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The HF-LF minilab for analysing dielectric and semiconductor matter with the tunnel diodes and Corbino-electrodes in resonator

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Abstract— **Study the quantum-size structures of matter is important in order to coupling nanotechnologies and use of the nanomaterials. The high frequency (HF) resonant method in research of semiconductors and dielectrics at low temperature is sensitive and exact in row others. This is due to high quality of resonance at low signal-to-noise ratio and at small energy loss in tested matter. The concept of "giga - nano" takes a place here. The use of compact tunnel diodes as the generator and detector coupled with resonator considered in this work is attractive for low-temperature studies of nanostructures. The feature of work is also that the bottom of resonator is coaxial system of rings - Corbino geometry. The Corbino system serves, on the one hand, as analyzer of matter properties of at low frequencies (LF), on other one, serves as a modulator of HF field in resonator. Filling the vacuumed cavity by various gases additionally can serve by the specific theme of researches. So, proposed HF-LF mini-analyzer of matter for the low- temperature investigation. The main composition of device on resonator basis is given.**

Keywords—nanomaterials, dielectrics and semiconductors; HF cavity; superfluid helium; nanowires

I. INTRODUCTION

Study of the structural characteristics of dielectrics and semiconductors, in particular, quantum-electron formations in them, is necessary for applications. The chips with quantum-size structures play a crucial role in modern devices. At commensurable of structure with the electron wavelength, its quantum-mechanical nature, described by the Schrödinger equation with the corresponding boundary conditions, is clearly expressed. These structures include quantum wells, quantum wires, quantum dots, and superlattices. The practice interest is effects such as size quantization, resonant tunneling, superposition, and entanglement of quantum states. One of concepts the quantum interaction of electrons with matter was considered in [1].

Devices using nanostructured chips take place in many areas: receivers and transmitters of irradiation, information and computer systems, etc. At creating of artificial nanostructures with given kinetic and spectral properties use the methods of "zone engineering" and "engineering of wave functions". Both the low temperatures and the high carrier's mobility are necessary for the qualitative realization systems with quantum wells. The quantized energy levels of carrier in the Heisenberg uncertainty relation, $\Delta\varepsilon \cdot \Delta\tau \leq h$, (the values $\Delta\varepsilon$ and $\Delta\tau$ are uncertainties in energy and relaxation time, respectively, h - Planck's constant) should be clearly resolved against the background of thermodynamic energy $k \cdot T$ (k is Boltzmann constant). The quantum-size effects at relatively high temperatures take place in semiconductors with an electron mobility of at least 1000 $см^2$ / V • s at structures up to 100 nm. The coherence of the particle states at boundary should be enough and the roughness lateral size should not exceed de Broglie wavelength. Modern nanotechnologies allow obtaining samples with the atomic- smooth surfaces, and the use of the separation layers (spacers) essential shields the charged defects.

Many methods and tools is used for a detailed study of both the bulk and the surface features of matter, namely: EPR (electro-paramagnetic resonance) and NMR (nuclear-magnetic resonance); Raman spectroscopy; x-ray spectroscopy; tunnel and atomic force scanning microscopy. Modernized methods for study the microstructures of matter can be applied in study of the nanostructures. The method of high frequency (HF) resonance at low temperatures is sensitive and exact at studying the subtle effects in dielectrics and semiconductors [2-6]. At low temperatures the quality factor, Q of microwave resonator reaches high value (especially the superconducting resonator), and the "scanning" resonance line is extremely narrow. In such conditions the power of thermal noise in matter does not exceed the quantum limit, and the external fields are shielded by the conducting shell of resonator. The Q- factor of resonator reaches values more 10^{10} at helium temperatures and the measurement resolution, determined by width of the resonance line Δf, is less than 1 Hz at frequency of ~ 10 GHz.

Notable is study of dielectrics and semiconductors under pulses of heat, light, or irradiation. Such parameters as Fermi level, the carrier recombination time, the energy ionization of traps, the carrier free path, the effective capture cross section and the effective carrier masses can be determined. In the microwave range at a magnetic field it is possible to study the EPR of matter. The topological dielectrics and the weakly conducting materials have special attention in modern studies. One of the goals here is search for Majorana quasiparticles and creation of a quantum bits of quantum computer on their basis.

HF resonance method as usually complicated because large composition of HF devices: generator, receiver, attenuators, circulator etc. In this work for the improvement of situation proposed the combination of an HF resonator with tunnel diodes as a generator and detector.

The coplanar system of ring electrodes (Corbino system) takes place here too. On the one hand the system serves as a analyzer of the matter properties at low frequencies (LF) and, on other one, serves as a modulator of HF field in resonator. Need to be notice the filling vacuumed cavity by gases or condensed matters additionally is specific theme of researches.

II. THE DEVICE DESIGN.

A. CAVITY.

High-frequency electrical oscillation H_{011} -type in the cylindrical resonator is most acceptable mode in the experimental studies of semiconductors and dielectrics. The matter interacts weakly with electric field near walls of resonator [2, 3]. The conductivity, σ is determined by the losses of HF energy in the matter relative to an accumulated energy in the cavity volume.

$$\frac{1}{Q} - \frac{1}{Q_0} = \frac{4\pi n e \mu}{\omega} \frac{\int_S E^2\, dS}{\int_V E^2\, dV} \qquad (1)$$

here n is the electron density, μ is the electron mobility of charge e and ω is frequency. The value of azimuthally component of the electric field $E\varphi$ along both the axe *(z)* and the radial *(r)* coordinate is the relation $E\varphi\ (z,\ r) = E_0 \cdot \sin(\pi z/l) \cdot J_1(3.83\ r/a)$ (here J_1 is the Bessel function, a is resonator radius, l is resonator height). The conductivity of a disk-shaped insert with thickness d near bottom is expressed as

$$\sigma = \Delta(1/Q) \cdot \omega \cdot 1/\left[8 \sin^2(\pi \cdot d/l)\right] \qquad (2)$$

The Q -factor can be calculated by the decrement method: $Q = \omega_0 \cdot \tau / 2 \cdot \ln(V1 / V2)$, where τ is time of change of the output HF pulse from value of $V1$ to $V2$. The magnitude of voltage is measured exactly enough by the comparator method. At the power changes in e- time, the Q-factor is determined by simplest expression as $\omega_0 \cdot \tau$. The relative change in resonance frequency, given by the dielectric constant ε, for thin insert ($d / l << 1$) is

$$\Delta f / f_0 = \left(\pi^2/3\right) \cdot (\varepsilon - 1) \cdot (d/l)^3 \qquad (3)$$

The promise of this method was noted at studying of surface electrons above helium film on dielectric substrate in resonator [6]. With Q-factor of a superconducting resonator about 10^7 the electron mobility was determined as ~ 1 $cm^2 / V \cdot s$, and with higher of Q-factor this value was significantly lower.

From the expressions for Δf and σ, the values of both the losses, $tg\ \delta$, and the polarization of helium determined as $1{,}8 \cdot 10^{-9}$ and $\sim 10^{-9}$ respectively.

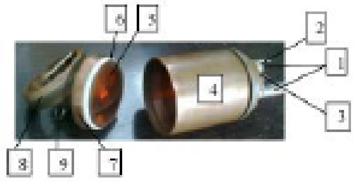

Fig. 1. Cylindrical microwave resonator with Corbino system (photo): 1 – the tubes for coupling the microwave resonator with the generator and the detector; 2 – the capillary of filling the cavity with gaseous or liquids; 3 – the heat line connecting the resonator with the refrigerator; 4 – the resonator housing;; 5 – the coplanar system of ring measuring electrodes - Corbino system; 6 – the insulating ring- high mode choke; 7 – the conical flange of the vacuum seal; 8 – the clamping ring; 9 – the power supply connector (DC and AC).

The combined design of microwave resonator is shown in Figure 1. It is a copper cylinder (resonator) with internal diameter and height of 42 mm for H_{011} mode. Resonator has two tubes for placing tunnel diode modules. The Corbino electrode system was situated on the resonator bottom. Structural elements of the resonator are shown in items to Fig. 1. The internal surface of resonator, for specific research tasks, can be covered with a layer of superconducting material (usually lead or tin) with thickness exceeding the skin- layer.

B. TUNNEL DIODE MODULE

It was noted above that the complex composition of HF devices in traditional measurements limits the use of resonance method. Tunnel diodes are used to simplify of apparatus at low-temperature measurement. The tunnel diode coupled with the resonator can operate either in the HF generator regime or in the HF detector one. The regime is set by the operating point on the N-shaped current-voltage characteristic.

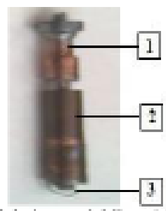

Fig. 2. The tunnel diode module in coaxial line: 1 is the piston with adjusting wheel; 2 is the section of short-circuit coaxial line; 3 is binding loop of the tunnel diode with cavity.

An image (photo) of the tunnel diode module with the tuning piston on coaxial line and with the coupling loop to resonator is shown in Fig.2. The tunnel diode operates at relatively low potential of ~ 0.2V and here need high stability bias source. The frequency- pulling regime leads to an increase the resolution HF resonance method [7]. The frequency tuning of generator by the electric potential on tunnel diode reaches 250 MHz. The relative frequency instability during measurement time is estimated to be less than ~ 10^{-14}.

C. CORBINO SYSTEM.

A coplanar combination of rings (Corbino's geometry) located on resonator bottom (Fig. 3. The Fig. 1, p. 5 shows this Corbino's geometry system in composition of HF-LF minilab on resonator basis).

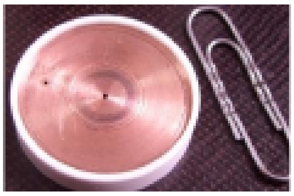

Fig. 3. The coplanar system of ring measuring electrodes - Corbino system. It consist the (in radial direction): inner disc is electrode to LF amplifier (or bridge), the separating ring at the ground potential, outer measurement ring - to LF generator signal, guard ring for forming the surface electron spot, the insulated ring

It added as low-frequency system for analyzing conductivity of matter up to 50 MHz in minilab. The components Corbino system in this device have following dimensions: internal disk the diameter 15 mm, rings with external diameters of 17 mm, 36 mm and 39 mm, respectively. The gap between components is smaller 0.1 mm. In this system, the LF- impedance of matter are determined by the Sommer-Tanner method [8]. The capacitive coupling of the substrate with ring electrodes connected to a sensitive device (for example, to a capacitive bridge or to a two-phase closed amplifier - lock-in-amplifier) is considered.

The long line model for calculating the characteristics of a substance is considered in [9]. The phase shift of the signal relative to the electrodes of the generator and amplifier depends on the specific resistance of the substrate ρ, the capacitive coupling of the substrate to the electrodes C, and the geometric factor G, determined by the ratio of the diameter of the rings, $\Delta\varphi \sim \rho \cdot C \cdot G$. The magnetoresistance of electrons localized above liquid helium using Corbino systems are measured in [10]. The study of magnetoresistance was considered for both the Drude mode and the ultra-quantum limit mode.

The system with Corbino electrodes, in addition to low-frequency study of substance, makes it possible to modulate the HF field in the resonator. The sensitivity of measurement increases. The Corbino system is housed in a cone-shaped flange, vacuum sealed using vacuum grease (Fig. 1, p. 7). The vacuumized cavity can be filled with the corresponding gas during complex studies of semiconductors and dielectrics. A sample of a disk-shaped substance is placed near the bottom of the resonator (for ease of calculation).

III. EXAMPLE OF RESERCHE.

Modern nanotechnologies have led to creation of, for example, one-dimensional (1D) or quasi-one-dimensional (Q1D) conducting systems. The charges move freely in one direction, while the other movements of the charge are quantized. Study of 1D system in semiconductors motivated the creation of this system based on surface electrons over helium - SE. The Q1D system of electrons over helium in the grooves of a profiled substrate with a clamping field, $E_\perp$, was first realized by Kovdrya and Nikolaenko [11]. The advantages of SE are high plasma homogeneity, wide range of variation of electron density and width of conductive lines in separate experiment.

Figure 4 demonstrates the result on study by Sommer-Tanner method the conductivity of Q1D- surface electrons on a negatively charged profiled substrate. The experiments on this question were carried out with subsequent analysis (the analysis is not given here). The procedure arrangement of this system was follows. Electrons are emitted from a free source onto a substrate to form charge bands. Then the electrons are directed by the field into the grooves with helium to form lines from the surface electrons. The depth of the potential well for SE is estimated as $\varphi \sim e \cdot E_\perp \cdot \delta$ (δ is the deviation of the fluid surface in the groove with a radius of curvature of about 40 microns), with a quantization of the spectrum ~ 0.1 K. The charged bands of the dielectric substrate shift the spectrum of surface electrons as $\omega^2 \sim \pi^2 \cdot e^2 \cdot n_x / m \cdot a^2$ (here n_x is the density of the linear charge of the substrate, a is the distance between the charges). The temperature dependence of the conductivity σ at the substrate charge potentials and surface electrons of about 15 V has a stepwise behavior at temperatures below 1.4 K. The observed feature is not described by SE scattering on helium atoms in a gas or on rplons. Dependence shows the behavior of the Q1D system. The energy interval $\hbar \cdot \omega$ in this case corresponds to the distance between the peaks. The parameters of the steps in different experiments were different.

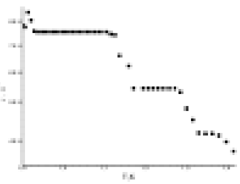

Fig. 4. The conductivity vs temperature of quazi-one-dimensional surface electrons over superfluid helium at charged profiled substrate. The measuring is performed by Sommer-Tanner method.

IV. CONCLUSION

Thus, the universal mini-system for high-frequency studies of dielectrics and semiconductors using tunnel diodes as the generator and the detector was proposed on the basis of a microwave resonator. For low-frequency studies of matter, the coplanar combination of coaxially arranged rings (Corbino geometry) at the bottom of resonator was used. The compact tunnel diodes near resonator provide a simple design and that at low temperatures lead to decrease in noise potential. Modulation of the microwave signal by a low-frequency signal through the Corbino system increases the sensitivity and accuracy of measurements. Filling the evacuated cavity with gases or other condensed substances allows analyzing their influence on the properties of semiconductors and dielectrics.

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The number of researches takes a part in this work and we thank them for that.

The authors hope that this work will be stimulating for further research semiconductors, dielectrics and surface

electrons over helium. The results must use in nano-electronic considering the quantum features matter.

REFERENCES

[1] A. Gritsunov, I. Bondarenko, A. Pashchenko, O. Babichenko, "Theory of Natural Oscillatory Systems and Advance in Nanoelectronics", Proc. of the 14-th International Conference "Modern problems of radio engineering, telecommunications and computer science" (TCSET 2018), Ukraine. Lviv-Slavske, Feb. 23-26, pp. 92-97, 2018

[2] A.A. Brandt, "Study of dielectrics at microwave frequencies", M .: Fizmatgiz, 403 p., 1963.

[3] I.N. Bondarenko, F.F. Mende, "Investigation properties both the dielectrics and the semiconductors use cooled and super conducting cavity", Kharkov , 72 p., 1980 (in Russian).

[4] I.N. Bondarenko, "Examination of dielectrics by means of the cooled microstrip resonators", Telecommunications and Radio Engineering, V53, № 7-8, 1999, pp. 171-175, DOI: 10.1615/ TelecomRadEng.v53.i7-8.260.

[5] I.N. Bondarenko, A.V. Galich, "The resonant sensors". Proc. of24thInternationalCrimeanConferenceMicrowave &TelecommunicationTechnology(CriMiCo'2014), pp. 984-985.

[6] Yu.Z. Kovdrya, F.F. Mende, and V.A. Nikolaenko, "High-frequency conductivity of electrons above helium film in the regime of localization on substrate potential inhomogeneities", Phys. Nizk. Temp., V.**10**, №11, pp. 1129–1140, 1984 (in Russian).

[7] J. Jimenez, J. Benard, P. Sudraud, A. Septier, //Proc. IEEE, v.61, p.121, 1973.

[8] W.I. Sommer, and D.J. Tanner, "Mobility of Electrons on the Liquid ^{4}He", Phys. Rev. Lett.,V.27, №20, pp..1345-9, 1971.

[9] R. Mehrotra, Q.J, Guo, Y.Z. Ruan, D.B. Mast, and A.J. Dham, "Density-dependent mobility of a two-dimensional electron fluid", Phys. Rev. B 29, pp 5239-5242, 1984.

[10] Yu.Z. Kovdrya, V.A. Nikolaenko, O.I. Kirichek, and V.N. Grigor'ev, "Magnetoresistance of electrons localized above liquid helium", Phys. Nizk. Temp., **18** (**7**), pp. 673 – 678, 1992, (in Russian); Sov.J Low Temp. Phys. 18 (7), pp. 477-480, 1992.

[11] Yu.Z. Kovdrya, V.A. Nikolaenko, "Quasi-one-dimensional electron system over liquid helium", Fiz. Nizk.Temp. , **18**, pp.1278-80, 1992 (in Russian).