CASE STUDY

Determined the Low-Frequency Noise Source in Cryogenic Operation

Advanced measurement science helps identify and quantify MOSFET noise sources across frequency and temperature

KEYSIGHT

Organization

- National Institute of Advanced Industrial Science and Technology

Challenges

- Noise is a limiting factor in qubit coherence time
- Noise sources in MOSFETs at cryogenic temperatures emit noise across a wide spectrum
- Conventional I-V analyzer measurements mask low-frequency device noise due to a high noise floor and a narrow frequency range

Solutions

- Create an advanced low-frequency noise setup using a Keysight E4727B controlled by an external workstation running Python, which also coordinates temperature sweeps of the cryogenic refrigerator controller during measurements
- Connect E4727B using 2m coaxial cables with additional wrapped shielding

Results

- Obtained breakthrough wide-range, low-frequency noise measurements on p- and n-channel MOSFETs at cryogenic temperatures
- Measurements quantified device trap energy levels changing with temperature, confirming a theory about charge trapping near the band edge

Pulling MOSFET Noise Out of a Cryo Noise Floor

Japan's National Institute of Advanced Industrial Science and Technology (AIST) teams at the Tsukuba Research Center work on emerging computing technologies, including devices and applications for quantum computing. One of their nine-person teams is uncovering new insights into low-frequency noise observed in qubit control circuits. Their measurements of random telegraph noise (RTN) in short-channel MOSFETs at cryogenic temperatures using the Keysight E4727B Advanced Low-Frequency Noise Analyzer is expanding the understanding of noise sources in quantum computing, paving the way for faster machines moving forward.

Challenges

A crucial metric in quantum computing is the qubit coherence time, or how long it holds its complex quantum state – and the information it carries. If a qubit's spin collapses, it takes its stateful information and any calculations in progress depending on that information with it. The longer silicon spin stays in phase within a qubit, the longer a qubit has to perform operations, increasing the throughput of each qubit and helping scale the quantum computer.

Low-frequency noise dephases silicon spin qubits, and the effect worsens as cryogenic temperatures push lower. However, researchers have had difficulty seeing how much low-frequency noise exists in a quantum computing qubit or even validating where the noise sources are. Many noise sources exist in larger transistors, making higher levels of composite noise easier to observe. As transistors get smaller, fewer sources create noise, but conventional semiconductor measurement systems have difficulty seeing the lower noise since they have a higher noise floor than the measurement they are attempting.

Theories on noise sources in semiconductor devices at cryogenic temperatures exist but so far have evaded proof. Prior research at AIST suggested that noise in MOSFETs is associated with charge traps, moving from inner-oxide traps to interface traps, with the noise worsening as temperatures drop. They also theorized that when the gate voltage is near the threshold voltage ($V_g = V_{th}$), the surface Fermi level of the MOSFET would approach the band edge at low enough temperatures, inferring that charge trapping near the band edge would be the major contributor to noise at cryogenic temperatures.

Understanding how to reduce low-frequency noise in qubits drove AIST to shift investigation to the microscopic level of MOSFETs. For this research, they fabricated 90nm long, 100-120nm wide short-channel bulk MOSFETs with silicon oxynitride dielectric layers on a Si(100) wafer. Self-aligned extension implantation and halo implantation help mitigate short-channel effects. Figure 1 shows the MOSFET structure and a plot of I_d versus V_g with V_d set at 50mV, indicating that the threshold voltage increases with decreasing temperature, as expected.

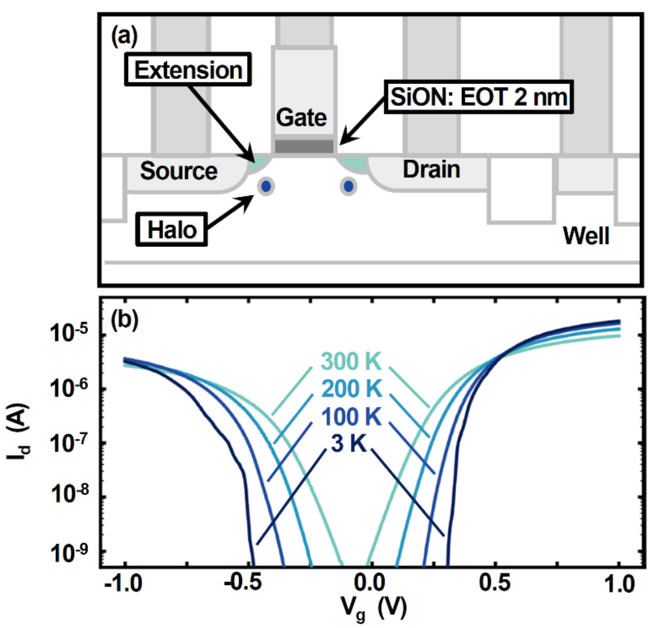

Figure 1. Short-channel bulk MOSFET structure and current-voltage plots at cryogenic temperatures

Solutions

Conventional semiconductor test instrumentation solutions from Keysight and other vendors accurately measure MOSFET device currents and voltages. However, these instruments lack built-in low-frequency noise measurement capability. It normally uses a Keysight B1500A Semiconductor Device Parameter Analyzer and a similar instrument from a Keysight competitor, capturing time-series drain current data and then running a Fourier transform on the data to obtain plots of power spectral density (PSD) versus frequency. With both instruments, they noticed the Fourier transforms were only producing the noise floor of the instrument, revealing nothing about the noise of the MOSFET devices under test. Neither instrument reached far enough in its frequency range to create a complete noise profile.

Keysight E4727B Advanced Low-Frequency Noise Analyzer (Figure 2) is a dedicated instrument designed for direct turnkey measurements of 1/f noise and RTN. The E4727B's noise floor of 1E-28 A^2/Hz is three orders of magnitude better than the B1500A, and its frequency range covers from 30 mHz to 100 MHz. It automatically chooses source and load impedances to expose device noise, allowing manual settings control if desired.

Figure 2. Keysight E4727B Advanced Low-Frequency Noise Analyzer (A-LFNA)

Reliable low-frequency noise measurements with the E4727B require careful attention to cabling and power supply. With the cryogenic chamber about 2 meters away, The additional wrapped shielding for coaxial cables for A-LFNA's amplifier is a good way to reduce conducted external noise. The E4727B rejects power line noise when using a dedicated AC outlet with grounding (precluding an unexpected ground loop), eliminating a 50 Hz spike in the normal Fourier transform results. Completing the setup, RTN measurements are automated with a Python script that controls the E4727B and the cryogenic refrigerator's temperature controller, creating frequency and temperature sweeps.

Results

With its substantially lower noise floor and wider bandwidth, direct plots from the E4727B tell a detailed story about short-channel bulk MOSFET RTN.

- AIST's initial findings were consistent with prior research: as temperatures drop, noise worsens. Figure 3(a) visualizes a noise map – essentially multiple RTN runs – showing a denser block of orange at lower frequencies as the temperature approaches 0 K.
- Individual MOSFETs display some RTN variance but generally exhibit noise peaks at different temperatures. Figure 3(b) illustrates a noise map for a different device than in Figure 3(a). The solid blue curve extrapolates one of the noise peaks along a Shockley-Reed-Hall (SRH) model of frequency and temperature.
- Slicing the noise map in Figure 3(b) horizontally across one temperature yields a familiar PSD plot. Figure 3(c) shows that at 42 K, PSD follows a $1/f^2$ characteristic in the frequency domain.
- A time lag plot shown in Figure 3(d), from raw I_d values measured for Figure 3(b) again sliced along 42 K, shows a square-shape correlation typical in a two-state system, indicating one RTN source.

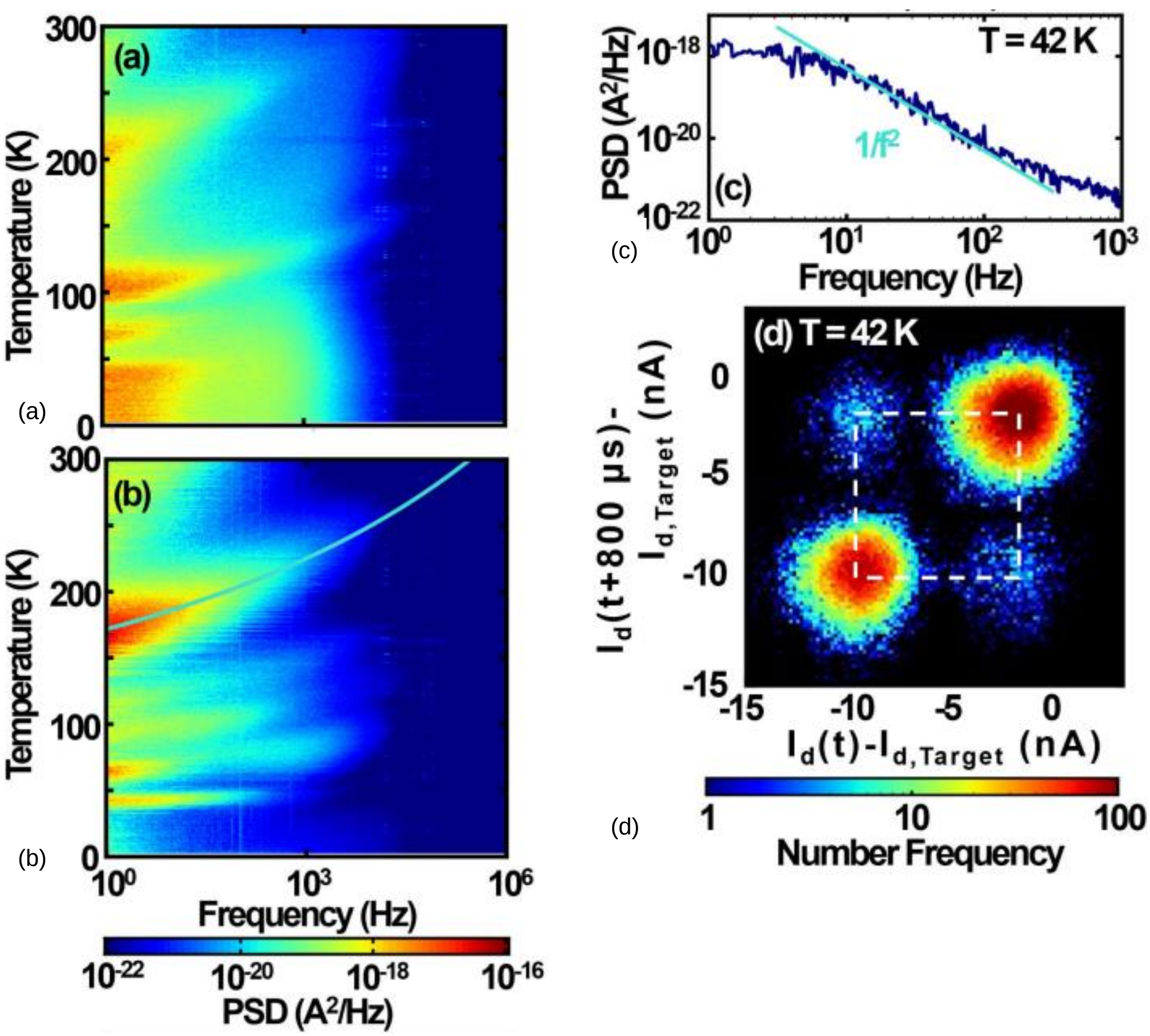

Figure 3. Frequency-temperature noise maps for two different MOSFETs, with PSD and I_d data sliced at 42 K

Pursuing the solid curve in Figure 3(b), an Arrhenius plot shown in Figure 4 with a linear relationship fitted to the data concludes charge traps exist at an energy level of 405 meV below the conduction band.

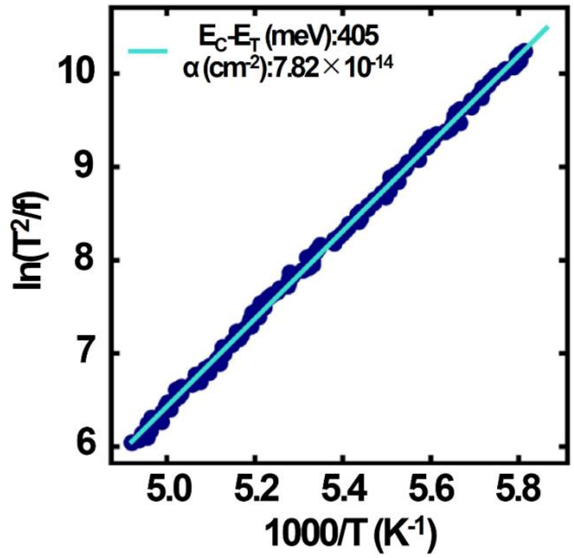

Figure 4. Arrhenius plot with a linear curve fit for quantifying charge trap energy level

Examining noise maps using this process helped AIST identify and quantify 20 noise peaks in data from measurements on five n-channel MOSFETs. Figure 5 summarizes the extracted energy levels, plotted against T_{1Hz}, the temperature at which strong 1 Hz RTN peaks appear.

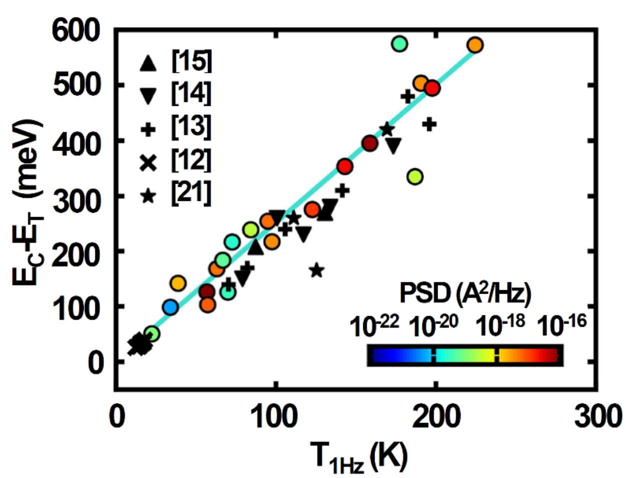

Figure 5. Visualization of energy levels represented in RTN peaks at various temperatures

These plots illustrate the power of the E4727B as a low-frequency noise measurement analyzer. A single measurement in AIST's scenario across frequency and temperature with the E4727B takes two to three days, depending on measurement conditions, yielding raw data and robust visualizations. For the first time, with the E4727B and a Python script controlling the cryogenic refrigerator, AIST has been able to measure and visualize low-frequency noise across frequency and temperature.

Learn More

- Determining the low-frequency noise source in cryogenic operation of short-channel bulk MOSFETs
- Temperature Dependent Variations of Low-Frequency Noise Sources in Cryogenic Short-Channel Bulk MOSFETs
- AIST Press Release (Japanese)

All figures except Figure 2 courtesy of AIST, as published in IEEE Access