26th IMEKO TC4 International Symposium
24th International Workshop on ADC and DAC Modelling and Testing
IMEKO TC-4 2023
Pordenone, Italy / September 20-21, 2023

The development and tests of a preamplifier for the spectrum analyzer adopted for noise measurements in quantum Hall standard

Marcin Wojciechowski[1], Kateryna Hovorova[1]

[1]*GUM (Central Office of Measures), Elektoralna 2 Str., 00-139 Warsaw, Poland,*
marcin.wojciechowski@gum.gov.pl, kateryna.hovorova@gum.gov.pl

***Abstract* – This paper describes setups for measuring 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 QHRS quantum standards. The main emphasis was placed on the preamplifiers. The first design gives solution with equivalent input noise value of about 1 nV/$\sqrt{Hz}$ at 100 kHz and 400 V/V amplification, second - improves the spectrum analyzer's noise figure (NF) from 7 dB to 0.64 dB.**

I. 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 atomic 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]. 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 (f_c). This is a frequency on a broadband noise characteristic for which pink noise 1/f is equal to thermal white noise. Different semiconductor structures have different fc 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 structure 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 [4]. 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 Fig.1. exemplary characteristics of the noise spectral density for models made of two different materials with quite different f_c frequencies, for graphene [4] and a semiconductor material of MOSFET transistors with a channel length and width of 5/8 μm [5], were presented.

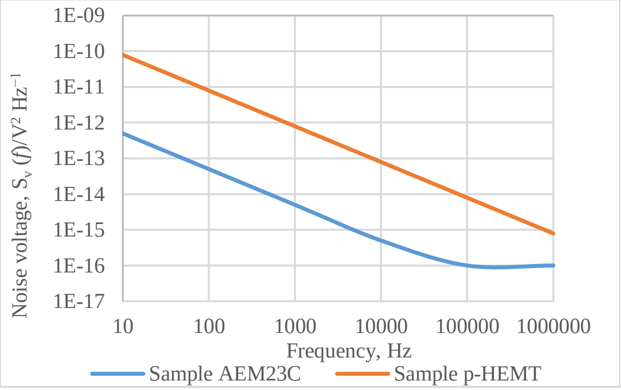

Fig. 1. Characteristics of noise spectral density for two models made of different semiconductor materials, showing differences in the occurrence of corner frequencies.

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.

II. DESCRIPTION OF THE CONSTRUCTION OF THE MEASURING SETUP

The measuring setup consists of two basic elements: a spectrum analyzer and a preamplifier.

A. *Spectrum analyzer*

The ESCI 3 measuring radio frequency receiver with a built-in spectrum analyzer function was used as a spectrum analyzer. 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 analyzer 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 analyzer 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 analyzer 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 [6]:

$$\overline{v_n^2} = 4k_BTR \tag{1}$$

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 analyzer 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:

$$v_n = \sqrt{\overline{v_n^2}}\sqrt{\Delta f} = \sqrt{4k_BTR\Delta f} \tag{2}$$

and the noise power dissipated by this resistor is [6]:

$$P = v_n^2/R = 4k_BT\Delta f \tag{3}$$

The noise arising on the output resistor of devices connected to the analyzer 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 :

$$P = k_BT\Delta f \tag{4}$$

where P is the thermal noise power in watts (W) and is independent of the noise-generating resistance [7]. The noise value visible on the spectrum analyzer 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:

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

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 $\mu V_{p\text{-}p}$).

B. *Preamplifier*

The preamplifier for the spectrum analyzer in the noise measurement setup usually consists of several amplification stages, and when using sensitive analyzers 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 analyzer; 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 analyzer. In this case, the NF of the ESCI analyzer 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 i index refers to the input and the o index 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 the Friis formula, the k index at F and power gain G denotes the number of the amplifying stage [8]:

$$F = \frac{SNR_i}{SNR_0} \tag{6}$$

$$NF = 10\log_{10}(F) = 10\log_{10}\left(\frac{SNR_i}{SNR_0}\right) = \\ = SNR_{i,\ dB} - SNR_{0,\ dB} \tag{7}$$

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

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

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 analyzer 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/$\sqrt{Hz}$ 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 a very 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 in JFETs not selected for flicker noise. The 1/f noise characteristics of JFET transistors are more linear than other transistors. [9,10]

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:

$$V_n^2 = \frac{K}{C_{ox}^2 WLf} \tag{10}$$

where *K* is a process-dependent constant, *K* equal to 5 x 10^{-9} fC^2/µm^2 for NMOS devices and 2 x 10^{-10} fC^2/µm^2 for hidden channel PMOS devices. C_{ox} is the oxide capacitance and *W* and *L* are the width and length of the channel, respectively. [11]

In graphene, the fc can be on the order of 100 Hz, but in MOSFETs and millimeter-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 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/$\sqrt{Hz}$, and typical transition frequency of 715 MHz, both parameters meet assumptions.

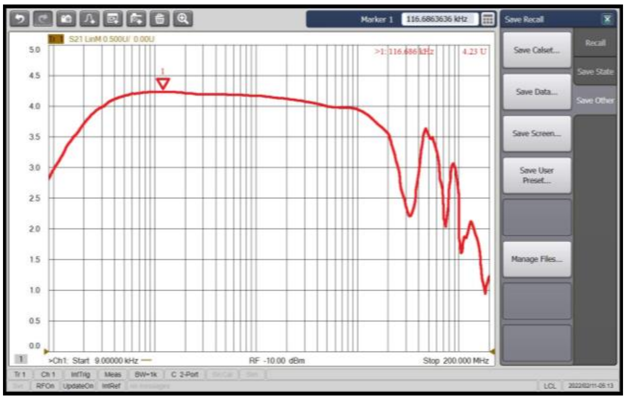

Fig. 2. The frequency response of the first-stage preamplifier based on the BF862 transistor.

The first stage of the preamplifier with an input impedance of about 100 kΩ was made. Fig. 2 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/$\sqrt{Hz}$. The preamplifier made in this way has an input noise equivalent of 1 nV/$\sqrt{Hz}$ 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 catalog 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 and the gain value of the entire preamplifier and the noise factor of the spectrum analyzer 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 analyzer alone to 0.64 dB for the entire measurement setup.

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.

III. 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 analyzer, amplifying the signal from the sample and improving the input noise parameters of the spectrum analyzer, and as the third element, the spectrum analyzer itself. To check the operation of one of the mentioned elements, the other two are reference devices with known parameters and characteristics.

An exemplary system for checking the parameters of the elements listed above is seen in Fig. 3. The noise source is the analyzer'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/$\sqrt{Hz}$, 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/$\sqrt{Hz}$ 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/$\sqrt{Hz}$ (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 analyzer input, the power of -52 dBm (6.3 nW) is transferred to the analyzer.

On the monitor screen of the spectrum analyzer shown in Fig.3, 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 analyzer itself and the components present in the analyzer, such as attenuators, filters, and conversion factors vary for different settings, which affect the final value of the input noise of the analyzer.

Fig. 3. 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 analyzer 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.

IV. CONCLUSION

This work aims to present the classical method of measuring electrical noise using a spectrum analyzer 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 analyzer. 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 analyzer. 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 analyzers 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.

V. ACKNOWLEDGEMENTS

This project 20FUN03 COMET "Two dimensional lattices of covalent- and metal-organic frameworks for the Quantum Hall resistance standard" has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

Funder ID: 10.13039/100014132

REFERENCES

[1] T. O. Wehling, A. V. Balatsky, "Dirac materials", Advances in Physics, vol.63, No.1, July 2014, pp.1- 76.

[2] Ed.: S. K. Ghosh, "Metal-organic frameworks (MOFs) for environmental applications", Elsevier Science, 2019, p. 451.

[3] M. Wang, M. Wang, H.-H. Lin, M. Ballabio, H. Zhong, M. Bonn, S. Zhou, T. Heine, E. Cánovas, R. Dong, "High-Mobility Semiconducting Two-Dimensional Conjugated Covalent Organic Frameworks with p-Type Doping", Journal of the American Chemical Society, vol.142, No.52, December 2020, pp.21622-21627.

[4] M. Marzano, A. Cultrera, M. Ortolano, L. Callegaro, „A correlation noise spectrometer for flicker noise measurement in graphene samples", Measurement Science and Technology, vol. 30, No.3, February 2019, p.9

[5] C. Toro, Jr., "Improved 1/f Noise Measurements for Microwave Transistors" (2004). USF Tampa Graduate Theses and Dissertations.

[6] J. B. Johnson, "Electronic noise: The first two decades," IEEE Spectr., vol. 8, pp. 42–46, Feb. 1971.

[7] M. J. Buckingham. Noise in Electronic Devices and Systems. Ellis Horwood Limited, Chichester, England, 1983.

[8] H. T. Friis Papers, Manuscript Division, Library of Congress, Washington, D.C., 2014.

[9] W.M. Leach Jr.," Fundamentals of Low-Noise Electronic Analysis and Design", Georgia Institute of Technology, Atlanta, Georgia 30332-0250 USA, 2000-2001.

[10] R. F. Voss, "Linearity of 1/f Noise Mechanisms". Physical Review Letters. 40 (14): 913–916, doi/10.1103/physrevlett.40.913, 1978.

[11] K. H. Lundberg, "Noise sources in bulk CMOS", Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, 2002.