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Measurement of brightness temperature of two-dimensional electron gas in channel of a high electron mobility transistor at ultralow dissipation power

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ABSTRACT

A technically simple and physically clear method is suggested for direct measurement of the brightness temperature of two-dimensional electron gas (2DEG) in the channel of a high electron mobility transistor (HEMT). The usage of the method was demonstrated with the pseudomorphic HEMT as a specimen. The optimal HEMT dc regime, from the point of view of the "back action" problem, was found to belong to the unsaturated area of the static characteristics possibly corresponding to the ballistic electron transport mode. The proposed method is believed to be a convenient tool to explore the ballistic transport, electron diffusion, 2DEG properties and other electrophysical processes in heterostructures.

1. Introduction

It is a common knowledge that the impact of a measuring device onto the object-under-test should be minimized if working with signal sources of essentially quantum nature. This is a general problem of non-disturbing quantum measurements. For electronic detecting facilities, especially amplifiers, it implies minimizing the energy, of noise or other origin, irradiated backwards to the object-under-test. The effect is a so called "back action", the phenomenon causing uncontrolled destruction of a quantum state of the object, e.g., qubit decoherencing, etc. [1–3]. The back action is detected and requires a quantitative description in a wide frequency band, orders of magnitude wider than the amplifier operation frequency band. Therefore, the "equivalent noise temperature" (T_n) determined for a relatively narrow operation frequency band of the amplifier (receiver) is an inadequate term here. Instead, the wide-spectrum brightness temperature (T_b) of the amplifier and its active elements should be considered as a proper quantifier, since it characterizes the total power of noise irradiation in a wide frequency band, from infra-low frequencies to optics.

One should clearly distinguish between the brightness (T_b) and noise (T_n) temperatures as referred to Friis formula [4]. The T_n obeys it while T_b does not. Let us illustrate this statement by an example. An ideal (not irradiation-contributing) attenuator with attenuation L placed after a source with temperature T_b will weaken the source irradiation power, in temperature units, down to T_b/L. When attenuation L tends to infinity, the attenuated power falls down to zero. In contrary to T_b, the T_n following Friis formula will rise as T_nL tending to infinity along with the attenuation. Thus, the noise temperature T_n is a conditional value although having a clear physical meaning. In contrary, the brightness temperature T_b, being in a sense an effective temperature since the noise irradiation is not always equilibrium one, characterizes nevertheless a real power flow which is the back action in the current context.

The amplifiers intended for ultra-low temperature applications (to amplify signals from quantum detectors, single electron transistors and variety of other quantum structures) are typically based on field-effect transistors (FETs). Among them, a class of HEMTs is distinguished, the high electron mobility transistors. HEMTs feature a very wide operational frequency band while field-induced (as opposed to thermally-generated) current-carrier electrons, which form two-dimensional electron gas (2DEG) in the channel, principally enable the transistor to operate at temperatures down

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to the absolute zero. Owing these advantages, the HEMTs are widely used in ultra-sensitive readout amplifiers [5,6] for measuring quantum device signals. Consequently, a quantitative description of the back action as applied to HEMTs is a hot issue.

Thermal noise is generated in HEMT input (gate-source) terminals due to power dissipation in the transistor input circuit. The dissipative losses come mainly from the gate metallization resistance, under-gate channel resistance and source resistance. Corresponding irradiation (for perfect matching, or zero input reflection coefficient) is characterized by the gate temperature T_g which is close to the physical temperature of the transistor crystal lattice T_{latt}. Cooling down to cryogenic temperatures is an effective method to suppress the thermal irradiation. If an ultra-deep cooling is supposed, it should be accompanied by a considerable decrease (down to a few microwatts and less) in the transistor consumed/dissipated power to avoid excessive Joule overheating of its active area. The situation with overheating becomes even more severe because of low thermal conductivity of the heterostructures [7]. Small cooling capacity of ultra-low-temperature cryorefrigerators, especially below 100 mK, also strongly limits the HEMT dissipated power. Provided if heat sink is effective, the input-circuit-generated thermal noise is reduced sufficiently and can be neglected regarding back action.

The "hot" electron irradiation from the gate-drain channel region is another cause of the back action. A high effective electron temperature in the drain region T_d exceeding the lattice temperature by two orders of magnitude for commonly used saturated HEMT regime is inherent for this mechanism. The irradiation of 2DEG in the gate-drain part of the channel goes backward to input via intrinsic drain-gate capacitance of the transistor. The excitation of waveguide modes by output circuit in a conductive cavity (where the amplifier, often along with a signal source, is placed) is an additional way.

An estimation for T_b of the amplifier input which governs the back action can be easily derived using reverse transmission gain (S_{12}) from the transistor S-matrix and two-temperature Pospieszalski model [8] treating the HEMT amplifier input as a black body. Thus, for an ideal matching of complex impedances of a source and the amplifier:

$$T_b = T_g + |S_{12}|T_d, \tag{1}$$

The effect of T_d can be roughly estimated assuming (see above) $T_g \approx T_{latt} \approx T_{amb},\ T_d \approx 100T_{latt} \approx 100T_{amb}$ [8,9] for commonly used saturated HEMT regime. For the ultra-low-consumption (unsaturated) HEMT regime [10], as we will see below, T_d can be much smaller, down to $T_d \approx T_{latt} \approx T_{amb}$.

Typically, $|S_{12}|$ is about −20...−30 dB at 1 GHz frequency. The $|S_{12}|$ rises almost linearly with frequency so the effect of T_d can prevail over that of T_g. If the amplifier has a high input impedance (S_{12} is defined for 50-Ω network), then the reverse transmission increases stimulating one to search for the ways of T_d reduction.

It is worth noting that the problem of optimal matching of the signal source and amplifier impedances is of great importance when designing an ultra-low noise amplifier. Optimal matching circuit synthesis based on adequate equivalent circuits of the signal source and amplifier first-stage transistor is a classic radio-engineering task. In the case of readout amplifier with low back action, the matching optimization is a special multifactor problem which is out of scope of the paper. We will use the simplified expression (1) as an "upper estimate".

The T_d and T_g are commonly used to calculate basic noise characteristics of a transistor, namely, the minimal noise temperature, optimal source impedance and noise conductivity [8]. Both T_d and T_g figures are extracted from a series of noise measurements by solving inverse problem [9] on the basis of the electrophysical transistor model which is inevitably limited to certain frequency band and temperature range. Integrally, the extraction procedure is sophisticated and ambiguous. The same can be said about other noise models and other similar noise invariants [11]. In the context of the back-action problem, it would be desirable to elaborate a simple method to measure mainly T_d since $T_g \approx T_{latt}$.

First, to measure T_d instrumentally, the contribution of the amplified noise of input circuit to the integral output noise irradiation of the transistor should be excluded. Referring to modern transistors with cut-off frequencies of tens and more gigahertz, such an elimination is hard enough because of stability problem. Moreover, it becomes much more complicated under deep-cooling conditions. However, the ultra-low power consumption of the transistor associated with deep-cooled amplifiers results in decrease in the cut-off frequency by two orders of magnitude while the stability factor exceeds the unity. Consequently, the stability is not further an issue, and direct instrumental measurements of T_d become possible.

Wide-spectrum noise irradiation of the HEMT channel is governed by the electron temperature T_{el} of the 2DEG which by both physical sense and value is close to T_d, as it will be seen from the following. Thus, both T_{el} and T_d are, in fact, brightness temperatures that determine a wide-band noise irradiation from the HEMT amplifier output (bearing in mind matching considerations). In this work we propose a simple method to measure directly the brightness temperature of 2DEG in a HEMT channel. The experimental results are discussed and recommendations on choice of the HEMT dc regime are formulated concerning the back action phenomenon.

2. Measurement technique

To measure the brightness temperature of a HEMT channel, we used a technique which was principally based on the routine procedure for calibrating the noise of an active four-terminal device with the thermal noise of a reference resistor [12], but modified it with some novelties to take into account inherent features of the object-under-test. While measuring the noise of a cooled HEMT channel, one should bear in mind the following. Firstly, the informational signal has a noise nature and very low power. Secondly, the channel differential resistance in the regime of interest may range, roughly, from 100 to 1000 Ω [13]. If one use a standard noise-measuring equipment at room temperature, the signal would be highly attenuated and distorted by shunting action of the transmission line at frequencies of about tens megahertz and above. At lower frequencies, the $1/f$ type noise expectedly emerges. To eliminate effect of the transmission line, we used a separate amplifier placed near the HEMT in the cryostat. The absence of a mechanical switch alternating connection of the amplifier input to either object-under-test or noise reference is a yet another important feature of our measuring procedure which enhances the result reproducibility.

Although the proposed procedure exploits neither two-temperature noise source (hot/cold loads method), nor fixed cooled attenuator with an external noise source (cold attenuator method), our method could be referenced to as a modification of the well-known Y-factor method.

Simplified diagram of the experimental setup is shown in Fig. 1. The essence of the technique is by-turn measurement and further comparison of the powers of two signals. The first one is produced by output circuit of the transistor-under-test (Q1), the second one is a reference, taken from a variable resistor R having ambient temperature. During the calibration procedure, the resistance R is set equal to the channel differential resistance in a specified point of the transistor static characteristics. The measurement cycle is described below in more detail.