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The development of measuring setup for electrical noise research in two-dimensional semiconductor structures for quantum Hall resistance standard

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ABSTRACT
This paper describes setups for measuring electrical noise in the frequency range from 10 kHz to 100 MHz of semiconductor structures made of new Dirac- materials - 2D-COF/MOF intended for the construction of quantum Hall resistance standard (QHRS). In measurement systems consisting of a spectrum analyzer working with a preamplifier, an input noise value of approximately 1 nV/√Hz at 100 kHz was achieved at a preamplifier gain of 400 V/V, and the noise figure (NF) of the entire measurement system was reduced to below 0.4 dB for higher frequencies, where this coefficient for the spectrum analyzer itself was of the order of 7 dB.

Section: RESEARCH PAPER

Keywords: electrical noise measurement; 2D-COF/MOF; QHRS; ULNA

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1. INTRODUCTION

Revolutionary changes in the International System of Units, the recognition of classical standards as too inaccurate, and the transition to standard physical constants force scientists to work on increasing the number of significant figures of these constants. Promising this direction is the development of quantum standards characterized by excellent repeatability with physical constants accuracy. An important path here is the development of semiconductor materials from the Dirac-materials family [1].

After tests with graphene for the implementation of the quantum Hall resistance standard (QHRS), the time has come for even more chemically and physically attractive structures of two-dimensional covalent-metalorganic frameworks (2D-COF/MOF) [2], [3].

The transition from graphene, a hexagonal structure of connections of carbon atoms with two double bonds, to the structure of a hexagonal flat benzene ring with three double bonds between carbon atoms and entering the field of organic hydrocarbon chemistry opens up enormous theoretical possibilities for the creation of new semiconductor materials by inserting metal atoms into these structures. Once this technology is mastered, an avalanche of new semiconductor materials may be created, including two-dimensional ones, useful for the implementation of QHRS.

When creating measurement standards based on electrical transducers, electrical noise is extremely important. Noise is everything that disturbs the measurement signal. This interference may come from outside, e.g. as a result of the passage of an electromagnetic wave, but it may also be generated inside the transducer. It is relatively easy to predict and estimate the broadband thermal white noise with a flat frequency characteristic accompanying each resistance. Unfortunately, semiconductor materials are additionally characterized by difficult-to-predict $1/f$ noise, i.e. noise whose size is inversely proportional to frequency (f), and which is called flicker noise or pink noise [4].

The characteristics of electrical noise as a function of the frequency of semiconductor structures used in the production of

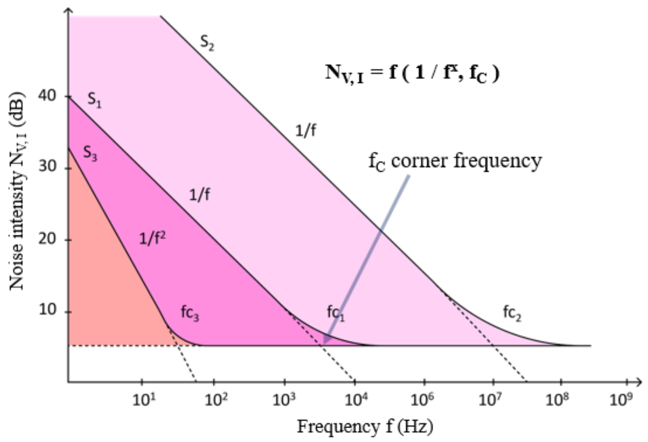


Figure 1. Graph of voltage or current noise intensity expressed in decibels vs. frequency on a logarithmic scale for three theoretical structures, showing different shapes and corner frequencies.

electronic components and measurement transducers do not have a shape perfectly suited to the $1/f$ function, but rather to a function where f in the denominator is raised to a power slightly higher than 1, but not exceeding 2. This is because in the frequency range in which flicker noise is observed, other types of noise can also be detected, such as shot noise [4], [5].

In Figure 1. frequency response curves of electrical noise of three theoretical structures (S_i) are presented. S_2 has the same shape as S_1 but is shifted to the right because it has a higher corner frequency (f_c), i.e. the frequency of intersection of the $1/f$ characteristic into a straight line parallel to the frequency axis representing the white thermal noise of the structure. S_3 has characteristics consistent with the $1/f^2$ function (both $1/f^x$ need current flow to observe the noise). The frequency characteristics of real structures have a shape between S_1 and S_3, but closer to S_1. Structures made of the same or similar material do not differ in the shape of the noise frequency characteristics but may have a different corner frequency because it also depends on the dimensions of the structure and the dimensions of the contacts supplying the structure with voltage and transmitting the signal [5], [6].

The area under the frequency response curve of individual structures indicates the total noise of a given sample. For structures made of similar material and compared at the same temperature, regardless of whether it is a cryogenic temperature or room temperature, the structure with a higher corner frequency will always have a higher total noise and the structures with a higher cross-frequency should be rejected.

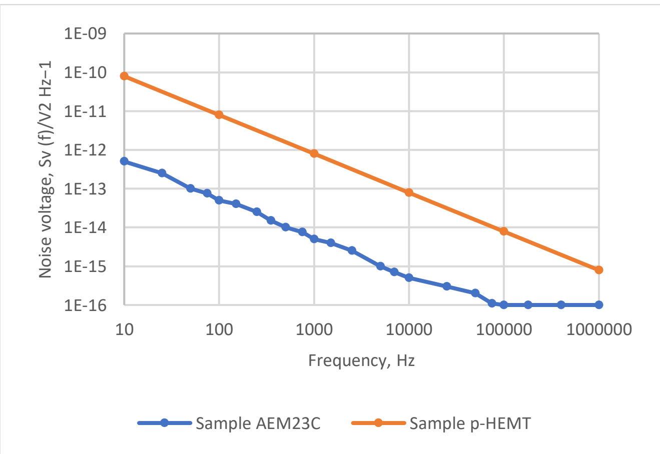


Figure 2. Characteristics of noise spectral density for two models made of different semiconductor materials (structure of graphene and MOSFET), showing differences in the occurrence of corner frequencies.

Models made of new materials will be subjected to various tests. The measurement of electrical noise is quite important here because, in the case of too much noise, it will not be possible to measure a given quantity with sufficient precision to be able to determine as many significant figures of a given constant as possible after conversion.

In the international EURAMET EMPIR 20FUN03 COMET project called "Two-dimensional lattices of covalent- and metal-organic frameworks for the Quantum Hall resistance standard', one of the tasks is to adapt the equipment to measure the noise of model semiconductor structures with the greatest possible precision. The model of the new semiconductor structure designed to build the standard of the measurement unit should be characterized by low noise. It is difficult to estimate its value for a hitherto unknown structure intended for a specific application here. Measuring its total value in a wide frequency band can also be difficult due to the frequency limitations of individual methods and measuring instruments. For the selection of the measurement method and the design of the target measuring apparatus using a given semiconductor structure model, it is important to determine the corner frequency. Different semiconductor structures have different f_c frequencies, the value of which can range from a few kilohertz to hundreds of megahertz. In the project, work on the study of electrical noise characteristics of the new semiconductor structures is carried out in two ways. Noise in the low-frequency range, where the highest noise power values occur, mainly associated with pink 1/f noise, is studied, and correlation methods are used to eliminate noise inside the instruments [7]. Work is also underway to prepare a set of measuring equipment for broadband noise testing of a semiconductor structure model, including the purpose of determining its f_c frequency. In Figure 2. exemplary characteristics of the noise spectral density for models made of two different materials with quite different f_c frequencies, for graphene [7] and a semiconductor material of MOSFET transistors with a channel length of 5 µm and a width of 8 µm [8], were presented.

The article will describe the components of the measurement system for testing the broadband noise of the model of the new semiconductor structure in the frequency range from 10 kHz to 100 MHz, which will also make it possible to find the f_c frequency.

2. DESCRIPTION OF THE MEASURING SETUP

The measuring setup for broadband noise and finding f_c frequency consists of two basic elements: a spectrum analyser and a preamplifier.

2.1 Spectrum analyser

The ESCI 3 measuring radio frequency receiver with a built-in spectrum analyser function was used as a spectrum analyser. The precision of this measuring device is evidenced by the fact that it allows the measurement of antenna signals at the level of several microvolts.

The spectrum analyser measures the magnitude of the electrical power of the input signal over the full frequency range, which is from 9 kHz to 3 GHz. Since the 3 GHz frequency reaches the microwave band, it is important to match the input and output impedances of other devices connected to it to avoid signal reflections. There are two impedance-matching systems for high-frequency ranges. Television systems use 75 Ω and microwave measuring systems use 50 Ω. The measurement setup is operated in a 50 Ω impedance matching system in this task.

It is possible to set the spectrum analyser to a different reading unit instead of power, e.g. voltage, but the instrument will convert this voltage from the measured power on 50 Ω input impedance. If a voltage source with an impedance other than 50 Ω is connected to the input, the indicated voltage value will not correspond to the actual voltage connected to the input. Although we are operating at lower frequencies, the 50 Ω impedance matching rule still applies, so preamplifiers should also have a 50 Ω output impedance.

The spectrum analyser measures the power of variable signals dissipated into its input resistance. The noise power spectral density of this resistance expressed as the root mean square (RMS) of the noise voltage per 1 Hz of the band, is given by [5]:

$$\overline{v_n^2} = 4\, k_B\, T\, R\,, \tag{1}$$

where k_B is the Boltzmann constant in joules per Kelvin (J/K), T is the absolute resistor temperature in Kelvin (K), and R is the analyser input resistance in ohms (Ω).

The RMS of the noise voltage for a given bandwidth Δf in Hertz (Hz) measured with the input resistor is:

$$v_n = \sqrt{\overline{v_n^2}}\,\sqrt{\Delta f} = \sqrt{4\, k_B\, T\, R\, \Delta f} \tag{2}$$

and the noise power dissipated by this resistor is [5]:

$$P = \frac{v_n^2}{R} = 4 k_B\, T\, \Delta f\,. \tag{3}$$

The noise arising on the output resistor of devices connected to the analyser is transferred to its input. The maximum noise power transfer occurs when the equivalent resistance of the input circuit is equal to the noise-producing resistance. In this case, there are two 50 Ω resistors. The noise power dissipated in the resistors is divided equally between each of them. Because only half of the source noise voltage is deposited across each of these resistors, the outcome noise power is given by:

$$P = k_B\, T\, \Delta f\,, \tag{4}$$

where P is the thermal noise power in watts (W) and is independent of the noise-generating resistance [9]. The noise value visible on the spectrum analyser in the absence of active devices connected to the input depends only on the temperature.

This power, expressed in dBm at room temperature assumed to be 300 K for a given band Δf, is expressed by the formula:

$$P(\mathrm{dBm}) = -174\ \mathrm{dBm} + 10\log(\Delta f)\,, \tag{5}$$

therefore, for the assumed frequency range, it gives a noise power value of -94 dBm, which corresponds to about -13 dBμV, and the RMS value of the noise voltage for the assumed 50 Ω system of 4.5 μV (about 13 $\mu V_{p\text{-}p}$).

2.2 Preamplifier

The preamplifier for the spectrum analyser in the noise measurement setup usually consists of several amplification stages, and when using a sensitive analyser, it can have a total amplification of only a few hundred times. It is a trans-impedance electronic component. Its task is to match the impedance of the tested element to the input impedance of the analyser; hence its output impedance must be 50 Ω, and the input impedance should be matched to the impedance of the tested noise source.

The second task of the preamplifier is to reduce the noise figure (NF) of the measurement setup with the spectrum analyser. In this case, the NF of the ESCI analyser is 7 dB.

The NF and the noise factor (F) are values that indicate the deterioration of the signal-to-noise ratio (SNR) caused by components in the signal chain. These values are used to evaluate the performance of an amplifier or radio receiver, with lower values indicating better performance.

In order to organize the entire theoretical part of the task, the known formulas describing the relationships between SNR, F, and NF will be presented below, where the index 'i' refers to the input and the index 'o' to the output of individual amplification stages or the entire measurement system, and the dB index means that the value is presented in decibels. In Friis' formula, the k index at F and power gain G denotes the number of the amplifying stage [10]:

$$F = \frac{SNR_\mathrm{i}}{SNR_\mathrm{o}} \tag{6}$$

$$NF = 10\log_{10}(F) = 10\log_{10}\left(\frac{SNR_\mathrm{i}}{SNR_\mathrm{o}}\right) = SNR_{\mathrm{i},dB} - SNR_{\mathrm{o},dB} \tag{7}$$

$$F_\mathrm{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1\, G_2} + \frac{F_4 - 1}{G_1\, G_2\, G_3} \tag{8}$$

$$F_\mathrm{setup} = F_\mathrm{LNA} + \frac{F_\mathrm{SA} - 1}{G_\mathrm{LNA}}\,, \tag{9}$$

where F_setup, F_LNA and F_SA are the noise factors of the whole measuring setup, the low-noise preamplifier (LNA), and the spectrum analyser itself, respectively, and G_LNA is the gain of the LNA.

It is important to choose the right components for the construction of the first amplifying stage of the preamplifier, especially the active element, i.e., the transistor. This project decided to choose a transistor with a noise level below 1 nV/√Hz operating at least in the frequency range of up to 100 MHz. Typically, transistors with such a low noise factor also have a low crossover frequency of pink noise with white noise. MOSFETs can have a remarkably high f_c frequency of up to several GHz. JFETs and BJTs have lower f_c even below the kHz range, but JFETs typically exhibit more flicker noise at low frequencies than BJTs and can have f_c as high as several kHz. The $1/f$ noise characteristics of JFET transistors are more linear than other transistors. [6], [11]

The spectral density of the $1/f$ noise voltage in the CMOS fabrication process as a function of the frequency f is often modelled as:

$$V_n^2 = \frac{K}{C_\mathrm{ox}^2\, W\, L\, f}\,, \tag{10}$$

where K is a process-dependent constant, K equal to 5×10^{-9} fC²/μm² for NMOS devices and 2×10^{-10} fC²/μm² for hidden channel PMOS devices. C_ox is the oxide capacitance and W and L are the width and length of the channel, respectively [12].

In graphene, the f_c can be on the order of 100 Hz, but in MOSFETs and millimetre-wave structures it can be several GHz, hence the f_c frequency of a new and untested semiconductor structure may be in this range.

Due to the non-linearity of the noise characteristics and the low input impedance of the BJT transistors and the too- high f_c

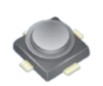
Figure 3. The frequency response of the first-stage preamplifier based on the BF862 transistor.

frequency of the MOSFET transistors, it was decided to use a JFET transistor. Finally, the BF 862 N-FET transistor with the following parameters was selected: equivalent noise input voltage at 100 kHz typical value of 0.8 nV/√Hz, and typical transition frequency of 715 MHz, both parameters meet assumptions.

The first stage of the preamplifier with an input impedance of about 100 kΩ was made. Figure 3 shows the frequency response of the first stage of the preamplifier, from which its gain can be estimated at about 4 V/V in the range from about 10 kHz to about 30 MHz. The LMH6629 operational amplifier was used in the second and third stages. These stages have a gain of 10 V/V in the 900 MHz range and an input noise voltage equivalent of 0.69 nV/√Hz. The preamplifier made in this way has an input noise equivalent of 1 nV/√Hz and a gain of about 400 V/V, which gives the RMS noise at the output of the entire preamplifier, including the band up to 30 MHz, at the level of 5.5 μV. Although the first stage of the preamplifier with the BF 862 transistor can work up to 100 MHz, its characteristics above 30 MHz do not indicate the possibility of making precise measurements, for these reasons, for operation in the higher frequency range, it was decided to use in the first stages a wideband FET transistor with the symbol CE3512K2, with the best catalogue value NF = 0.30 dB, which means that to obtain the output noise value, the input noise must be multiplied by the gain and multiplied by 1.035. Finally, the second version of the preamplifier was made of two CE3512K2 transistors and an LMH6629 circuit. Due to the battery power supply, the transistor drain current is limited to 3 mA. This allowed us to obtain NF at the level of 0.5 dB and gain of the stage at the level of 12.5 dB. The first two preamplifier stages, made identically, allowed to obtain NF of 0.53 at 25 dB gain. The third stage has NF = 8 dB and a gain of 20 dB.

After substituting all components of the noise factors and power gains of the individual amplification stages of the preamplifier into the formula (8), the resulting value F_{LNA} = 1.15, which allows the calculation of NF_{LNA} = 0.59 dB. After substituting the above-calculated F_{LNA} value, the gain value of the entire preamplifier, and the noise factor of the spectrum analyser F_{SA} = 5.01 into the formula (9), a slight change in noise factor was obtained (F_{setup} = 1.16), and as a result of the noise figure of the entire measurement setup at the level of 0.64 dB. This means that thanks to the use of the preamplifier made here, an improvement in noise figure was obtained from 7 dB for the spectrum analyser alone to 0.64 dB for the entire measurement setup.

Table 1. List of parameters of selected four-stage preamplifiers with optimal parameters of electrical noise and amplification.

		**SYSTEM = 4 stages preamplifier + RF receiver**
First two stages: CE3512K2 NF = 0.3 dB $F_{1,2}$ = 1.07 G_1 = 4 G_2 = 16	Next two stages: LMH6629 NF = 8.0 dB $F_{3,4}$ = 6.30 $G_{3,4}$ = 100 (10 V/V)	F_{ULNA} = 1.07 + (1.07 - 1) / 4 +(6.3 - 1) / 64 +(6.3 - 1) / 6400 = 1.17 NF_{ULNA} = 0.68 dB F_{SYSTEM} = 1.17 + (5.01 - 1) / 64000 ≈ 1.17 NF_{SYSTEM} = 0.68 dB G_{V} = 800 V/V
First three stages: CE3512K2 NF = 0.3 dB $F_{1,2}$ ≈ 1.05 $F_{2,3}$ = 1.07 G_1 = 4 $G_{2,3}$ = 16	Fourth stage: LMH6629 NF = 4.2 dB F_4 = 2.63 G_4 = 100	F_{ULNA} = 1.05 + (1.07 - 1) / 4 +(1.07 - 1) / 64 +(2.63 - 1) / 1024 = 1.083 NF_{ULNA} = 0.33 dB F_{SYSTEM} = 1.083 + (5.01 - 1) / 102400 = 1.084 NF_{SYSTEM} = 0.35 dB G_{V} = 320 V/V

The second variant of the preamplifier has a voltage gain of about 178 V/V. An additional LMH6629 stage can be added to increase the amplification. It is also possible to connect a commercial amplifier HVA-200-40-F to the first two stages of the preamplifier, the connection of which will slightly reduce the quality of the noise parameters of the system but will enable operation with the overall amplification of the extended version of the preamplifier up to 65 dB and extend the f_{c} frequency search range to 200 MHz.

Further work focused on four-stage preamplifiers, which turned out to be the most beneficial in reducing the electrical noise of the entire measurement setup with the ESCI 3 receiver spectrum analyser. The parameters of the two most interesting variants of four-stage preamplifiers are presented in Table 1. In order to reduce the NF below 0.4 dB, the necessary is to take special measures by selecting from a batch of transistors the one with the smallest NF and placing it in the first stage of the preamplifier.

3. TESTING THE BROADBAND ELECTRICAL NOISE MEASUREMENT SETUP

There are three elements in the measurement process here: the measured sample, which is the source of noise, the preamplifier matching the impedance of the sample to the impedance of the spectrum analyser, amplifying the signal from the sample and improving the input noise parameters of the spectrum analyser, and as the third element, the spectrum analyser itself. To check the operation of one of the mentioned elements, the other two are reference devices with known parameters and characteristics.

In Figure 4 a block diagram of the basic configuration of the system for broadband measurement of electrical noise of preamplifiers implemented in the project is presented. The system enables the measurement of various noise factors – expressed in V/√Hz or dB, using various measurement methods, including the Y-factor method [13]. Before measuring the preamplifier noise, the spectrum analyser is calibrated.

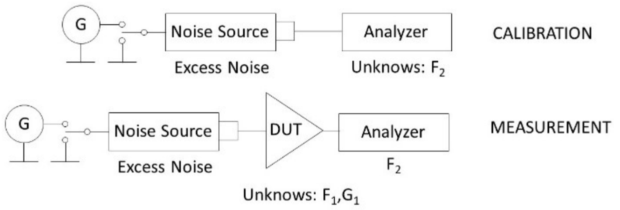


Figure 4. The block diagram of the basic broadband electrical noise measurement setup of the amplifier as the device under test (DUT) with calibration of the spectrum analyzer.

In Figure 5. The measurement set used in GUM is presented, consisting of the SML 3 generator and the spectrum analyser in the ESCI 3 radiofrequency measurement receiver. Depending on the frequency range, different noise sources can be used. An SNS18 noise source can be used to test preamplifiers to the required range of frequency.

An exemplary system for checking the parameters of the elements listed above is seen in Figure 6. The noise source is the analyser's 50 Ω terminator, which is connected to the inputs of an amplifier with known parameters. The terminator shorts the high 1 MΩ impedance of the HVA- 200M-40-F amplifier, hence the input noise is at the level of 1 nV/√Hz. and the prominent noise is the noise of the electronic circuits related to the inputs, which in the midpoint of the 100 MHz band is 5.5 nV/√Hz with 10 V/V gain set. So, the total noise related to the input being the square root from the sum of the squares of both noises is 5.6 nV/√Hz (the input current noise is omitted due to the low input resistance). The last numerical value, after taking into account the above gain and bandwidth values, gives the RMS voltage value of the broadband noise occurring at the output of the amplifier at the level of 560 μV, which corresponds to 55 dBμV. Due to the impedance matching of the amplifier output with the spectrum analyser input, the power of -52 dBm (6.3 nW) is transferred to the analyser.

On the monitor screen of the spectrum analyser shown in Figure 6, there is a graph of the measurement of the noise mentioned above and the amplifier shown in the same photo. The average noise value in the design-relevant range, i.e. from 10 kHz to 100 MHz, is almost constant at -102.7 dBm. Above 100 MHz, the noise decreases slightly with increasing frequency, so towards the end of the visible 200 MHz range it is a few dBm less. During the measurement in the non-essential frequency range, the amplifier was disconnected to show in one picture the displayed floor noise level, the average value of which is almost constant and amounts to -123.9 dBm. The given value exceeds the value calculated from the theoretical formula (5). First of all, the formula does not take into account the NF of the analyser itself and the components present in the analyser, such as attenuators, filters, and conversion factors vary for different settings, which affect the final value of the input noise of the analyser.

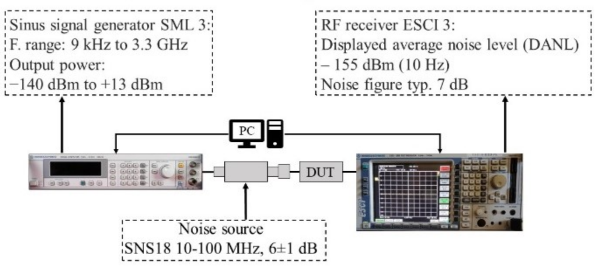


Figure 5. Testing the broadband electrical noise measurement setup.

Figure 6. An essential setup for checking the parameters of components included in the measurement system, consisting of a spectrum analyzer, an amplifier -with known parameters, including equivalent voltage and current of input noise and frequency characteristics, and a source of white noise.

There are two more important pieces of information on the spectrum analyser screen: RBW 100 Hz and AQT 160 s. This means that the IF (intermediate frequency) filter with 100 Hz band resolution (RBW) has been applied according to the setting.

The second abbreviation means acquisition time (AQT) and is equal to 160 s, but it also means that the video bandwidth (VBW) filter, which is used to smooth the waveforms on the screen, has been abandoned in favour of the FFT (fast Fourier transformation) filter, which allows for greater precision of measurement data processing and accelerates the frequency sweep on the screen. When using the FFT filter, it must be considered about the RWB bandwidth conversion factor of 1.056 when converting RMS noise to noise spectral density.

The method of broadband noise testing of semiconductor material samples in the band from 10 kHz to 100 MHz is intended to quickly eliminate samples unsuitable for QHRS applications. If the sample has the corner frequency in the above range, its total noise will be so high that it cannot be used to build a resistance standard. This method is used at room temperature because at temperatures close to a cryogenic temperature the

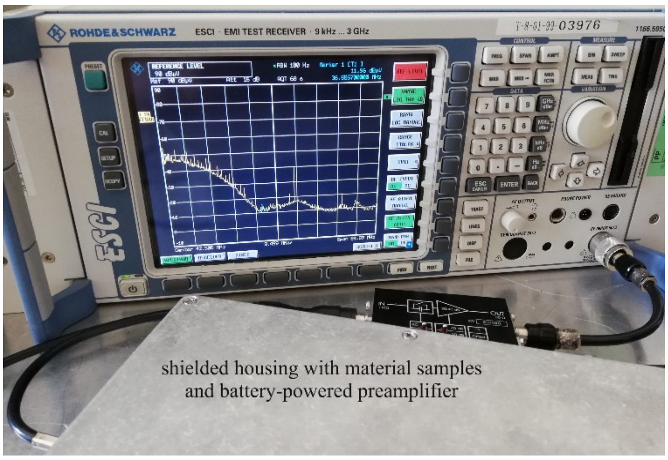


Figure 7. Example measurement of broadband electrical noise of a semiconductor material sample.

corner frequency will only shift towards higher frequencies due to lower thermal noise.

Figure 7 shows the measurement system with the measurement result on the analyser screen for a sample made of semiconductor material that is not suitable for making a QHRS due to too high a corner frequency, which, as indicated on the screen, is about 36 MHz, and consequently too high total electrical noise. The sample is placed in a shielded housing with a system forcing the sample current at a level of several microamps and the preamplifier. Power batteries are also placed there.

The initial part of the characteristic presented on the screen is flicker noise. The flattening at the beginning of the characteristic is caused by the lower limit of the preamplifier's frequency band, which is approximately 10 kHz. Uplifts above the corner frequency are caused by the nonlinearity of the preamplifier gain.

Samples of semiconductor materials that did not show cross-frequency in the band from 10 kHz to 100 MHz and have appropriate voltage-current characteristics in the current range of +/-5 μA are subjected to further noise tests in the range up to 10 kHz using precise cross-correlation methods for instrument noise cancellation and are further investigated at low temperatures [7].

CONCLUSIONS

This work aims to present the classical method of measuring electrical noise using a spectrum analyser as a modern tool in the search for f_c frequency at the crossover of pink 1/f noise and white noise frequency characteristics, thanks to a special approach to the construction of the device connected at the input of the analyser. This device is an ultra-low noise preamplifier in which special attention has been paid to the selection of the first amplification stage. The selection of subsequent stages was to lead to the optimal reduction of the noise figure of the whole setup and impedance matching to the 50 Ω input of the analyser. Although the use of the correlation method of noise elimination from the theoretical point of view gives better possibilities of eliminating the noise of the measuring device, the set of apparatus presented here gives better possibilities for the broadband measurement of the amount of electrical noise and detection of the f_c frequency of the tested semiconductor structures, including 2D- COF/MOF structures used for building models of the quantum Hall resistance standard, while using popular spectrum analyser and minimizing expenditure on additional measuring equipment. The proposed electrical noise measurement setup meets the assumptions for operation in the frequency range from 10 kHz to 100 MHz.

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