Shot noise and squeezing in the conduction channel of a Field Effect Transistor at ultra-low temperature

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***Abstract*—We present two measurements of shot noise generated by the drain-source channel of a field effect transistor placed at ultra-low temperature. In a first experiment performed on a high impedance channel, we demonstrate classical, low frequency shot noise. In a second one performed in the microwave regime on a 50Ω channel, we observe quantum shot noise as well as vacuum squeezing. We also discuss the possibility of using another mechanism, the high frequency modulation of the gate voltage, to squeeze vacuum fluctuations.**

***Index Terms*—Shot noise, cryogenic, FET, quantum noise, squeezing**

Measurements of electronic noise at ultra-low temperature is often performed on devices that are specifically designed for the experiment. In particular, since inelastic processes have the tendency to kill shot noise, the latter is usually studied in small structures such as tunnel junctions [1], quantum point contacts [2], hybrid superconductor / normal metal junctions [3], nanowires [4], chaotic cavities [5], etc. Much less is known on the noise in more conventional structures such as field effect- or bipolar transistors at ultra-low temperature and very low bias. However, elastic transport can be achieved in such structures provided they are small enough and put at low enough temperature, so usual phenomena associated with noise in mesoscopic devices should be visible, like photo-assisted noise or quantum noise.

We present two measurements of the shot noise generated by the conducting channel of a commercial FET (pHEMT ATF-35143 from Avago Technologies) placed at ultra-low temperature T =30mK. We explore two very different regimes of drain-source channel with high impedance $R_{DS} = 10\text{k}\Omega$, and channel with low impedance $R_{DS} = 50\Omega$. The impedance of the channel is tuned by applying a voltage between the gate and the source of the FET. In the first case we perform a measurement at relatively low frequency (f <1MHz), which corresponds to the classical regime. In the second case where the channel is matched to microwave circuitry, we observe quantum noise measured at high frequency $f = 7.2$GHz. By exciting the FET with a microwave tone at 14.4 GHz, we observe photo-assisted noise. Then, with phase-sensitive detection we demonstrate that the channel can squeeze vacuum fluctuations. Finally, we propose another way to generate vacuum squeezing by modulating the resistance of the channel at high frequency.

I. Low frequency shot noise of high impedance channel

A. Experimental setup

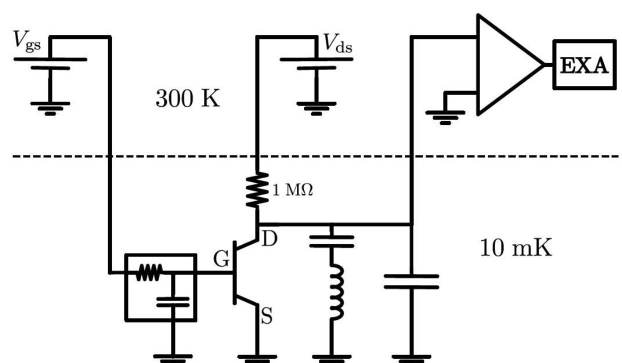

Fig. 1. Experimental setup for the measurement of low frequency noise (around 388kHz) for a channel of resistance 10kΩ. The capacitance symbol in parallel with the inductance represents the stray capacitance of the cable and the input capacitance of the amplifier. "'EXA"' refers to the Agilent spectrum analyzer.

In our first experiment we investigate the noise generated by the channel of the FET of resistance $R_{DS} = 10\text{k}\Omega$. This is achieved by imposing a gain-source voltage $V_{GS} \simeq -0.36$V. The measurement is based on low frequency techniques, with a cryogenic tank circuit and room temperature voltage amplifier. The experimental setup is presented in Fig. 1. A voltage source at room temperature followed by a cryogenic low-pass filter allows to impose V_{GS}. A voltage source followed by a $1\text{M}\Omega$

resistor placed at low temperature allows to impose the drain-source current I_{DS}. A detection of noise at low frequency would be limited one one end by the $1/f$ noise of the sample and/or the amplifier, and on the other end by the low-pass filter made of the resistance of the channel in parallel with the capacitance C of the several meter long cables in parallel with the input capacitance of the amplifier. To circumvent this problem we short the sample by an inductor $L \simeq 70\mu$H and work at the resonant frequency $f = 388$kHz of the LC circuit (a capacitor in series with L is necessary to block the dc current injected to bias the channel). The inductor is placed at the lowest temperature to avoid its Johnson noise. The total capacitance in parallel with the sample is $C = 2.3$nF and we obtain a bandwidth of ~ 20kHz for noise measurements. We record noise spectra after amplification by a high impedance voltage amplifier placed at room temperature, for various drain-source currents and gate-source voltages. The shape of these spectra as a function of frequency depends on the LC circuit but also on the frequency-dependent gain, input impedance and voltage/current noise spectral density of the amplifier (see an example of spectrum in the inset of Fig. 2). We have characterized the frequency dependence of the gain and impedances independently. We use the fact that the noise of the amplifier is independent of the current in the sample to extract their values from the noise spectra.

B. Results

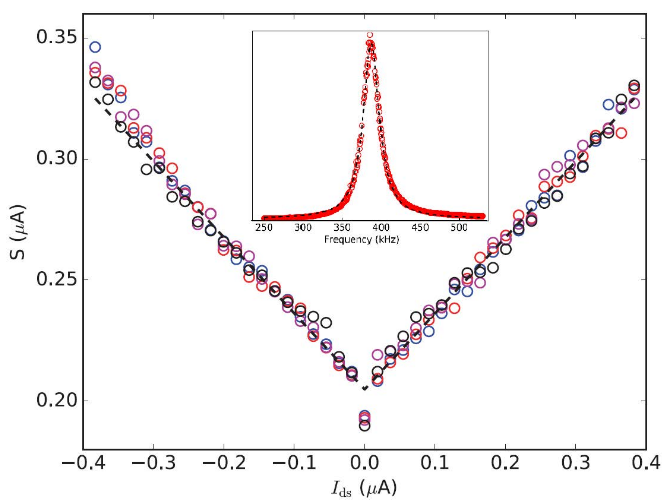

Fig. 2. Rescaled low frequency noise S/e of the conducting channel of the FET as a function of the dc bias current. The noise is measured at low frequency (388kHz) for a channel of resistance 10kΩ. The gate voltage is adjusted for each value of the drain-source voltage to keep the differential resistance of the channel constant. Inset: Example of voltage noise spectrum. The height corresponds to $2.5 \times 10^{-17}\mathrm{V}^2/\mathrm{Hz}$.

From the width of the noise spectra we deduce the value of the resistance R_{DS}. This avoids extra cables and lockin amplifier which would modify the impedance involved in the noise measurement. We observe that it depends on I_{DS}. Thus, the current noise of the amplifier flowing in the sample leads to a parasitic contribution to the current dependence of the total noise. As a matter of fact, the total voltage noise detected is given by:

$$\langle \delta V^2 \rangle = \langle \delta V_a^2 \rangle + |Z_{eff}|^2 (\langle \delta I^2 \rangle + \langle \delta I_a^2 \rangle) \quad (1)$$

where $\langle \delta I^2 \rangle$ is the current noise of the sample, which we seek to measure, and $\langle \delta V_a^2 \rangle$, $\langle \delta I_a^2 \rangle$ are respectively the voltage and current noise of the amplifier. Z_{eff} represents the impedance of the sample in parallel with the rest of the circuit. Thus if the sample resistance depends on the bias current, so does Z_{eff} and the measured voltage noise contains a parasitic bias-dependent term proportional to the current noise of the amplifier. In order to remove this effect we have repeated the measurements for many values of the gate-source voltage and combined the data that correspond to a constant R_{DS}. We show the result in Fig. 2. Different points on the curve correspond to different values of V_{GS} such that R_{DS} is kept constant at 10kΩ. We clearly observe that the current noise spectral density S of the sample obeys the usual law $S = Fe|I|$ for $|I| < 0.4\mu$A, with e the electron charge. We obtain a Fano factor of $F = 0.31$. This is close to that of a diffusive wire, indicating that transport in the channel is probably close to diffusive [4]. No thermal rounding is apparent at low voltage. We expect the cross-over between thermal- and shot noise to occur at a voltage of order k_BT/e which corresponds to a current of ~ 0.26nA. At very low current we observe a jump in the noise, which is also associated with a strong dependence of R_{DS} vs. I_{DS}. We do not know the origin of this effect, which looks like trapping of the charge carriers at low electric field.

II. HIGH FREQUENCY SHOT NOISE OF LOW IMPEDANCE CHANNEL

A. Experimental setup

Our second experiment is a phase-sensitive detection of high frequency quantum shot noise (at f =7.2GHz) with a low impedance channel ($R_{DS} = 50\Omega$). This experiment is based on the observation of squeezing of shot noise in a tunnel junction [6]. The experimental setup is presented in Fig. 3. A dc voltage source followed by a cryogenic low-pass filter imposes $V_{GS} \simeq -0.19$V to set the channel resistance to 50Ω. Another dc voltage source followed by 1MΩ resistors forces a current I_{DS} into the FET. A microwave triplexer is used to separate the signals of the FET into three frequency bands. The 0-4 GHz band is used for the dc bias (with an additional 1.9MHz low-pass filter). The 8-18 GHz band is connected, through many cryogenic attenuators, to a microwave source. This source allows to excite the drain of the FET with an ac voltage at 14.4 GHz. The 4-8 GHz band is used to send the noise emitted by the sample into a cryogenic amplifier (placed at 3K) after crossing two circulators, which prevent the noise emitted by the amplifier to impinge on the sample and heat its electrons. After cryogenic and room temperature amplification, band-pas filtering around 7.2 GHz, the noise generated by the sample is downconverted to low frequency by an IQ mixer with a 7.2 GHz LO phase-locked with the 14.4 GHz excitation. The mixer provides the amplitudes of

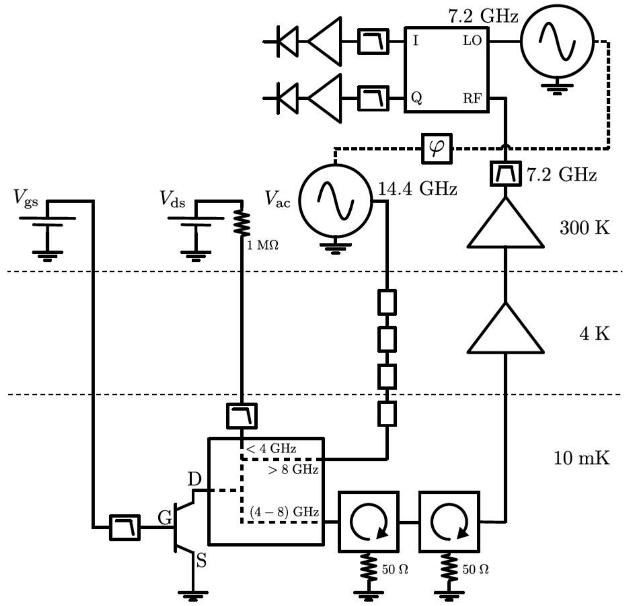

Fig. 3. Experimental setup for the phase-sensitive measurement of high frequency noise. The microwave generator at 14.4 GHz provides photo-excitation of the sample. The one at 7.2 GHz is used for downconversion of noise around that frequency. The phase lock between the generators (symbol φ) can be switchen on or off. When switched off, both channels I and Q give the same result which is the usual noise or photo-assisted noise. Switching the phase lock on allows separate measurements of the noise along the I and Q quadratures, which is used to demonstrate vacuum squeezing.

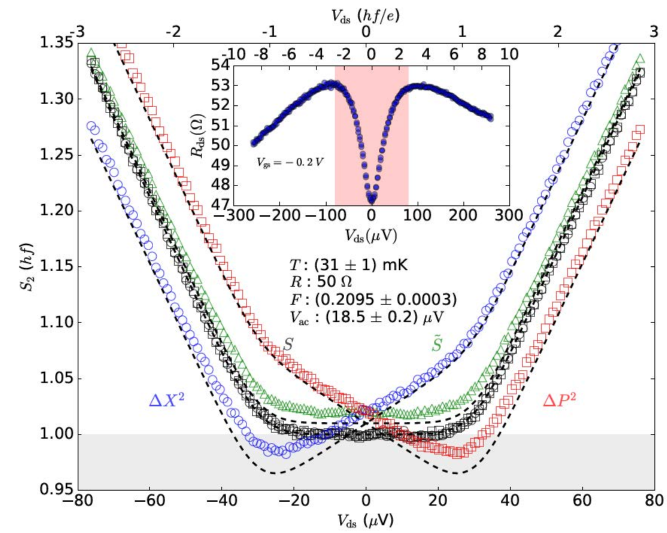

Fig. 4. Rescaled high frequency noise spectral density vs. dc bias voltage V_{DS}. The noise is normalized to its value in vacuum. Black symbols: no ac excitation. Green triangles: photo-assisted noise for an excitation of 18μV at 14.4GHz. Red and blue symbols: phase sensitive noise on the two quadratures. Dashed lines correspond to theoretical expectations. The shaded region corresponds to vacuum squeezing. Inset: resistance of the channel R_{DS} vs. V_{DS}. The shaded region correspond to that of noise measurements.

the signal that is in-phase (X) and out-of-phase (P) with its reference. Two power detectors are then used to measure the power of the two quadratures I and Q, i.e. ΔX^2 and ΔP^2, integrated over a bandwidth of 200 MHz.

B. Results

The results are plotted in Fig. 4 as a function of the dc bias of the channel. Black symbols correspond to $\Delta X^2 \simeq \Delta P^2$ in the absence of photo-excitation. This is the noise generated by the sample due to the dc voltage. The plateau at V_{DS} correspond to vacuum fluctuations, since no photon of energy hf can be emitted for voltages smaller than hf/e. The shaded region corresponds to noise being below that of vacuum fluctuations. The rounding of the noise at $eV_{DS} \sim hf$ is a direct measure of the electron temperature. By fitting our data with theory we find an electron temperature of $T_e = 31$mK. We clearly observe that the noise increases only when the bias voltage is greater than hf/e, demonstrating that transport is elastic. The Fano factor $F = 0.21$ is significantly smaller than the one we observed for a more resistive channel, which probably indicates that transport is closer to the ballistic regime at low resistance. Our observation of a plateau for voltage smaller than hf/e shows that the FET generates quantum noise. In the presence of photo-excitation but when detection and excitation are not phase-locked (green triangles), $\Delta X^2 \simeq \Delta P^2$ corresponds to photo-assisted noise as usually measured, which is above vacuum fluctuations. This measurement provides us with a way to calibrate the ac voltage experienced by the sample. The observation of photo-assisted noise is another proof that the noise generated by the channel of the FET is of quantum origin. Restoration of the phase lock between the two microwave generators allows to separate ΔX^2 (blue circles) from ΔP^2 (red squares). Clearly there is a voltage range in which $Delta X^2$ or ΔP^2 is smaller than its value in the absence of excitation, i.e. smaller than vacuum fluctuations: this is vacuum squeezing. The average $\Delta X^2 + \Delta P^2)/2$ is the photo-assisted noise (green triangles).

Dashed lines of Fig. 4 represent theoretical expectations. The measured photo-assisted noise is slightly above its expectation which results in vacuum squeezing being smaller than expected. We observe a squeezing by $\sim 2\%$. A possible explanation for this is a slight non-linearity of the sample. The inset of Fig. 4 shows the resistance R_{DS} as a function of the voltage bias. R_{DS} varies between 47 and 53Ω when the bias voltage is varied between $\pm 80\mu$V. The observed dip disappears at higher temperature. Further investigations are necessary to understand the possible effect of this non-linearity.

The amount of squeezing we observe is rather modest. However, it is in principle very broadband, and should run from 0 to 14.4 GHz [7]. In comparison, a measurement of such broadband two-mode squeezing using Josephson junction has been reported recently [8]. In this study the squeezing was of the same order as with our method. Thus noise modulation can achieve a degree of squeezing that is similar to that of a Josephson junction in the absence of a resonator. The resonator, by forcing the signal to experience many times the non-linearity of the junction, leads to higher degree of squeezing at the cost of reduced bandwidth. In contrast, noise modulation as we do it here would not be enhanced by a resonator.

III. Channel resistance modulation

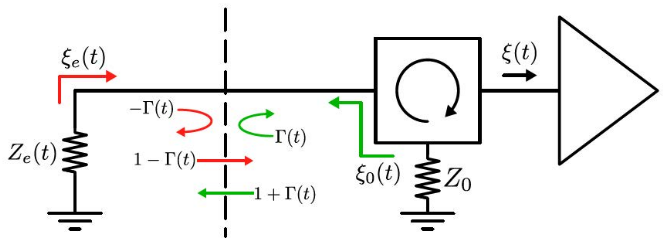

Fig. 5. Schematics of generation of vacuum squeezing by resistance modulation. Red arrows correspond to the noise generated by the modulated resistance Z_e. Green arrows correspond to the noise generated by the load of the circulator Z_0.

The generation of squeezing in the high frequency experiment is based on the idea that shot noise can be modulated at frequency $2f$ even when $eV < hf$, i.e. in the regime where the noise in the absence of photo-excitation is that of vacuum. Here we want to explore the same idea when replacing shot noise by thermal one: thermal noise of a resistor is proportional to the conductance of the sample, and given by vacuum fluctuations for $hf > k_B T$. Can one generate vacuum squeezing by modulating a resistor at high frequency ? It has been indeed predicted that modulating the damping rate of a resonator can lead to perfect squeezing [9]. A time-dependent resistor could be realized with a FET by applying a time-dependent gate-source voltage $V_{GS}(t)$ in the absence of bias on the drain-source channel, i.e. $V_{DS} = 0$. Below we make a simple calculation based on a semi-classical picture of noise.

We consider the simple circuit of Fig. 5. The signal $\xi(t)$ detected by the amplifier is the sum of the noise $\xi_e(t)$ emitted by the modulated resistance $Z_e(t)$ and that, $\xi_0(t)$ emitted by the load of the circulator Z_0 that is reflected on Z_e with a time-dependent reflection coefficient $\Gamma(t) = [Z_e(t) - Z_0]/[Z_e(t) + Z_0]$:

$$\xi(t) = [1 - \Gamma(t)]\xi_e(t) + \Gamma(t)\xi_0(t) \quad (2)$$

This problem is equivalent to two semi-infinite coaxial cables being connected together, one of characteristic impedance Z_0, the other with a time-dependent characteristic impedance $Z_e(t)$. Eq. (2) immediately leads to a non-zero term $\langle \xi(\omega)^2 \rangle$ which reveals the existence of squeezing. The degree of squeezing depends on the shape of the time-dependence of $Z_e(t)$. For a small sinusoïdal variation, $Z_e(t) = Z_e[1 + A\sin(4\pi f t)]$ we find a degree of squeezing that is optimal for two values of Z_e that are on each side of Z_0, and equal to $0.3A$, i.e. 3% for $A = 0.1$.

Experimentally, modulating the gate voltage while keeping V_{DS} is challenging because of capacitive coupling between the gate and the drain of the FET. To modulate significantly the resistance of the channel below 100Ω requires tens of mV of ac voltage. In contrast, we have observed shot noise for a drain-source voltage of some tens of microvolts. We have indeed tried to detect squeezing with gate modulation and could not observe it. Another, maybe more promising approach would be to have a macrosopic resistor and a fast shunt, possibly made with a Josephson junction. This is reminiscent of the setup of ref. [8] though conceptually quite different.

IV. Conclusion

We have reported measurements of: i) low frequency shot noise in the channel of a FET when gated to be high impedance. ii) high frequency quantum shot noise, photo-assisted noise as well as vacuum squeezing in the same transistor gated to be of 50Ω impedance. Our results show that existing commercial technology of micro-electronics could be used to generate quantum states of microwave radiation such as squeezed vacuum. We have also proposed another way to generate squeezed vacuum fluctuations by modulating the gate voltage of the FET in the absence of drain-source bias.

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