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AUTOMATED MEASURING SYSTEM FOR INVESTIGATING TEMPERATURE DEPENDENCE OF LOW-FREQUENCY NOISE SPECTRA IN ELECTRONIC ELEMENTS AND STRUCTURES

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In this paper a measuring analytical system for low-frequency noise spectroscopy is presented. The measuring system is adapted for the automated study of low-frequency noise spectra in electronic elements, components and semiconductor materials and structures. A distinctive feature of the proposed measuring system is an automated complex local and precise study of the dependence of the low-frequency noise spectra in the sample on electrical voltage and temperature. The frequency range is 0.001-10000 Hz, DC bias range is 0-50 V and the temperature range is 7-500 K. The measuring system is adapted for use with an atomic force microscope for local measurements of electronic materials and structures noise characteristics. The measuring system makes it possible to obtain a larger amount of experimental data, which makes it possible to draw comprehensive conclusions about the mechanisms and causes of noise generation in the test sample. The results of testing the operation of the measuring system are given as an example of the Schottky diode-like structure study.

Keywords: low-frequency noise spectroscopy; temperature measurements; automation of measurements; barrier structures; atomic force microscopy

Introduction

Commonly during measuring any physical value noise is a negative influencing factor. It adds an error to the results of measurement. Fluctuations of current and voltage in electronic devices determine the lower limit of their sensitivity. In the case of high level of such noise useful component of the signal could be unobtainable. Noises in electronic vacuum and solid-state devices limit the dynamic range of their characteristics. Noises depend on the minimal size of these devices and the chosen minimal value of supply voltage [1].

On the other side, current and voltage fluctuations contain valuable information about internal properties of electrical systems. Thus, an analyzing mechanisms of noise formation provides the necessary data about characteristics and parameters of these systems. In this case fluctuations are used to obtain such information about physical processes leading to noise [2]. Some types of electric noise do not contain useful information. For instance, the thermal noise is the intrinsic and irremovable property of conductive materials with non-zero electrical resistance [3]. The power spectral density (PSD) of the thermal noise depends only on temperature and resistance of noise source. Besides that, it practically contains no useful data. The noise spectrum or dependence of is one of the most significant characteristics of fluctuation process [4, 5].

Shot noise, studied by Schottky in 1918 [6], is generated by discreteness of the number of charge carriers moving from one environment to another. In solid state structures shot noise is associated with charge carrier injection through the depletion region of p-n junction. It looks like a sequence of short pulses which create electrical current. Spectral density of such signal is uniform in a wide frequency range. Therefore, in the first approximation shot noise is considered as a white according to the corresponding PSD. Shot noise is the same as thermal noise. It doesn't provide information about the energy spectrum of electronic states in semiconductors. The low frequency (LF) noise in the metals and semiconductors used to control the quality of electronic components. It's spectral density depends on frequency f as a function $1/f^{\gamma}$, where γ is in the range 0.6-2.5 [1, 7].

Modern computer techniques increased the level of experiments to investigate noises [8]. Special attention is focused on automation of data processing and obtaining to achieve real time calculations. Nowadays it is hard to find a general universal model of generating electrical noise in all semiconductor and metal devices and structures [1, 2]. There are some models of noise generation for some semiconductor devices and metal films [1] due to the large number of non-obvious factors affecting the formation of the noise component of electrical signals. The temperature dependent noise is used to determine the electromigration activation energy, interconnect reliability, phase transitions, radiation damage, etc. [9-11].

To carry out precision studies of semiconductor barrier structures by LF noise spectroscopy the use of specialized equipment is required to measure the temperature dependence of the spectral density of noise power. On the other hand, local electrical measurements can be carried out using atomic force microscopy. Of interest is the joint use of atomic force microscopy to ensure local measurement and noise spectroscopy. A sensitive preamplifier is required to match the conductive probe of an atomic force microscope with a noise spectrometer.

As an amplifier of the noise signal for example Stanford Research Systems SR560 [12] or Ithaco 1211 [13] are used. Dynamic signal analyzers such as Stanford Research Systems SR785 [12] or SR780 [13], and other measuring devises as Agilent 5052A [14], for example, are applied. There are complete commercial systems for measuring noise such as NMS-NOYSYS 7 (Synergie Concept, French). Its advantage is easy to use and availability of software for managing and plotting noise spectra. However, such equipment provides several limitations. For example, papers [12-14] present spectra with bottom frequency limit 1 Hz, while the described in this paper system has the bottom range equals 0.001 Hz. NMS-NOYSYS 7 has lower sampling rates (250 kHz), bias voltage (till 10 V) and initial frequency (1 Hz). The complete software using leads to limitations about spectra processing and plotting.

1. Description of the measuring system

The influence of intrinsic noise of the amplifier on measurements was reduced by designing of the low noise amplifier with 10 parallel channels (Fig. 1). Application of N parallel amplifying channels allows decreasing the level of intrinsic noise in √N times. A disadvantage of the solution is increase of input capacitance in N times and decrease of input amplifier resistance in N times. The input level of amplifier noise is 3.9 nV/√Hz at 1 kHz (for comparison: input noise of amplifier SR560 is 10 nV/√Hz t 1 kHz). Changing resistance of R1, R2, R3, R4, provides the necessary gain factor.

During developing topology of amplifier, we wired the conductive paths in the way that power bus and signal bus were located as far as possible from each other. We used low-noise operational amplifiers AD795 that has normalized by the input voltage of the noise in the range of 0.1-10000 Hz.

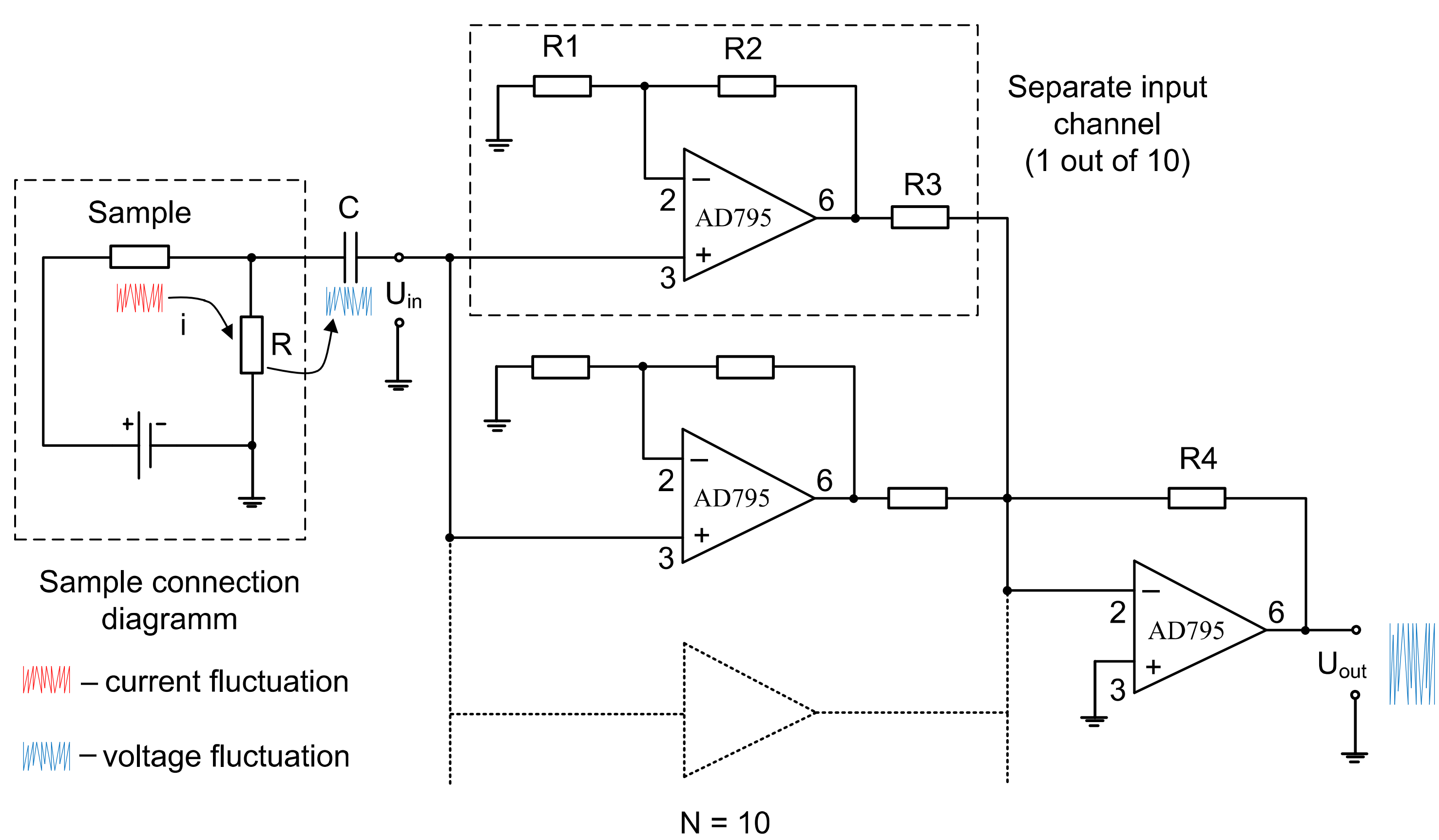

Fig.1. The scheme of the sample wiring with constant bias voltage source to the preamplifier

A constant voltage is applied to the sample from the bias circuit. The current fluctuation leads to appearance of voltage fluctuation on the reference resistor R. That fluctuation arrives the input of pre amplifier through the capacitor C blocking constant component. C is the high-quality film capacitor at the input of the amplifier. In our case R = 1-100 MΩ and C = 2 × 4.7 μF that provide RC = 9.4-940 s. The capacitor helps to remove the constant component of voltage on the reference resistor and work with voltage noise component only. The choice of the resistor R value is determined by the internal resistance of the sample and the lower boundary frequency in the noise spectrum. The upper frequency limit of the preamplifier can be increased by changing the parameters of the frequency correction circuits. The frequency limit of 10 kHz is due to the fact that the setup was designed specifically for studying low-frequency noise.

For investigating temperature dependence of noise SPD closed cycle helium cryostat Janis CCS400/204N with thermocontroller Lakeshore 335 are included in the measuring system (Fig. 2). The cryostat and the thermocontroller provide a temperature range of 7-500 K and the accuracy of maintaining the temperature to 0.1 K. Galvanic elements that reduce influence of noises from electrical network are used to supply the amplifier and apply bias voltage to the sample. The signal through the data acquisition board NI PCIe-6361 and terminal block NI BNC-2120 goes to the PC, which records, processes and stores the received data. The constant bias voltage is applied to the sample by commutation of the galvanic elements from the PC through the terminal block NI BNC-2120 using reed relay with gold-plated contacts. Parameters of the measuring system are shown in the table 1. The sensitivity of the preamplifier allows it to be connected to a conductive probe of the atomic force microscope and to conduct local measurements of the noise spectrum.

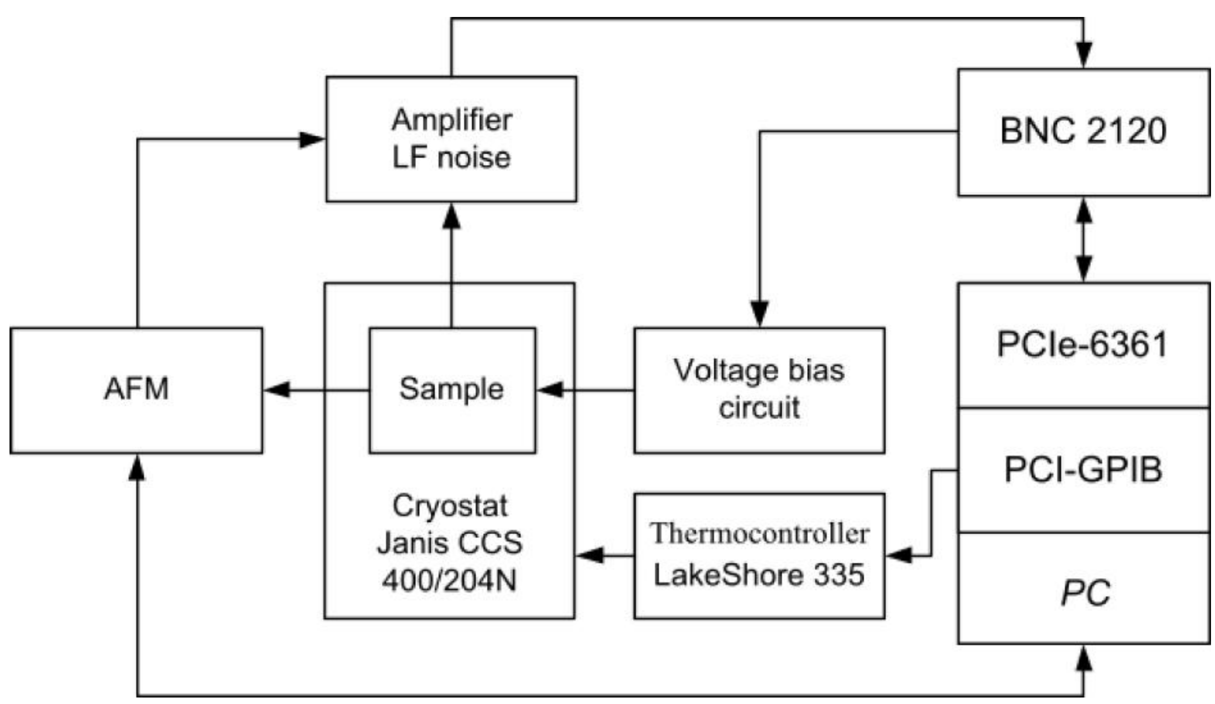

Fig. 2. The block diagram of the measuring system for low-frequency spectroscopy.

Table 1. Parameters of the LF noise spectroscopy measuring system

Parameter	**Range**	**Parameter change step**
Bias voltage	1.5-49.5 V	1.5 or 9 V
Frequency range	0.001 Hz – 10 kHz	0.001, 0.01, 0.1 and 1 Hz
Experiment duration	not limited	-
Temperature range	7-500 K	1-100 K
Gain factor	1-1000	A multiple of 10
Amplifier input impedance	1-200 MΩ	-
Sampling frequency	up to 2 MHz	-
ADC bit	16 bit	-

One can set bias voltage change step as 1.5 or 9.0 V depending on the switching galvanic element. Addition of voltage divider in the switching circuit provides lower steps. Time to receive one PSD spectrum depends on the chosen frequency range, i.e. minimum set frequency. In the case of minimum frequency equals 1 Hz frequency change step is also set as 1 Hz, that provides measuring duration equals at least 1s. In the case of minimum frequency 0.01 Hz the step value is 0.01 Hz and the duration is not less than 100 s. Resistance of the reference resistor is chosen as approximately equal to dynamic active resistance of the sample.

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2. Automation of measurements

Commonly, noise parameters of electronic structures are measured at quasi-steady state condition, i.e. at constant current value and constant temperature. Therefore, algorithms controlling the equipment have to consider temporary pauses that are necessary for total relaxation of transient processes, caused by change of voltage or temperature. Increase of pause duration provides approximately steady state condition, however it increases duration of experiments. Thus, pause duration is chosen according to the time of establishing constant current and duration of measurements. Duration of pauses is estimated experimentally by series of preliminary experiments for different samples and depends on electrical resistance of these samples.

In practice, the higher resistance means higher pause and measurement durations, which defined by time constant of RC circuit, formed by resistance of the sample, the reference resistance and the input capacitor blocking constant component at the input of the pre-amplifier [6]. For automatic recording experimental data one can set a delay after changing of external factors. Another way is tracking the average voltage across the sample. According to the data one finds a valid range of values (Fig. 3). This way is preferable as it reduces the duration of the experiment.

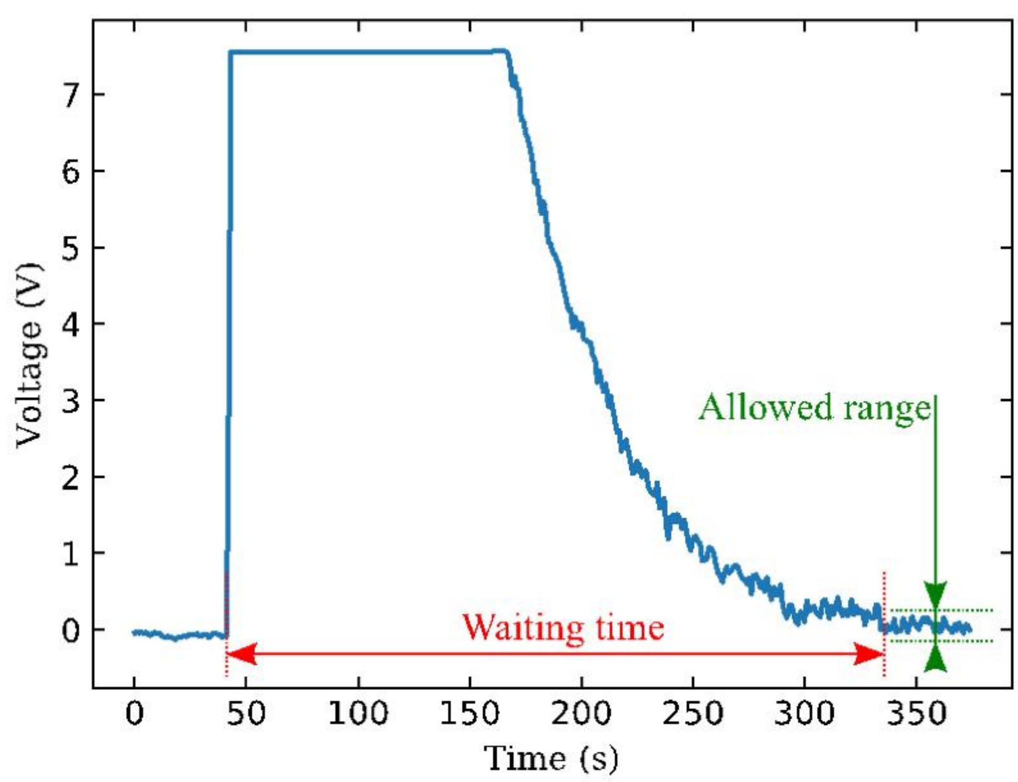

Fig. 3. Factors to start automated experimental measurements

The measuring system is controlled by the software written in LabVIEW [15, 16]. A bias voltage is applied by transferring a specific binary code to the digital block NI BNC-2120. The switching system after receiving this code includes the required number of galvanic elements in the circuit. The system could be simplified due to replacing the bias circuit containing galvanic cells by applying a bias voltage from a controlled source. Such approach helps to set a bias voltage with different steps. However it increases noise level from the electric network.

PSD is calculated using LabVIEW built-in libraries. For fast Fourier transform algorithm radix-2 [17] is used. Blackman-Harris window is used. That helps to display the obtained data in the form of time dependence of voltage and calculated noise spectrum in real time. This spectrum is found and shown for different voltage values with subtracted average trend. To get PSD data it is necessary to choose a weight function and frequency range before starting averaging and recording the data. As fluctuations are stochastic, so we average noise PSD over several measurements for reproducible result. We choose number of averages according to the case, that dispersion is slightly decreased with increase of number of averages.

As a results PC records only averaged noise PSD and shows all the data obtained at every measurement. Depending on the chosen value range, PSD can contain millions values due to the minimum frequency of the measuring system 0.001 Hz with step 0.001 Hz. Noise meters are usually designed for a lower operating frequency 1 Hz. The used sampling frequency is many times higher than the upper frequency of the studied signals 10 kHz. Artifacts associated with the influence of sampling frequency and digital filtering can fall into the high-frequency part of the spectrum.

3. Experiment

According to the physical model [18-20] LF noise PSD $S(\omega)$ as a steady state random process is described by superposition of the Lorentz function components:

$$S(\omega) = C\frac{\tau}{1+\omega^2\tau^2}, \tag{1}$$

where ω is the circular frequency ($\omega = 2\pi f$); C is the proportionality coefficient; τ is the relaxation time of an activation processes.

Characteristic points on the frequency axis f_b, corresponding to the change in the slope of the dependences are called as the break frequencies [1]. The characteristic frequencies correspond to the relaxation time τ of the process responsible for LF noise generation [21]:

$$\omega\tau = 1. \tag{2}$$

In semiconductor barrier structures the generation process is influenced by defects that create deep energy levels in a band gap. Determination of deep level ionization energy ΔE_t by LF noise spectroscopy is provided by a model function describing change in relaxation time of deep centers recharging $\tau(T)$, according to Boltzmann's law:

$$\tau = \tau_0 \cdot \exp\left(\frac{\Delta E_t}{k_B T}\right). \tag{3}$$

where k_B – Boltzmann constant, T – temperature, physical meaning of τ_0 is different and depends on a current physical model (for instance, τ could be relaxation time of crystal lattice oscillation) [22].

Relaxation time is defined from a break frequency of PSD dependence at constant temperature. A set of the measured relaxation times at different temperatures allows to construct Arrhenius plot. Analyzing its tilt angle gives the value of ionization energy ΔE_t. Arrhenius lines are plotted in semi-logarithmic scale versus reverse temperature:

$$ln(\tau) = ln(\tau_0) + \frac{\Delta E_t}{k_B T}. \tag{4}$$

Using the developed measuring system, we investigated test silicon Schottky diode with n-type base containing electrically active deep centers in the temperature range 90-290 K. The obtained LF noise PSD (Fig. 5) one can divide into three temperature sections with characteristic break frequencies: 100-140 K, 160-190 K and 270-290 K. Temperature investigations are measured in the frequency range 10^{-1}-10^4 Hz. In this case, there was no need to make noise measurements at frequencies below 0.1 Hz due to the characteristics of the sample. A feature of the silicon sample is the fact that defects with deep energy levels in the selected temperature range appear on the noise spectrum in the frequency range up to 10 kHz.

The attachment of Fig. 4 shows Arrhenius plot in logarithmic scale. The calculated ionization energies are presented in Table 2. We didn't detect deep centers in this test sample using DLTS [23] due to the limited sensitivity of this method in the range of relaxation times more than 0.1 s.

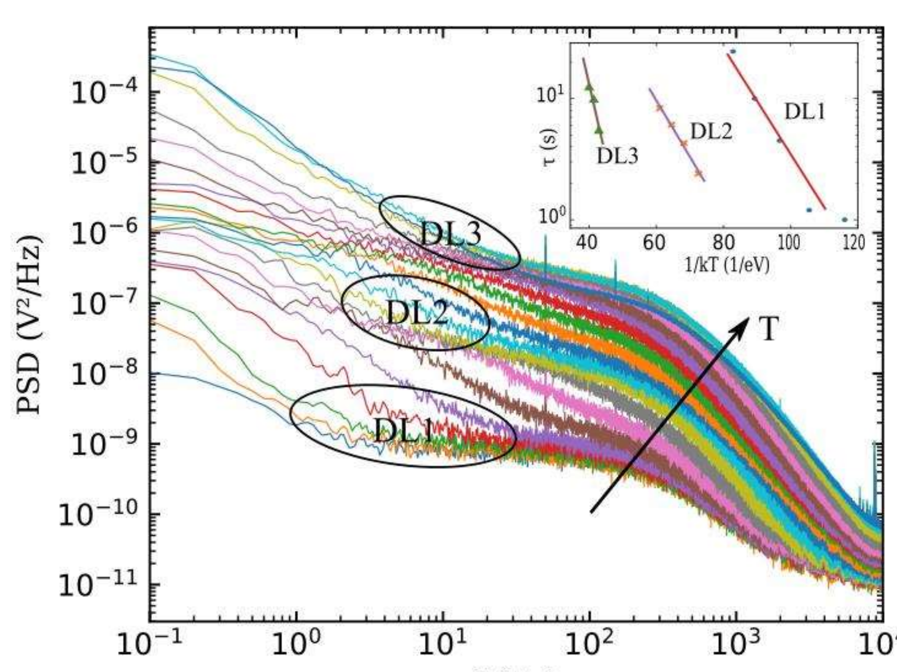

Fig. 4. LF noise PSD of the test Schottky diode at different temperatures

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Table 2. Parameters of deep levels

Deep level	DL1	DL2	DL3
ΔW_t (meV)	101	107	279
τ_0 (s)	$1.86 \cdot 10^{-6}$	$2.63 \cdot 10^{-5}$	$1.76 \cdot 10^{-7}$

Noise spectroscopy allows to study influence of electric field on reduction of potential barrier for charge carrier emission from deep levels of their capturing by deep levels according to the Poole-Frenkel effect [21]:

$$\Delta E_t = k_B T \ln\left(\frac{1}{2\pi f_b \tau_0}\right) + \sqrt{\frac{q}{\pi\varepsilon\varepsilon_0}\sqrt{\frac{qN}{2\varepsilon\varepsilon_0}(U_k - U)}}\ , \tag{5}$$

where U_k – contact potential difference, q – electric charge, N – shallow dopant concentration, ε_0 – dielectric constant, ε – permittivity, f_b – break frequency.

Doping concentration and contact potential difference could be found from capacitance-voltage (C-V) method [24]. The high break frequency at room temperature equals 350 Hz. Using RLC-meter Agilent E4980A (measuring complex described in Ref.23) we measured C-V characteristics and found U_k = 0.4 V. Ionization energy of deep level DL4 is ΔE_t = 0.54 eV.

LF noise PSD measured at reverse bias voltage in the range 1.4-20.2 V (Fig. 5). Change in the break frequencies under increase of bias voltage (attachment of Fig. 5) gives the data for calculating dependence of potential barrier reduction for charge carriers involved in recharging of DL4 from electric field in the base of the test diode. Dependence, shown in Fig. 6, points on grow of DL4 ionization energy reduction with increase of applied electric field.

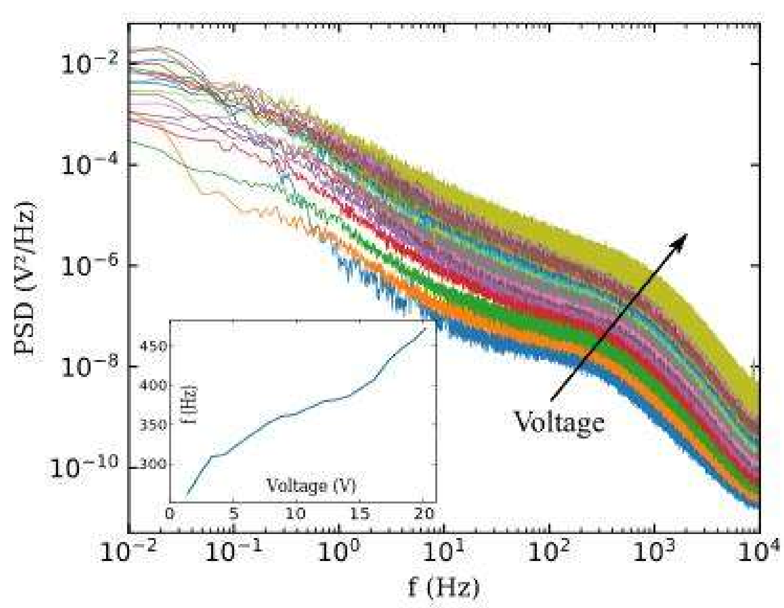

Fig. 5. LF noise PSD at different applied voltage

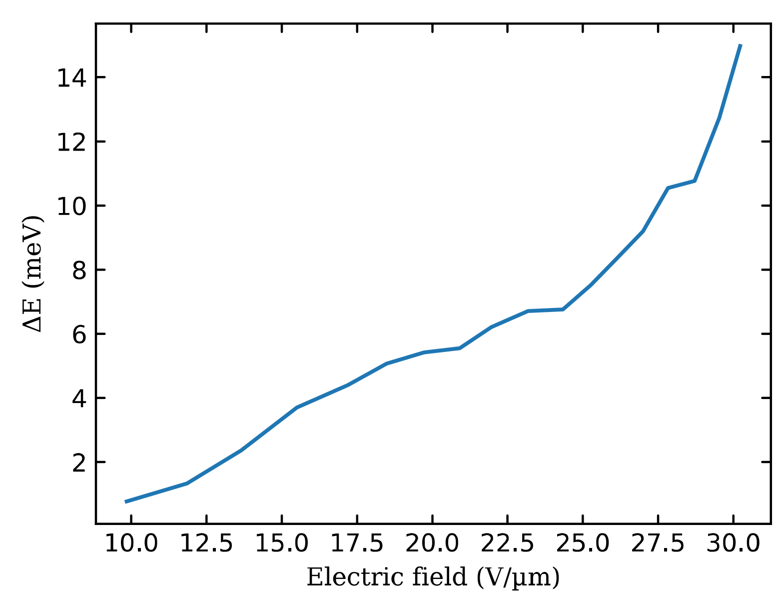

Fig. 6. Dependence presents reduction of ionization energy of deep level DL4 from electric field in the base of the Schottky diode

Conclusion

Using the proposed measuring system it was possible to demonstrate a precision measurement of the of the low frequency noise spectra temperature dependence and determine the parameters of defects with deep energy levels in a semiconductor barrier structure.

The system provides studying influence of electric field and temperature on noise spectra of electronics elements and structures. Application of modern approaches for measuring system automation makes LF noise spectroscopy powerful sensitive and informative tool for investigating of electronic energy levels in semiconductor barrier structures. The use of a conducting probe of an atomic force microscope in the measuring cell to form an electrical contact to the test sample makes it possible to perform a local study of the noise spectra.

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References

1 Zhigalsky G.P. *Fluctuations and noise in electronic solid state devices*. Moscow, 2012, 512 p. [in Russian]

2 Razumenko D.V. Low-frequency noise of electronic components as a tool for diagnosing internal defects. *Components and technology*, 2008, No. 9, pp. 168-174. [in Russian]

3 Buckingham M.J. *Noise in electronic devices and systems*. New York: Ellis Horwood Ltd. 1983, 399 p.

4 Kogan Sh.M. Low-frequency current noise with 1/f spectrum in solids. *Soviet Physics Uspekhi,* 1985, Vol. 28, pp. 170-196. doi: 10.1070/PU1985v028n02ABEH003853

5 Bonani F., Ghione G. *Noise in Semiconductor Devices*. Springer-Verlag Berlin Heidelberg, 2001, Vol. 7, pp. 1-38. doi: 10.1007/978-3-662-04530-5_1

6 Schottky W. Über spontane stromschwankungen in verschiedenen elektrizitatsleitern. *Ann. der Phys.,* 1918, Vol.57, pp. 541-567. doi: 10.1002/andp.19183622304

7 Sikula J., Levinshtein M. *Advanced Experimental Methods for Noise Research in Nanoscale Electronic Devices*. Nato Science Series II: Springer Netherlands, 2004, 368 p. doi: 10.1007/1-4020-2170-4

8 Kostryukov S.A., Ermachikhin A.V., Litvinov V.G., Kholomina T.A., Rybin N.B. A measuring System for the Spectroscopy of the Low-Frequency Noise of Semiconductor Diode Structures. *Measurement Techniques*, 2013, Vol.56, Iss. 9, pp. 1066-1071. doi: 10.1007/s11018-013-0331-x

9 Liu G., Rumyantsev S., Bloodgood M.A., et al. Low-Frequency Electronic Noise in Quasi-1D TaSe3 van der Waals Nanowires. *Nano Letters,* 2017, Vol. 17, 1, pp. 377-383. doi: 10.1021/acs.nanolett.6b04334

10 Empante T.A., Martinez A., Wurch M., et al. Low Resistivity and High Breakdown Current Density of 10-nm Diameter van der Waals TaSe3Nanowiresby Chemical Vapor Deposition. *Nano Letters*, 2019, Vol. 19, no. 7, pp. 4355-4361. doi: 10.1021/acs.nanolett.9b00958

11 Geremew A., Qian C., Abelson A., Rumyantsev S., Kargar F., Lawbce M., Balandin A.A. Low-frequency electronic noise in superlattice and random-packed thin films of colloidal quantum dots. *Nanoscale*, 2019, Vol. 11, No.42, pp. 20171-20178. doi: 10.1039/C9NR06899F

12 Kumar A., Heilmann M., Latzel M., Kapoor R., Sharma I., Göbelt M., Christiansen S.H., Kumar V., Singh R. Barrier inhomogeneities limited current and 1/f noise transport in GaN based nanoscale Schottky barrier diodes. *Scientific Reports*, 2016, Vol. 6, 27553. doi: 10.1038/srep27553

13 Song Y., Jeong H., Chung S., et al. Origin of multi-level switching and telegraphic noise in organic nanocomposite memory devices. *Scientific Reports*, 2016, Vol. 6, 33967. doi: 10.1038/srep33967

14 Luan X., Huang Y., Li Y., McMillan J.F., Zheng J., Huang S.-W., Hsieh P.-C., Gu T., Wang Di, Hati A., Howe D.A, Wen G., Yu M., Lo G., Kwong D.-L., Wong C.W. An integrated low phase noise radiation-pressure-driven optomechanical oscillator chipset. *Scientific Reports,* 2014, Vol. 4, 6842. doi: 10.1038/srep06842

15 Essick J. *Hands-On Introduction to LabVIEW for Scientists and Engineers*. Oxford Univ. Press, 2012, 624p.

16 Zhao M., Huang J.X., Wong M.H., et al. Versatile computer-controlled system for characterization of gas sensing materials. *Review of Scientific Instruments*, 2011, Vol. 82, Iss. 10, 105001. doi: 10.1063/1.3648132

17 Das A.D., Mahapatra K.K. Real-Time Implementation of Fast Fourier Transform (FFT) and Finding the Power Spectrum Using LabVIEW and Compact RIO. *Proceeding of the International Conference on Communication Systems and Network Technologies*, 2013, pp. 169-173. doi: 10.1109/CSNT.2013.45

18 Zhigal'skii G.P. 1/fnoise and nonlinear effects in thin metal films. *Physics-Uspekhi,* 1997, Vol. 40, pp. 599-622. DOI: 10.1070/PU1997v040n06ABEH000246

19 Scholz F., Hwang J.M., Schroder D.K. Low frequency noise and DLTS as semiconductor device characterization tools. *Solid-State Electron*, 1988, Vol. 31, No. 2, pp. 205-218. doi: 10.1016/0038-1101(88)90129-3

20 Yau L.D., Sah C.T. Theory and experiments of low-frequency generation-recombination noise in MOS-transistors. *IEEE Trans. Electron. Devices*, 1969, Vol. ED-16, No. 2, pp. 170-177. doi: 10.1109/T-ED.1969.16586

21 Kholomina T.A. Peculiarities of LF Noise Generation Processes in Semiconductor Barrier Structures. *Bulletin of RGRTU*, 2012, No. 39-2, pp. 117-121. [in Russian]

22 Zhigal'skii G.P., Kholomina T.A. Excess noise and deep levels in GaAs detectors of nuclear particles and ionizing radiation. *J. Commun. Technol. Electron.*, 2015, Vol. 60 (6), pp. 517–542. doi: 10.1134/S1064226915060200

23 Ermachikhin A.V., Litvinov V.G. An Automated Measuring System for Current Deep-Level Transient Spectroscopy. *Instruments and Experimental Techniques*, 2018, Vol. 61, Iss. 2, pp. 277-282. doi: 10.1063/1.1663719

24 Sze S.M., Ng Kwok.K. *Physics of Semiconductor Devices*. Hoboken: Wiley, 2006, 815 p. doi: 10.1002/0470068329

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