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Field-Controlled Superconducting Transistor (FIST)
SCOPES-Switzerland National Science Foundation Research Project

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1 Summary

The project aims at demonstrating the practical possibility of a transistor-like device controlled by a magnetic field at superconducting-ferromagnet junctions. It is based on the Andreev reflection of a spin-injection current. The project uses high-Tc materials superconductors and manganite ferromagnets or other related coumpounds thought to have close to 100% spin polarization, striving to achieve a high-quality junction's matching. The effect will be tested by experimental determinations of the spin polarization, and by measuring the resistance drop caused by spin injection.

This project can be thought of as part of the development of spintronics : effects and solid state devices based on the spin of the conduction electrons. This work addresses various issues in this field, in particular the spin polarization, which can be measured by tunneling from the ferromagnet into a superconductor. The device size is limited by the spin diffusion length, which is in the nanometer range. Consequently, nanostructures must be designed. Various phenomena at the superconductor-ferromagnet interface must be characterized or mastered. When high-Tc materials and manganites are involved, these issues pertain to current fundamental research in experimental solid state physics.

The theory of Andreev's reflection will be thoroughly reformulated and generalized to including the spin-carrying currents, from basic principles to comparison with experiments, and the optimization of the nature, quality and geometry of the device will be carried out. The main problems to be addressed are the spin-diffusion range, the effect of the interface, the spin-flip scattering and related magneto-resistive effects, the coupled dynamics of charge- and spin-carrying currents in the presence of a superfluid-like condensate, the role of dimensionality and geometry; as well as other side effects, like the effect of Andreev's bound states, interference and beats, non-linearities, noise, finite-size and Casimir transport. The connection to, and relevance for mesoscopic and nanostructural transport will also be discussed, in particular effects of a possible non-local conductance.

2 Background

2.1 Participating Research Teams

The Swiss group (applicant #1) has been involved since 1992 in the study of the magnetic and transport properties of nanostructures produced by electrodeposition in porous membranes. The group has produced original results on Giant Magnetoresistance with current perpendicular to the interfaces (CPP-GMR). It has contributed to the study of the tunneling magnetoresistance between two ferromagnets. Lately, the group has demonstrated the effect of the spin polarization on the magnetization. Currently, one graduate students carries out an NMR investigation of manganites and related materials at the University of Illinois at Urbana-Champgain, jointly with Prof. Slichter. The "Institut de Physique Expérimentale" at Lausanne has also produced a series of paper on the NMR of manganites, under the direction of one its senior scientist, Dr. Dimitropoulos. So far, we do not hands-on experience with measuring spin polarization by tunneling into a superconductor. We are limited to quoting literature results.

The Bulgarian team (co-applicant #2 T. Donchev) belongs to the Laboratory of Superconductivity and Cryoelectronics at the Institute of Electronics, Bulgarian Academy of Sciences. It carries out scientific and application-aimed research in the field of High Temperature Superconductivity (HTS) since 1986. It is active in the field of colossal magnetoresistance (CMR) since 1998. The team has extensive experience in deposition of high-quality HTS, CMR and buffer thin films by different methods, their characterization, processing and microfabrication for test device elaboration. The patterning of structures was accomplished by wet and dry etching, as well as ion-implantation. This group adopted the Optical Emission Spectroscopy (OES) for plasma diagnostics and monitoring the technological processes. The Laboratory has successfully accomplished in 1998 a multinational, three-year Copernicus Initiative project CIPA-CT94-01193 "Fabrication and application of high-Tc superconducting thin films for high performance circuits". A special technique was developed for magnetron sputtering of manganese ferrite targets. Furthermore, the spin polarized electron injection in CMR/insulator/HTS heterostructures is under investigation.

The Romanian team (co-applicant #3 M. Apostol) belongs to the Condensed Matter Physics group at the Institute of Atomic Physics, Magurele-Bucharest. This group performs basic research in the theory of condensed matter physics and related fields. The team participating to this proposal consists of two members of this group (M. Apostol and L. C. Cune). The main activity of the group focuses on high-temperature superconductivity, Fermi liquid, strongly-correlated electrons, Luttinger liquid, quasi-one-dimensional materials, electrons in magnetic field, superfluidity, atomic clusters, mesoscopic systems and nanostructures, transport theory. The group has developed an original theory of high-Tc superconductivity, derived the semi-phenomenological theory of the Fermi liquid from first principles, developed an original many-body scheme of treating the Hubbard model in one dimension, formulated the quasi-classical description for the Luttinger liquid and derived the zero-sound solitons, developed an electron-crystal model in one dimension, formulated the theory of four-fermion condensate (as a development of the general dynamics of the superfluid-like condensate wavefunctions). The priorities of the group at this moment are the self-consistent field approach to atomic clusters, and the transport theory in mesoscopic systems and nanostructures, with emphasis on nanowires and physical systems with a quasi-one-dimensional geometry.

The design of the device, the sample preparation and characterization, and the experimental measurements are assumed by the main applicant (applicant #1) and by co-applicant #2 within the present project. Their work will be guided and complemented by the theoretical work of co-applicant #3, which will be focused on the basic theory, the inclusion of spin-polarization and spin-scattering effects, and the interpretation of the experimental data.

2.2 Account of the State of Research in the Field

The transistor-like phenomenon at superconducting-normal metal junctions has recently been pointed out by a few researchers in the field of high-Tc superconducting materials with spin-polarization normal to ferromagnetic injectors. It has mainly been suggested that the phenomenon might successfully be used for accurate determinations of spin polarization. Devices based on the control of electric flow in the superconductor by injection of spins has also been suggested. This control can be performed either by a suitable doping of the superconducting contact, or by a change in the spin polarization of the injector, as brought about by a magnetic field. In the latter case one can hope to achieve a continuous fine tuning, and a field-controlled superconducting transistor (FIST) can be realized. The materials considered permit relatively high operating temperatures, tackle current issues of fundamental solid state research, and provide a wide temperature range for the characterization of the processes involved.

The experimental difficulties reside in the short coherence length of the high-Tc superconductivity materials, which impose constraints on the size and quality of the contacts, and in the spin-flip scattering at interfaces and magnetoresistive effects, related with the spin-diffusion length, which require an optimization of the nature, quality and geometry of the junction.

On the theoretical side, the transport at superconducting-normal metal junctions is based on the so-called Andreev reflection, originally devised for thermoconductivity, though, in principle, it is applicable to any other kind of transport. Consequently, the general theory has to be adapted for electric conduction, then generalized to spin-polarized injecting currents, and thereafter the optimal conditions must be determined for high-quality experimental data. Various other side effects, like steady waves, beats, interference, noise and non-linear effects must be estimated for a proper description and control of the experiment. In addition, magnetoresistive effects, as well as material transport through multiple conducting paths are to be addressed.

2.3 Account of Applicants' Research in the Field

The Lausanne group has used measurements of GMR as a function of the thickness of the layers in Co/Cu multilayers grown into nanopores to infer the spin diffusion length in the Cu layers. Similar work by another group has yielded the spin-diffusion length in the ferromagnet. In either case, it goes from a few nanometers to a few tens of nanometers. Later, the Lausanne group succeded in producing tunnel junctions inside the nanopores. It has also obtained tunnel junction between nanowires and an oxidizing metal sputtered on the membranes (unpublished results). This would be precisely the geometry used to measure spin polarization by tunneling from a ferromagnet into a superconductor. NMR was used to study, first the crystalline microstructure, then magnetic excitations in Co and Co multilayers. Another line of research of the Lausanne group has been the study of the effect of spin-polarized currents on the magnetization of nanostructures. A strong current was shown to induce irreversible magnetization reversal in Co nanowires. Further work is under way to demonstrate that the effect is not an artifact due to spurious heating of the wire by the current or by the field induced by the current. It will be necessary to use materials such as manganites, whose conduction electrons are known to have highly polarized spins. We will need a manganite layer on top of our membranes for these experiments.

Co-applicant #2 has developed a special technique for magnetron sputtering of La-Sr-Mn-O (LSCMO) ferrite manganese targets. Our investigation till now comprised deposition of LSMO and LCMO thin film manganese on single crystals and on polycrystalline substrates (Si/YSZ or

Si/MgO). We found that the Curie temperature decreases with increasing mismatch between manganese film and substrate, as well as with increasing the stresses in the film. The conductance in these films, explained by Zener by a double exchange mechanism, involves the simultaneous transfer of an electron from the Mn3+ to the oxygen and from the O2- to the neighboring Mn4+, if the spins of the two d shells are parallel. That is the basic reason for the high degree of spin polarization in these materials and we use them at the moment for spin oriented electron injection in YBCO superconducting thin films. This group adopted the technique of DC magnetron sputtering with two opposed targets for deposition of high-quality epitaxial YBCO films. The deposition conditions were controlled by optical spectroscopy, which monitored the plasma content of atomic oxygen. The optical emission spectroscopic measurements during YBCO thin film sputter deposition process aimed at stabilization of discharge parameters and lowering the deposition temperature. The oxygen dissociation by catalytic effect of small additions of trace gases to the Ar/O2 sputtering gas was studied.

Co-applicant #3 developed an original theory of high-Tc superconductivity, whereby, among others, the dependence of the superconducting properties on the dopant concentration is included. This theory identifies the strongly-correlated character of the high-Tc superconducting electrons (holes), as well as the strong local interaction between charge carriers and vibration spectrum of the oxygen cages in high-Tc materials. The results will be useful for accounting for the experimental data obtained within the present project. This applicant formulated the theory of four-fermion condensate, where the dynamics of the condensate wavefunction and of the superfluid-like gap has been studied within a more general frame. Superconducting correlations have been treated in this previous work by means of coupled-gap equations between two types of superconducting pairs; the corresponding general theoretical setting will be used in the present project, in order to derive for the Andreev reflection the coupled Gorkov-Bogoljubov-deGennes equations for the superconducting gap. The experience gained by co-applicant #3 in the theory of the Fermi liquid, and the transport in quasi-one-dimensional materials, as well as in the dynamics of the electrons in magnetic field, will also be employed for generalizing the Andreev reflection to spin-polarized currents in linear geometries, and for estimating the spin-flip scattering and magnetoresistive effects. The previous work of co-applicant #3 in this direction pertains to the derivation of the semi-phenomenological Landau theory of the Fermi liquid from basic principles, the effects of lower dimensionality, and the quasi-classical description of the Hall effect in layered geometries, including the field-induced spin-density wave in Bechgaard salts. The additional peculiar effects related to the transport in mesoscopic systems and one-dimensional nanowires, which occur in the project, will be treated by making use of co-applicant #3's previous work in quasi-one-dimensional materials, Luttinger liquid and transport theory, whereby noise, interface scattering, Casimir conduction and finite-size effects have been estimated.

3 Research Plan

3.1 Objectives

On the experimental side the objectives are:

1. To develop the technological precursors which will enable us to use high electron spin polarization of some ferromagnetic metals and compounds, like perovskite manganese, for fabricating spin-polarized injection devices. Based on published literature and on our own original ideas and preliminary test experiments, we will select a promising design of the test structures;

2. To implement the materials processing methods and to set up the measurements of transport in high-Tc superconductors - ferromagnet heterostructures;

3. To study the impact of spin injection from different ferromagnetic materials on the superconductor and the Andreev reflexion at the superconductor/ferromagnet interface;

On the theoretical side the project's objectives are:

4. Adapting the theory of Andreev's reflection to electrical conduction and reviewing the basics of electrical transport at superconducting-normal metal junctions; the change in the electron density at the Fermi level are to be estimated, as function of the voltage bias across the sample, and the general formula for electric resistance, both positive-and negative-valued, are to be derived for a linear geometry; at the same time, the possibility will be assessed of general by-side phenomena, like interference, backscattering and spin-flip scattering, especially at the junction's interface;

5. Generalization of Andreev's reflection theory to spin-polarized injection currents, based on previous work reported in the literature; the density of states at the Fermi level will be derived for arbitrary values of spin polarization, as determined by an external magnetic field, either in normal metals or ferromagnets; special emphasis will be put on the spin-flip disruption of Cooper pairs, and on the theory of the two coupled spin-polarized electric currents flowing through a superconducting contact;

6. Optimization of the device geometry by estimating the various side effects, like interface spin-flip scattering, magnetoresistance, interference, finite size-effects, noise and non-linearities; interpretation of the experimental data.

3.2 Scientific and Technical Description

The first main task (1) of the project consists in preparing the adequate superconducting samples and spin-polarized injectors, with special emphasis on their high-quality matching.

This will require preliminary optimization of the deposition conditions in order to preserve the high quality of the superconducting films down to small thicknesses (especially in multilayer structures), as well as of the barrier and injector films. For this purpose experiments aimed at reducing the deposition temperature will be carried out based on additional oxygen atomization by different optical, plasma and plasma-chemical methods. The atomic oxygen concentration will be monitored by Optical Emission Spectroscopy (OES). The films will be characterized by resistive and inductive transport measurements, XRD and SEM. The lithographic technique will be further developed, in order to achieve smaller pattern dimensions. Where appropriate, facilities of other laboratories in the collaborating institutions will be used, in particular the SQUID magnetometer at Lausanne. It will be useful for the characterization of both the superconducting films and the magnetic layers.

The Lausanne group is particularly interested in achieving electrodeposition of superconducting metals (ferromagnetic or superconducting). The electrodeposition of superconducting BaKBiO3 was recently achieved and constitutes an interesting alternative. Anaqueous electrolytes will be necessary in order to respect chemical compatibility with the sensitive HTS surface. Electrodeposition is a low cost method which is easily transferable to partner institutions. The second main task (2) is the choice of the adequate geometry for carrying out the tests, and the calibration of the experimental set-ups.

Two types of structure geometry will be implemented: first, spin-oriented electron injection in the same plane of the superconducting film from closely situated ferromagnetic injector contacts, and second, sandwich structures with a thin superconducting layer between the injectors. The injectors might be either long narrow thin film strips or nanowires in insulating medium. The third main task (3) is the experimental measurements of spin-polarization by Andreev's effect at the superconducting-ferromagnetic junction. The effect of the spin injection on the superconductor critical current will be studied.

At the same time, the theoretical side of the project will be developed, according to its objectives (4)-(6) described before. The reformulation of Andreev's reflection theory for electric conduction (task (4)), as well as its generalization to spin-polarized currents (task (5)) are original elements of the project; this enterprise requires a thorough investigation of the basic elements of the theory, starting from the ab-initio principles of quantum phase transitions, superfluid-like gap dynamics, and transport theory in mesoscopic and nanostructures; however, these objectives are feasible, in view of the fact that Andreev's reflection theory has already been illustrated for thermal conduction, and the possibility of the superconducting transistor-like phenomenon has been pointed out as well. Difficulties are expected with the strongly-correlated character of the superconducting charge carriers in high-Tc materials, which, however, may be overcome by using the previous experience of the teams in this field of research; in principle, these difficulties are related with the short coherence length, the unusual dependence of the gap on the sample depth at the contact interface, and also the general dependence of the superconducting gap on the sample doping. Another possible difficulty will be related to an adequate density of states at the Fermi level in the spin-polarized injector, and its dependence on the magnetic field; as well as with an adequate spin-diffusion length; the experience of the teams in Fermi liquid theory, magnetoresistive phenomena and transport theory are assets for a successful investigation of this problem. In addition, the investigation of the role played by the spin-flip scattering of charge carriers at interfaces in the electric transport within the general basic theory of Andreev's reflection is another element of originality, whose treatment will be carried out by means of the electron dynamics in one-dimensional conductors. The optimization of the device, and the various test modellings will be performed on the basis of similar enterprises reported recently in the literature.

The milestones (a) through (f) are included in the Planning section, and correspond to the completion of the objectives (numbered 1 through 6).

3.3 Co-Ordination and Management

Superconducting samples will be prepared at Sofia, and tested at Lausanne. Characterization by magnetometry will be performed with the main applicant (#1) group at Lausanne, where the co-applicant #2 will pay 4 visits. Transport measurements can be performed at Sofia or at Lausanne.

The theoretical work will mainly be carried out at Magurele-Bucharest by co-applicant #3, and a visit will be paid by co-appliacnt #3 at Sofia and Lausanne at the middle of the second year in order to establish the final way of attack of the problem, out of several other hypotheses and proposals devised till then. Computing facilities acquisition of co-applicant #3 will be finalized till the beginning of the second year, such as the testing, modelling and optimization process can begin for the final stage of the project. Grants start to be paid to co-applicant #3 from the beginning of the project, in order to ensure the continuity of investigation.

3.4 Valorisation

The results of the investigation will be published in scientific journals specialized in the field. They will also be discussed and analyzed within group's meetings, involving the collaborative contacts of the group, as specified in the project's application form. Pending on the degree of attainment of the technical requirements for a practical device, a patent application may be filled.

4 Significance of Planned Work

4.1 Scientific Significance

The scientific significance of the results consists in the demonstration of the possibility of a practical device with transistor-like effect controlled by charge-carriers spin-polarization; in the generalization of Andreev's reflection to spin-injecting junctions, which is a basic topic; and in the assessment of the much-troubling phenomenon which is the spin-flip scattering at the interfaces, and the related and by-side effects, as described in the project.

4.2 Significance for Transition

The success of the project will help to proving, to unbelievers of both inside and outside, the still existing strength and capacity of the scientific and technical potential in East-European countries like Bulgaria and Romania; it will help to proving the accordance and high-quality matching between such countries and Western Europe countries, like Switzerland, thus demonstrating that countries like Bulgaria and Romania are already, and have been since long, scientifically, technically, and culturally "inside Europe"; and that the remaining inadequacy issues are politicians' problems of both sides; an issue to be possibly addressed within the European Community and Union.

4.3 Significance for Strengthening Research Capacities

The experience gained in carrying out the project will help in tackling other modern issues in quantum electronics, materials science and theoretical physics. The test, modeling and optimization procedures described in the project may represent examples of original problems of modern research in class, and might be proposed as such to students for practical work; the basics of Andreev's reflection represent an attractive example of theoretical quantum electronics in condensates, and may be used to this end in class too; young scientists may find a good problem of research in quantum transport in superfluid-like condensates for their MSc or PhD degrees. The financial and organizational support is however essential in such enterprises.