Measuring electron energy distribution by current fluctuations

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Abstract—A recent concept of local noise sensor is extended to measure the energy resolved electronic energy distribution \( f(\varepsilon) \) at a given location inside a non-equilibrium normal metal interconnect. A quantitative analysis of \( f(\varepsilon) \) is complicated because of a nonlinear differential resistance of the noise sensor, represented by a diffusive InAs nanowire. Nevertheless, by comparing the non-equilibrium results with reference equilibrium measurements, we conclude that \( f(\varepsilon) \) is indistinguishable from the Fermi distribution.

I. INTRODUCTION

Interest in local measurements of non-equilibrium conductors at the nanoscale motivated various kinds of spatially resolved sensors. The energy averaged approaches characterize the effective local temperature of the electronic system, via the resistive measurements [1], the measurements of tiny heat fluxes [2], [3] and the nearfield imaging of a terahertz emission [4]. Raman thermography permits a local evaluation for the lattice temperature [5]. Energy resolved electronic measurements are conventionally based on the energy selective tunneling, which involves a superconducting tunnel probe [6] or a quantum dot [7]. In both cases, the energy resolution is naturally limited to the excitations below, respectively, the superconducting gap or dot level spacing.

An alternative approach to gain energy selectivity, without an obviously limited excitation energy, was suggested in 1999 by Gramespacher and Büttiker [8]. They derived a relation between the local electronic energy distribution and the shot noise of a tunneling contact, which served as a bias controlled energy selective probe, see [9], [10] for later developments. Recently, a local noise thermometry was demonstrated by means of diffusive semiconductor nanowires with a resistance much higher than the conductor under test [11]. Here, we extend this approach and perform energy resolved local noise measurement in a metallic interconnect.

II. SENSING ELECTRON DISTRIBUTION FUNCTION

It has been shown recently, that an InAs nanowire (NW) can be used as a miniature noise probe, capable of non-invasive local shot noise measurements in a non-equilibrium conductor [11]. In a system of interest, one end of such nanowire (a test end) contacts a non-equilibrium conductor, while the other (a cold end) is kept at the base temperature \( T_0 \), thus having an equilibrium electronic energy distribution (EED) at \( T_0 \). In the case of elastic diffusion, the spatially dependent EED in the NW can be represented as a linear combination of distributions.

\[
\int d\varepsilon f_{\text{cold}}(\varepsilon)(1 - f_{\text{cold}}(\varepsilon)) + \int d\varepsilon f_{\text{test}}(\varepsilon)(1 - f_{\text{test}}(\varepsilon)) + \frac{1}{2} \int d\varepsilon f_{\text{test}}(\varepsilon)(1 - f_{\text{cold}}(\varepsilon)) f_{\text{cold}}(\varepsilon)(1 - f_{\text{test}}(\varepsilon))
\]

The first two terms represent \( T_N(0) \) and \( T_N(L) = T_0 \) respectively and are independent of \( V_b \). The other terms,
However, contain the product $f_{\text{cold}}(\varepsilon)f_{\text{test}}(\varepsilon)$, which enables the energy selectivity of the noise measurement [8]. Assuming that $f_{\text{cold}}(\varepsilon) = \exp\left(\frac{-eV_b}{T_R}\right) + 1)^{-1}$, we obtain the derivative $dS_I/dV_b$, which simplifies in the limit $T_0 \ll T_N(0)$:

$$
\frac{dS_I}{dV_b} = \frac{2e}{3R} \int dz(1 - 2f_{\text{test}}(\varepsilon)) \frac{df_{\text{cold}}(\varepsilon)}{dz} \\
\approx \frac{2e}{3R} (1 - 2f_{\text{test}}(\varepsilon = eV_b)).
$$

(2)

Thus, the measured noise and the EED under test are related as:

$$
f_{\text{test}}(\varepsilon = eV_b) = 1/2 - \frac{3R}{4e} \frac{dS_I}{dV_b}
$$

(3)

Here, to prove this concept of the EED measurement, we consider a device (figure 1) consisting of a short metal strip with the test end of an InAs NW connected to strip’s center. The EED $f_{\text{test}}(\varepsilon)$ in the center of the strip is controlled by the external bias current $I_H$. The opposite, cold end of the NW, which is connected to noise measurement circuit is used to apply the bias $V_b$ (hence, the current $I_{\text{NW}} = V_b/R_{NW}$). Other contacts and side gates were not used in the present experiment. This sample has been previously used in [11], more details on the fabrication can be found in [14].

III. EXPERIMENTAL TECHNIQUE

To measure shot noise, we used resonant amplification of voltage fluctuations from the cold end, loaded on a 10 kΩ resistor. Signal is amplified by $\sim 75$ dB with an amplifier chain. All measurements were performed in a $^3$He/$^4$He dilution refrigerator with a 30 mK base temperature. A homebuilt low-T amplifier at $\sim 800$ mK was utilized as a first stage. Noise spectral power density was measured at $\sim 8$ MHz in a $\sim 500$ kHz band.

To precisely obtain the unknown full gain coefficient of amplification circuit the Johnson-Nyquist noise calibration procedure was performed. At a given equilibrium $T$, we measured the thermal noise $S_I = 4k_BT/R_{\text{par}}$ of the sample, the load resistor and the RF transistor, all connected in parallel. The total load resistance was varied between $R_{\text{par}} \approx 40$ Ω and $R_{\text{par}} \approx 5$ kΩ with the help of transistor gate voltage.

In Fig 2 we plot the output signal of noise amplification circuit $P_{\text{det}}$ as a function of $R_{\text{par}}$ at different $T$. The shape of resulting curves is determined by resistance-dependent full conversion coefficient $G(R_{\text{par}})$. $P_{\text{det}} = G(R_{\text{par}})S_I$. This calibration allows to determine both $G(R_{\text{par}})$ and the input current noise of the first stage ($2.5 \times 10^{-27}$ A$^2$/Hz). In addition, we verified that the lowest achievable electronic temperature in our setup is $\approx 100 \pm 20$ mK.

IV. RESULTS AND DISCUSSION

A. Local noise thermometry

To test the device operation a local noise measurement with an unbiased NW ($I_{\text{NW}} = 0$), similar to [11] was performed at the base temperature. The resulting $T_S$ dependence is shown in figure 2 together with a shot noise fit for $T_S$, assuming local equilibrium with temperature:

$$
T_N(0) = \sqrt{T_0^2 + \frac{3}{4r^2}(eI_H/k_B)^2},
$$

(4)
determined by balance between Joule heating and Wiedemann-Franz heat conductance [15]. The strip resistance fit parameter equals $r = 5.2$ Ω, substantially higher that the value $r \sim 3$ Ω previously obtained in [11]. Most probably, this is explained by the fact, that in previous experiments the sample was immersed into liquid helium, which resulted in better thermalization of the current leads.
with higher corresponding $T_0$ (red line with dark blue symbols, and dark red line with blue symbols). To verify if this observation is consistent with the EED sensing we plot the theoretical predictions for current noise in corresponding configurations, see figure 4b. For the non-equilibrium case, the electron temperature at the test end was calculated using eq. (4). Similar to the experimental data, the results for the equilibrium and non-equilibrium cases are also almost indistinguishable in figure 4b. We conclude that the EED in the middle of the current biased strip is very well captured by the Fermi-Dirac distribution with the local temperature given by eq. (4). A direct comparison to the experimental data is complicated because of a slightly nonlinear current-voltage response of the NW, which gives rise to $I_{NW}$ dependent differential resistance (see figure 5). Note that in spite of this similarity, the case of non-equilibrium strip is characterized by a strong temperature gradient along the NW, which manifests itself in thermoelectric measurements [14]. The EEDs on the two ends of the NW are sketched in the inset of figure 4b.

V. CONCLUSION

In summary, we experimentally realized the concept of the energy selective local noise measurement. The nonlinear current-voltage response of the NW complicates accurate extraction of the local EED under test. Yet, comparison with the theoretical calculations is consistent with the Fermi-Dirac shaped EED.

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