PROCEEDINGS OF THE YEREVAN STATE UNIVERSITY

Physical and Mathematical Sciences 2011, № 3, p. 47–51

Physics

NEEDLE-LIKE PROPERTIES OF THE PROBING RF FIELD OF "*MAGNETIC-FIELD*" PROBES BASED ON THE SINGLE-LAYER FLAT COILS

S. G. GEVORGYAN[1–3*], S. T. MURADYAN[1, 2], B. K. KURGHINYAN[1], M. I. QEROBYAN[1]

[1] *Superconductivity & Scientific Instrumentation Center, Chair of Solid State Physics, Faculty of Physics, YSU, Armenia*
[2] *Institute for Physical Research, National Academy of Sciences, Armenia*
[3] *Precision Sensors/Instrumentation Ltd., Armenia*

A single-layer flat-coil-oscillator activated by a low power backward tunnel diode has been elaborated and created. As an inductance in a pick-up circuit of the oscillator, such a flat coil served as a *"magnetic-field"* probe in such a measuring instrument. The created oscillator was activated both without and with an external capacitance C_0 in its resonant circuit, i.e. the flat-coil oscillator might be also activated with its own (internal) capacitance C_c. Investigation of "*probe-formative*" capabilities of this research instrument with such an unusual coil (versus C_0) showed that with a reduction of the value of this capacitance the feeling (probing) field of such a probe exponentially becomes longer, i.e. these probes become more far-ranging with decreasing C_0. The revealed property of "magnetic-field" probes would permit an essential widening of capabilities of flat-coil-based probe microscopes. It may also permit to enhance the efficiency of searching and detection of the nodal structure, arising at an unusual phase transition from the "*uniform*" to "*non-uniform*" superconductivity, predicted independently by Fulde and Ferrell, and Larkin and Ovchinnikov.

Keywords: Single-layer Flat-Coil-Oscillator method; SFCO technique based "magnetic-field" probe; Fulde–Ferrel–Larkin–Ovchinnikov superconductivity; measurement technique for the searches of the nodal structure in FFLO-state.

Introduction. The single-layer flat-coil-oscillator method (SFCO technique) offers many unique opportunities. It enables observation of *Angstrom*-scale changes of the "*skin*"-depth of normal conducting materials and the penetration depth of superconductive materials at low temperatures [1–3], and detection of negligibly small power absorptions (or insignificant energy releases) of $\sim 10^{-9}$ *W* [4] – especially in thin plate-like objects. According to our earlier investigations [2, 5], the single-layer flat-coil sensors are notable for strong dependence of the measured signal on both the spatial gap between a test-object and the detecting coil, and the lateral position of the object relative to the coil surface. Besides that, such sensors are "*nonperturbative*" (influence of the measuring radio-frequency (RF) field on a tested object is less than 10 *nW*), and capable of long distance probing of objects (starting from tenths of millimeters and even up to few millimeters). The said advantages of the flat-coil sensors favored the initiation of a new direction in a probe microscopy – creation of a conceptually new class "*magnetic-field*" probes [5].

---

[*] E-mail: gevs_sam@ysu.am; gevs_sam@web.am

Since the invention of tunneling microscopes (TM) [6, 7], the scanning probe microscopy has enabled a burst of nanotechnology achievements. It enabled to visualize, characterize and even manipulate by material structures at nanometer scales, including the features of atomic dimensions. Strong dependence of the measured signal on the size of the spatial gap Z between the solid-state probe and the surface of the object is the main physical principle of the probe microscopy [8]. The operation of both tunneling [6, 7] and atomic-force microscopes (AFM) [9] is based on this principle. But, unfortunately, the working gap between the probe and objects under test is too small in these microscopes ($Z < 1$ *nm*) that limits strongly chances of the researcher for applying any kind of testing perturbation. Besides, probe microscopes have also other disadvantages (uncontrolled thermo-extension of the probe due to its ohmic heating, destructive actions inserted into the object under study by the probe, complexity of fabrication of solid-state probes (needles and cantilevers), etc.), to overcome of which, and for making wider abilities of probe microscopes there was need to formulate new concepts and approaches in this area. To that end we have suggested [5] to develop and produce conceptually new "magnetic-field" probes, based on the use of flat shape single-layer pick-up coils. The probes of this kind are neither solid-state, far-ranging, "nonperturbing", nor needing a special fabrication technology.

So, the sensitive flat-coil method, capable of detecting too small changes of inductance ($\sim 10^{-12}$ *H*) [1–3] and power release ($\sim 10^{-9}$ *W*) [4, 10] even in sub-*mm* size micron-thick flat objects, seems may suit the probe microscopy enough well. According to the results of our previous research [5], such a flat-coil sensor satisfies to all abovementioned requirements needed for its use in the probe microscopy. Besides, being essentially "*nonperturbative*" the SFCO sensor is also capable of probing an object from long (specified above) distance. It is worthy to note in this connection that the working gap Z between such a "probe-formative" flat coil and the test object may exceed by several orders of magnitude that for the conventional TM and AFM microscopes. Therefore, as a result of further research and development efforts a novel (new generation) "nonperturbing", non-contact, long-range action microscope may appear to provide the probing and investigation of sub-μm size objects, even at millimeter distances.

Measurable parameters for such a "magnetic-field" probing technique are the frequency, F_{meas}, and the amplitude, A_{meas}, of the flat-coil oscillator. The measured signals (observed effects) are formed as a result of the change of *MHz*-range measuring field distribution at the flat pick-up coil face and due to absorption of the same RF testing field power by the test sample, which, in their turn, lead to the changes of the measuring oscillator frequency and amplitude respectively [1, 2, 5].

In this work we have investigated peculiarities of the geometric configuration of the space distribution of the testing (probing) RF field of "magnetic-field" probes that were proposed and tested by our group first in 2005 [5].

Results and Discussion. So, we have created a flat-coil-oscillator ($\Phi_{coil} \sim 12$ *mm*), activated by a low-power tunnel diode (TD), and used the radio frequency testing field near the coil face as a "magnetic-field" probe. According to our earlier conclusions [11], it is evident that due to high value of Q-factor (~80 at ~24 *MHz* frequencies) and relatively big value of the own (internal) capacitance C_c of the flat coil used (~30 *pF*), it was not so hard to run the oscillator similar to that used in

[11] and obtain stable oscillations in the absence of the external capacitance C_0 (that is the one soldered to the oscillating circuit of the measuring TD-generator).

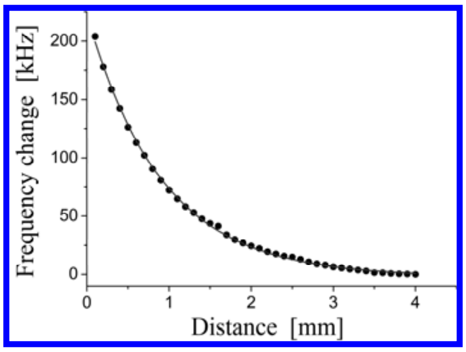

Fig. 1. The change of the frequency of a measuring oscillator versus the distance of the test tin ball (Φ~1 *mm*) from the flat coil face (Φ_{coil}~12 *mm*), obtained by scanning the position of test ball along the coil axis.

To obtain the configuration (geometric shape) of the probing (measuring) field distribution near the flat coil face we have made a feeling-scan of its *MHz*-range magnetic field using a normal-metallic (tin – Sn) ball of ~1 *mm* in diameter. During the 1st experiment the test-ball was moved along the axis of flat coil (it has been moved away from the coil). The obtained dependence of the frequency of measuring oscillator on the position of the ball is shown in the Fig. 1. The black circles on the figure correspond to the measured data, while the solid line – exponential approximation of the measured results by means of the least-squares technique.

During the second experimental run we moved the same test ball along the diameter of the flat coil at three different (but fixed during each test) distances h (2, 3 and 4 *mm*) from the surface of the face of the single-layer flat coil. The results of this series of runs are given in Fig. 2. As is seen in Figs. 1, 2, the measuring RF field near the surface of flat coil is a needle-like, and the measured signal enough strongly depends on both the spacing (spatial gap) between the probe (flat coil) and test object and the lateral position of the object relative to the flat coil surface. Owing to these features, the use of a flat single-layer coil technique as the "magnetic-field" probe is quite justified.

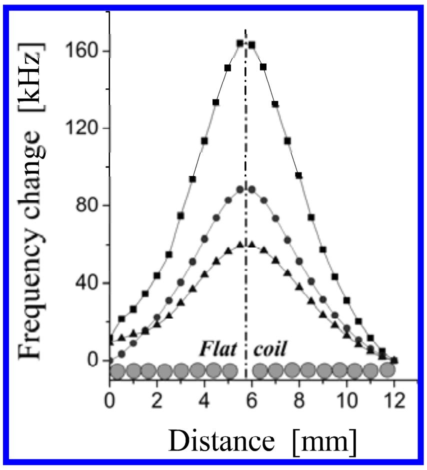

Fig. 2. The change of the frequency of a measuring oscillator versus the test ball position (Φ ~1 *mm*) along the diameter of flat coil (Φ_{coil} ~12 *mm*) at three different fixed distances h from the surface of single-layer flat coil: ■ – $h = 2$ *mm*, ● – 3 *mm*, ▲ – 4 *mm*.

Our experiments also indicate that the length of the probing RF field of flat coil in the surrounding space depends on the capacitance of external capacitor C_0, soldered to the oscillating circuit of the generator. Namely, with reduction of this capacitance the "magnetic-field" probes become more far-ranging – they become capable of discerning metallic objects at larger distances [11].

To estimate the strength of this dependence, one more experiment was conducted for various specified values of this capacitance, by moving the mentioned Φ~1 *mm* test ball (that was on the coil axis at the fixed distance h~1 *mm* from the coil) by the same value of Δh~100 μm along the coil axis. Here the absolute change of the frequency of measuring instrument (TD-oscillator) has been recorded due to the motion of normal-metallic tin ball. The results of this experiment are shown in Fig. 3. The squares in the figure correspond to the measurement data, while the solid line is the linear approximation of these data by means of the least-squares method.

Since the scale of the abscissa axis in Fig. 3 is logarithmic, the fact that the measured points lay on a straight line means that the sensitivity of flat coil based "magnetic-field" probe to the changes of metallic object position exponentially increases as the capacitance of external capacity C_0 decreases. Thus, with a decrease of the value of a capacitance of the external capacitor C_0 the position-change sensitivity of the measuring TD-oscillator for metallic objects (in our case, tin ball) increases by the exponential low. Hence, the length of RF measuring field of the flat coil as a "magnetic-field" probe exponentially increases with decreasing value of C_0 capacity. Thus, with a decrease of the capacitance of the capacitor soldered outwardly to the oscillating circuit of TD-generator, the *"needle"* of "magnetic-field" probes (the measuring field of a single-layer flat coil) exponentially becomes longer – the "needle" of "magnetic-field" probes becomes exponentially more far-ranging.

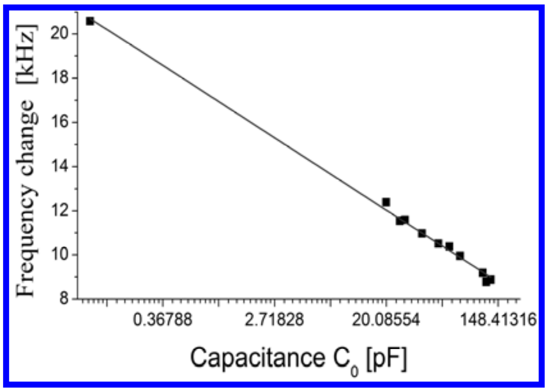

Fig. 3. (■) – change of the frequency of a measuring *TD*-oscillator due to the motion of *Φ*~1 *mm* tin test ball (being at the fixed distance of h~1 mm from the coil on its axis) by the same value of Δh~100 *μm* along the coil axis (Φ_{coil}~ 12 *mm*) versus the value of external C_0 capacitor, soldered to the flat coil.

Conclusion. In conclusion note that the study of peculiarities of the geometric configuration of the spatial distribution of testing (probing) RF field of "magnetic-field" probes, proposed and first tested by us [5], is urgent, because by changing the capacitance of external capacitor C_0, soldered to the oscillating circuit of the measuring TD-generator, it becomes possible to control both the range of action and sensitivity of these probes, using the sensitive flat-coil technique. Due to these, and other specific properties of these probes (described by us in [1, 2]) the new microscopes (including low-temperature ones) created on the basis of these probes may permit to make a distinction between magnetic and non-magnetic regions on the surface of objects (with sub-micrometric spatial resolution predicted in [5]). Further improvement of this technique transfer from *cm*-size hand-made present flat coils to the millimeter and sub-millimeter size lithographic spiral-chip-inductors deposited of a gold [12] can provide better spatial resolution to be higher at least by an order of magnitude. With these improvements capabilities of microscopes with discussed "magnetic-field" probes are expected to permit a detailed study of the unique phase transition from the "*uniform*" to "*non-uniform*" superconductivity. This fine phenomenon was predicted by Fulde and Ferrell [13] and independently by Larkin and Ovchinnikov [14] (the so-called FFLO state) and experimentally observed by Prof. Agosta's group [15] (unfortunately, only qualitatively). No detailed investigation of this effect was carried out up to date, however, due to the lack of measuring instruments with required spatial resolution.

However, in terms of the above discussed and other results of our works in this field [16–18] we hope that with construction of microscopes on the basis of described flat coils of ≤ 1 *mm* size [12] an instrument providing sufficient spatial resolution will be available for solving the above problem, that is of fundamental importance for understanding the nature of superconductivity in general, and the nature of Cooper pairs in particular. With such an instrument at hand (as an effective micro- and nanoprobing tool) it will be possible to detect and "visualize" the nodal structure in the FFLO state [15]. Such a fine probing instrument may help also to distinguish magnetic atoms from the non-magnetic ones (by the sign of frequency change of the measuring TD-oscillator) that is critical for studying the co-existence of superconductivity and magnetism – a fine effect that was experimentally observed only in sub-micrometer scale objects [19]. This phenomenon was also insufficiently studied due to the lack of methods having the required spatial resolution.

The investigations were financially supported by the Armenian National Foundation of Science & Advanced Technologies (NFSAT) and the U.S. Civilian Research & Development Foundation (CRDF) under the Grants #ISIPA 01-04, and #UCEP 07/07. The study was partially supported also by the State sources of the Republic of Armenia in frames of the R&D project #72-103.

Received 07.07.2011

REFERENCES

1. **Gevorgyan S., Kiss T., Movsisyan A., Shirinyan H., Hanayama Y., Katsube H., Ohyama T., Takeo M., Matsushita T., Funaki K.** Rev. Sci. Instr., 2000, v. 71, № 3, p. 1488–1494.
2. **Gevorgyan S., Kiss T., Ohyama T., Movsisyan A., Shirinyan H., Gevorgyan V., Matsushita T., Takeo M. and Funaki K.** Physica C, 2001, v. 366, p. 6–12.
3. **Gevorgyan S., Kiss T.** et al. Supercond. Sci. Technol., 2001, v. 14, p. 1009–1013.
4. **Gevorgyan S.G., Kiss T., et al.** Physica C: Supercond. & Applications, 2001, v.363, p. 113–118.
5. **Gevorgyan S., Azaryan M.** Proc. of 5th International Conference on "Semiconductor Micro- & Nano-electronics". Armenia, Aghveran, 2005, p. 82–86.
6. **Binning G. and Rohrer H.** Scanning Tunneling Microscope. U.S. Patent 4,343,993. Aug. 10, 1982. Field: Sep.12, 1980.
7. **Binning G.** et al. Appl. Phys. Lett., 1982, v. 40, p. 178–180.
8. **Bikov V.A.** Topical Review on Probe Microscopes: Russian Doctoral Degree Dissertation. M., 2000 (in Russian).
9. **Binning G.** et al. Europhy. Lett., 1987, v. 3, № 12, p. 1281–1286.
10. **Gevorgyan S., Movsisyan A., Movsesyan G., Shindyan V., Shirinyan H.** Mod. Phys. Lett. B, 1997, v. 11, № 25, p. 1123–1131.
11. **Muradyan S.T., Gevorgyan S.G.** Journal of Contemporary Physics NAS RA, 2008, v. 43, № 2, p. 97–100.
12. "Spiral Chip Inductors" (U.S. Microwaves Production – www.usmicrowaves.com).
13. **Fulde P., Ferrell R.** Phys. Rev., 1964, v. 135, № 3A, p. A550–A563.
14. **Larkin A.., Ovchinnikov Yu.** JETPh, 1964, v. 47, № 3 (9), p. 1136–1146 (in Russian); Sov. Phys. JETP, 1965, v. 20, p. 762.
15. **Radovan H.** et al. Journal of Low Temperature Physics, 2003, v. 133, p. 377–386; original information see in: NHMFL Reports, 2003, v. 10 (3), 1, magnet.fsu.edu.
16. **Gevorgyan S., Shirinyan H., Manukyan A., Sharoyan E., Takeo M., Polyanskii A., Sarkisyan A., and Matsushita T.** Nuclear Instruments and Methods in Physics Research A (NIM-A), 2004, v. 520, № 1–3, p. 314–319.
17. **Karapetyan G., Shirinyan O., Gevorgyan S., Gevorgyan V.** Proc. of the 7th Scientific and Practical Conference on "Educational, Scientific and Engineering Applications in "LabVIEW" Environment and Technologies of "National Instruments". Russia, Moscow, 28–29 November, 2008, sec. 1, № 1.0.2., p. 8–12 (in Russian).
18. **Gevorgyan S., Shirinyan H., Karapetyan G., Gevorgyan G., Polyanskii A.** Proceedings of the YSU. Physical and Mathematical Sciences, 2009, № 2, p. 50–54.
19. **Aoki D.** et al. Nature, 2001, v. 413, № 6856, p. 613–616.

Ս. Գ. Գևորգյան, Ս. Տ. Մուրադյան, Բ. Կ. Կուրղինյան, Մ. Ի. Քերոբյան. Միաշերտ, հարթ կոճերի հիման վրա գործող “մագնիսադաշտային” զոնդերի ռադիոհաճախային զոնդավորող դաշտի ասեղանման հատկությունները էջ. 47–51

ԱՄՓՈՓՈՒՄ

Մշակվել ու ստեղծվել է թույլ հզորության, շրջված թունելային դիոդով ակտիվացող հարթ կոճով ինքնագեներատոր: Լինելով վերջինիս ընդունող կոնտուրի ինդուկտիվությունը, հարթ կոճը ստեղծված սարքում ծառայել է որպես “մագնիսադաշտային” զոնդ: Ինքնագեներատորը գործարկվել է ինչպես առանց, այնպես էլ իր տատանողական կոնտուրին ամրացված արտաքին C_0 կոնդենսատորով: Այսինքն՝ հաջողվել է հարթ կոճով ինքնագեներատորը գրգռել նաև իր սեփական (ներքին) CK ունակությամբ: Այսպիսի անսովոր հարթ կոճով չափող սարքի “զոնդ ձևավորող” հատկություններն ուսումնասիրելու արդյունքում (C_0 ունակությունից կախված) ցույց է տրված, որ ունակությունը փոքրացնելիս այդպիսի զոնդի զգացող (զոնդավորող) դաշտը երկարում է էքսպոնենցիալ օրենքով, այսինքն՝ այդպիսի զոնդերը դառնում են ավելի հեռահար: “Մագնիսադաշտային” զոնդերի մեր կողմից բացահայտված այս հատկությունը կօգնի էապես ընդլայնել այսպիսի զոնդով մանրա-դիտակների հնարավորությունները: Ֆուլդի և Ֆերելի ու Լարկինի և Օվչիննիկովի կանխագուշակած “անհամասեռից” դեպի “համասեռ” գեր-հաղորդիչ վիճակի անսովոր փուլային անցման պահին ձևավորվող “հանգուցային” կառուցվածքը փնտրելիս և գրանցելիս այս հատկությունը կօգնի նաև բարձրացնել հետազոտությունների արդյունավետությունը:

С. Г. Геворгян, С. Т. Мурадян, Б. К. Кургинян, М. И. Керобян. Иглообразные свойства радиочастотного зондирующего поля “магнитно-полевых” зондов, основанных на плоских однослойных катушках стр. 47–51

АННОТАЦИЯ

Разработан и создан автогенератор на плоской катушке, активированный маломощным обращенным (backward) туннельным диодом. Являясь индуктивностью приемного контура осциллятора, такая катушка служила “*магнитно-полевым*” зондом. Созданный генератор запускался как без, так и с внешним конденсатором C_0 в его колебательном контуре, т.е. изученный нами автогенератор с плоской катушкой возбуждался также и на его собственной (внутренней) емкости C_K. При изучении зондообразующих свойств измерителя с такой необычной катушкой показано, что с уменьшением величины емкости C_0 прощупывающее (зондирующее) поле такого зонда удлиняется по экспоненциальному закону, т.е. такие зонды становятся более дальнодействующими. Выявленное нами свойство “*магнитно-полевых*” зондов поможет существенно расширить возможности зондовых микроскопов на их базе. Оно позволит также поднять эффективность исследований при поиске и детектировании узловой структуры, образующейся при необычном фазовом переходе “*однородная сверхпроводимость–неоднородная сверхпроводимость*”, предсказанном Фюльдом и Феррельем, Ларкином и Овчинниковым.