurements

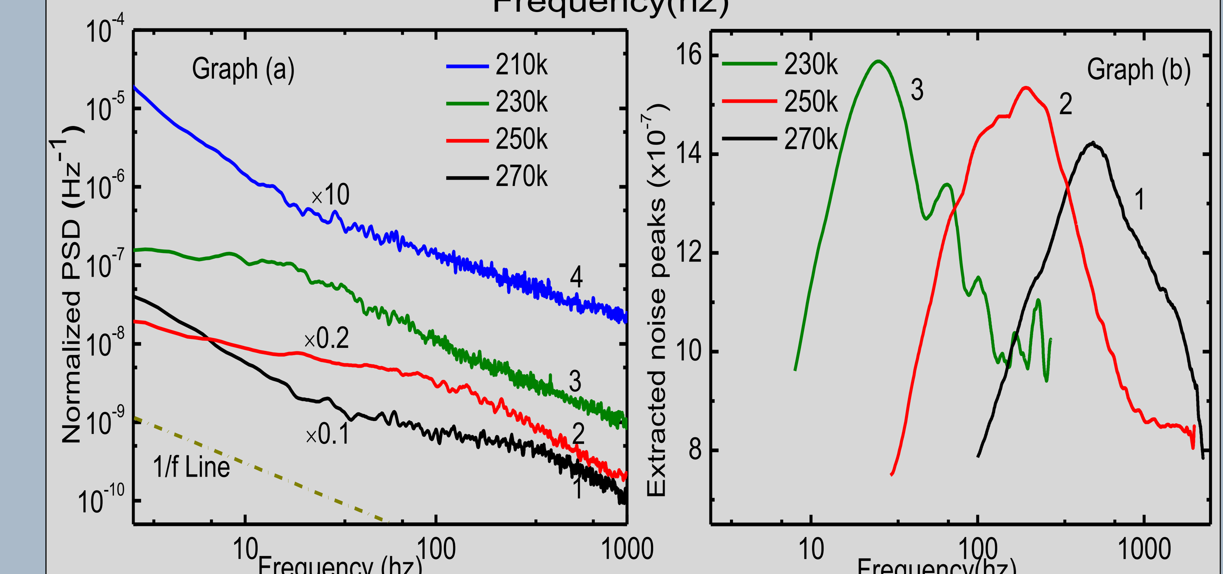




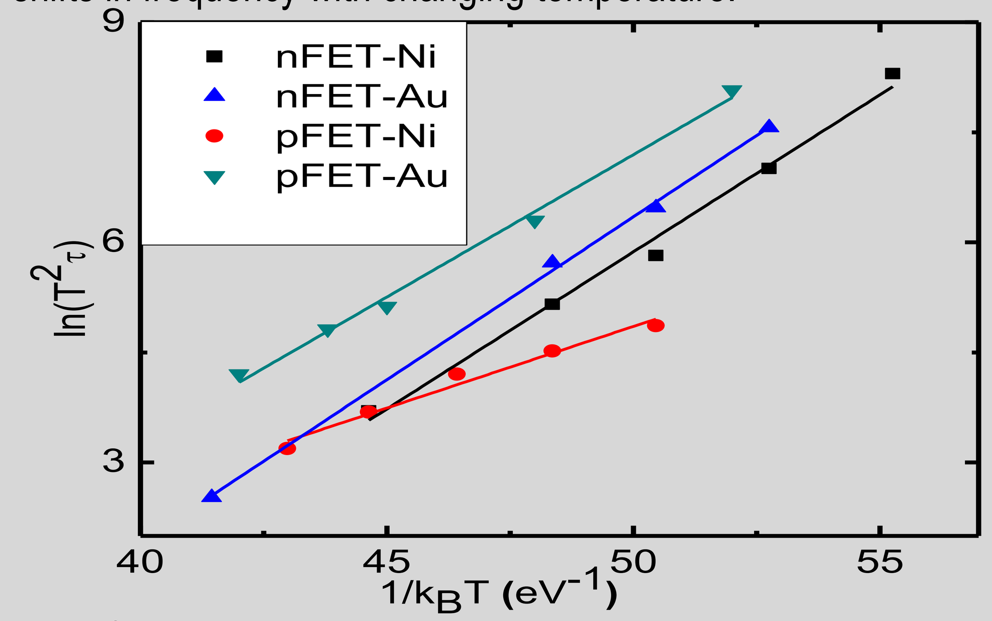
Arrhenius plot confirmed semiconducting behavior of the devices. Activation energy was computed using eq: $\ln(R) = \ln(R_0) + E_a/2k_BT$ (where R_0 is the intercept, E_a is the activation energy, k_B is the Boltzmann's constant, and T is absolute temperature).No information related to deep levels could be inferred from this data.

7. LFN measurement results





Graph (a) shows the temperature dependent noise measurement done on a single FET device. Evolution of Lorentzian behavior from low to high temperature is clearly obvious. Graph (b) show the peaks, extracted from the data of graph (a). It clearly depicts how the peak shifts in frequency with changing temperature.



$\ln(T^2\tau)$ vs. $1/k_BT$ plot for four FET devices(equations 1 and 2). Table shows all the computed values from this plot.

Device	Deep-level (eV)	Capture Cross section value of electron (cm²)	Capture Cross section value of hole (cm²)	Trap concentration (cm⁻³)
n-FET (Ni)	0.42	6.1×10^{-15}	6.1×10^{-15}	1.0×10^{12}
n-FET (Au)	0.44	8.4×10^{-15}	7.3×10^{-15}	1.8×10^{12}
P FET (Ni)	0.22	5.7×10^{-19}	5.0×10^{-19}	1.0×10^{16}
P FET (Au)	0.38	9.5×10^{-17}	1.4×10^{-16}	2.0×10^{12}

8. Conclusion

This study demonstrated the fact that properly optimized noise measurement setup can be very power technique to study carrier fluctuations in semiconductor materials and to understand the quality of nanoscale devices.

9. Contact information

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