Superconductivity Research and Development in the Ukraine

Summarized and collected by

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***Abstract* – Overview of superconductivity R&D activities in the Ukraine, with contributions from: Mikhail A. Belogolovskii on proximity-effect theory for an inhomogeneous Fe-based superconductor, Nickolay Cherpak on the experimental study of microwave impedance response of superconducting BaFeCoAs and FeSeTe composites, Alexander M. Gabovich on calculations of the stationary Josephson tunnel current for junctions made of superconductors partially gapped by biaxial or unidirectional charge density waves (CDW) and possessing a superconducting order parameter of d-wave symmetry, Alexander A. Kordyuk on correlation of electronic band structure with superconductivity in iron based superconductors, and Tatiana A. Prikhna on the distribution of nanostructural inhomogeneities acting as pinning centers in MgB_2 materials and thus affecting their critical current density**.

***Keywords* –Ukrainian superconductivity research, proximity effect, inhomogeneous superconductor, microwave impedance, iron-based superconductor, BaFe,CoAs, FeSeTe, tunneling current, charge density wave, band structure, bulk MgB_2, pinning in MgB_2**

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I. PREAMBLE

Before the discovery of the high temperature superconductors, research in the field of superconductivity was among the top secrets of the Soviet Union. Then, starting from 1986, practically in every research institution, university or company having physical, chemical or technical background, superconductivity was sustainably developed and considered to be of first priority at least for about five years (and happily became absolutely unclassified in the Soviet Union and then in the Ukraine). Declassification, close communications and cooperation with the progressive world scientific community promoted intensive development of superconductivity in the Ukraine. After the Ukraine attained independence, the Ukrainian scientific authorities considered superconductivity as a direction which could promote a fast input and support to the economy of the young country. However, after the first waves of the “superconductive euphoria” decreased, it was decided to restrict the financing of superconductivity in the Ukraine, especially the research targeted towards the development of new technologies and materials. Thus many Ukrainian scientists tried to shift their scientific interests towards other subjects. But it seems that superconductivity is like the first love: never disappears once it touched your heart.

II. OVERVIEW OF ACTIVITIES

At present, research in the field of superconductivity is conducted in many scientific establishments of the Ukraine, among which are:

1. **Bogolyubov Institute for Theoretical Physics of the National Academy of Sciences of Ukraine, Kiev, Ukraine:**

   Field of research: theory of superconductivity, theory of high-temperature superconductivity, theory of the coexistence of magnetism and superconductivity (V.M.Loktev).

2. **Institute of Metal Physics of the National Academy of Sciences of Ukraine named after G.V. Kurdyumov, Kiev, Ukraine**:

   Field of research:

- Mechanisms of superconductivity in HTS cuprates and iron based superconductors, search for new superconducting materials. ARPES on HTS and other 2D metals: electronic properties derived from the electronic structure, interplay with density waves. (A. A. Kordyuk)
- Electrodynamics of superconductors, theory and experiment. PLD of HTS films with controlled nanostructure for electrical transport and high frequency applications. (A. L. Kasatkin)
- Applications of superconducting levitation: detectors, motors, flywheels. (A. A. Kordyuk)
- Physics of Josephson junctions, development and creation of Josephson junctions based on multi-zone and high-temperature superconductors with different distribution functions transparencies (V. E. Shaternik)
- Study physics of tunnel junctions based superconductors and ferromagnets (E. M. Rudenko).

3. **Institute of Physics of the National Academy of Sciences of Ukraine, Kiev, Ukraine**

   Field of research:

- Magnetic phenomena in high-temperature superconductors. (S. M. Ryabchenko)
- Theory of solid state and high-temperature superconductivity: symmetry and anisotropy of the order parameter, the anomalous thermal conductivity, concentration dependencies of the critical temperature and isotopic shift, influence of the macroscopic lattice defects on T_c and critical current. (E. A. Pashitsky)
- Superconducting materials with anomalously small charge density. Theory of interaction of superconductivity and charge density waves. Theory of weakly coupled superconductors and Josephson junctions based on high-temperature superconductors and multiband superconductors (A. M. Gabovich, and V. M. Voytenko).

4. **V.M. Glushkov Institute of Cybernetics of the National Academy of Sciences of Ukraine, Kiev, Ukraine**

   Field of research:

Research and development of systems based on Josephson junctions and SQUIDs **(**I.D.Voytovich)

5. Institute for Superhard Materials of the National Academy of Sciences of Ukraine, Kiev, Ukraine

Field of research:

Study of the pressure (up to 5 GPa) - temperature effect on manufacturing process, structure and properties of MgB_2 bulk and wires, and melt-textured $YBa_2Cu_3O_{7-\delta}$-based materials. Investigation of optimized efficiencies of materials for applications in electromotors, generators, pumps, magnetic bearings, and fault current limiters. (T. A. Prikhna).

6. Taras Shevchenko National University of Kyiv

Field of research:

- Investigation of nonlinear properties of superconducting films; theory and application of superconducting microwave devices. (http://www.ewh.ieee.org/tc/csc/europe/europeguide/TarasShevchenko.html)
- Study of physics of Josephson junctions with different distribution functions of transparency, under the influence of microwave electromagnetic radiation (G.A. Melkov).

7. B. I. Verkin Institute for Low Temperature Physics and Engineering of the National Academy of Sciences of Ukraine, Kharkov, Ukraine

Field of research:

- Macroscopic quantum phenomena in weakly coupled superconductors with applications to SQUID's. Theory of Josephson effect in point contacts and microbridges, superconducting qubits (A. N. Omel'yanchuk)
- Research and development of superconducting qubits (V.I. Shnyrkov)
- Spectroscopy of high-temperature superconductors. (V. N. Samovarov)
- Theoretical investigations of magnetic properties of new iron-based superconductors. Magnetostriction in magnetic and superconducting compounds. (G. E. Grechnev)
- X-ray investigations of magnetic materials and superconductors. (V. A. Sirenko)
- Point-contact spectroscopy of the electron-phonon and electron-quasiparticle interaction in high-temperature superconductors. Transport phenomena in normal metals and superconductors. (Yu. G. Naydyuk)
- H-T phase diagrams, vortex pinning, critical states, and flux creep in type-II superconductors. (G. P. Mikitik)
- Research and development of systems based on Josephson junctions and SQUIDs (S. I. Bondarenko).

8. O.Ya. Usikov Institute for Radiophysics and Electronics of the NASU, Kharkov, Ukraine

Field of research:

- Theory of propagation and interaction of microwave electromagnetic radiation in systems based on superconductors, high-temperature superconductors and multizone superconductors (V.A. Yampolsky)
- Study of the properties of superconductors and unusual superconductors based on the results of experimental measurements of the temperature dependence of the surface impedance of the superconductors under microwave irradiation (N.T. Cherpak).

9. Donetsk Institute for Physics and Engineering named after O.O. Galkin of the National Academy of Sciences of Ukraine, Donetsk, Ukraine

Field of research:

- Dynamic and static properties of complex systems in the external fields. Theory of a non-stationary electron transport in superconductor heterostructures. (Y. G. Pashkevich)
- Theory of tunnel junctions and Josephson junctions based on superconductors, high-temperature superconductors and multizone superconductors. (M.A.Belogolovsky)
- Theory of tunne junctions and Josephson junctions based on ferromagnetics and high-temperature superconductors and multizone superconductors (V.M.Krivoruchko)
- Experimental studies of tunnel junctions based superconductors, high-temperature superconductors and multizone superconductors (V. Yu. Tarenkov)
- Magnetic, galvanomagnetic, impedance and magnetostriction properties of superconducting and magnetoresistive materials, the critical state of superconductors, stability and dynamics of their destruction (V.V.Chabanenko).

10. National Science Center Kharkov Institute of Physics and Technology, Kharkov, Ukraine

Field of research:
Synthesis of oxide high-temperature superconductors and medium-temperature superconductors. Structure of HTS. Electrical, magnetic and relaxation properties of HTS. Effect of irradiation on structure and properties of MgB_2. Creation of switching and logical elements on the basis of HTS. **(**V.A. Finkel**).**

11. V. N. Karazin Kharkiv National University, Department of Physics

- Magnetic flux dynamics in YBCO single crystals. Scattering of electrons and phonons in spatially inhomogeneous systems, including high temperature superconductors. Plastic flow processes and the formation of defect structure during loading of metals in the normal and superconducting states. (R. V. Vovk).

12. Institute for Condensed Matter Physics of NASU, Lviv

- Research into fundamental properties of high-$T_c$materials, theoretical engineering of high-T_c electronic devices. (N. Pavlenko)
- Analytical methods in the theory of strongly correlated electronic systems including high temperature superconductors (I. V. Stasyuk).

III. SELECTED RECENT HIGHLIGHTS

To this overview, recent scientific highlights obtained in the field of superconductivity are added. Further noteworthy studies and results from Ukrainian researchers will be published in forthcoming issues of SNF. Deviating from the standard SNF practice, we provide full official titles of authors.

A. *Calculations of Band Structure in Iron-based Superconductors*

Prof. Dr. Alexander Kordyuk, DSc in Superconductivity, Corresponding Member of the National Academy of Sciences of Ukraine, Head of Department of Superconductivity at the Institute of Metal Physics of the National Academy of Sciences of Ukraine (kordyuk@gmail.com, http://www.imp.kiev.ua/~kord).

The iron based superconductors (FeSC) promise interesting physics and applications, and, while the interplay of superconductivity and magnetism, as well as their mechanisms remain the issues of active debates and studies, one thing in the FeSC puzzle is clear, namely that it is the complex multi-band electronic structure of these compounds that determines their rich and puzzling properties [1]. What is important and fascinating is that this complexity seems to play a positive role in the struggle for understanding the FeSC physics and also for search of the materials with higher T_c's. This is because the multiple electronic bands and resulting complex fermiology offer an exceptionally rich playground for establishing useful empirical correlations. This is also because this electronic structure is well understood - the band structure calculations well reproduce its complexity: all the bands and their symmetry. As Alexander Kordyuk (Institute of Metal Physics) analyzes, the role of the experiment, in this case, is just to define the exact position and renormalization for each band. This piece of experimental knowledge, however, appears to be vitally important for an understanding of the electronic properties of these new compounds. Considering all the electronic band structures of FeSCs that can be derived from ARPES [3], it has been found that the Fermi surface of every optimally doped compound (the compounds with highest T_c) has the Van Hove singularities of the Fe $3d_{xz/yz}$ bands in the vicinity to the Fermi level [1, 2]. This suggests that the proximity to an electronic topological transition, known as Lifshitz transition, for one of the multiple Fermi surfaces makes the superconductivity dome at the phase diagram. Based on this empirical observation, one can predict, in particular, that the hole overdoping of KFe_2As_2 and LiFeAs compounds is a possible way to increase the T_c.

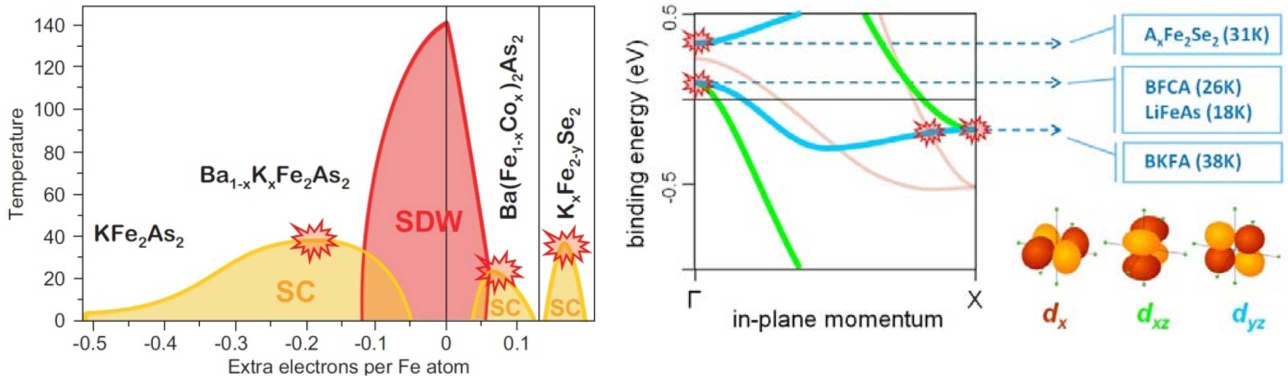

Fig. 1. Phase diagram of the 122 family complemented by the 122(Se) family as a generalized band structure driven diagram for FeSCs (left) and common electronic band structure of the FeSCs (right): the compounds with highest T_c has either top or bottom of the Fe $3d_{xz/yz}$ bands crossing the Fermi level (the orbital character of the bands marked by different colors, as shown in the inset) [1, 2].

1. A. A. Kordyuk, *Low Temp. Phys.* **38**, 888 (2012).
2. A. A. Kordyuk et al., *J. Supercond. Nov. Magn.* **26**, 2837 (2013).
3. A. A. Kordyuk, Complex electronic structure of iron based superconductors as a key to high temperature superconductivity, *1st Trilateral workshop on Hot Topics in HTSC: Fe-Based Superconductors*, Zvenigorod, 2013, http://hts-2013.lebedev.ru/data/presentations-pdf/MO/2/Kordyuk.pdf

B. Microwave Impedance Measurements on Iron-based Superconductors

Prof. Dr. Sci. (in Physics and Mathematics) Nickolay Cherpak, O. Ya. Usikov Institute for Radiophysics and Electronics, the National Academy of Sciences of Ukraine,
cherpak@ire.kharkov.ua

In the work of the research team, lead by Nickolay Cherpak, two sapphire cavity types have been used for microwave (MW) measurements, namely, a TE011-mode cylindrical cavity with hot-finger (jointly with IOP CAS) and quasi-optical resonator, which operated in X- and Ka-bands accordingly. The original quasi-optical resonator has a radial slot with a small unconventional SC sample under test and cuprate HTS conducting endplates (Fig.1). The work is devoted to a survey of the results obtained by the authors on the experimental study of the MW impedance response of superconducting BaFeCoAs and FeSeTe composites. The work was carried out in collaboration with M. Tanatar and R. Prozorov et al. (Iowa State University and Ames Laboratory, Ames, US) and Y.-S. He et al. (Institute of Physics, CAS, Beijing, China). The complex conductivity of the composites was obtained as function of temperature. Exponents n=2.8 and n=2.4 in $\Delta\lambda(T) \sim T^n$ were found for $Ba(Fe_{1-x}Co_x)_2As_2$ (x=0.074) and $FeSe_{0\cdot3}Te_{0.7}$ accordingly. The results support the extended s-pairing symmetry (i.e. s± symmetry) with pair breaking scattering. The data show sharp decrease with T of the scattering rate $\tau^{-1}(T)$.

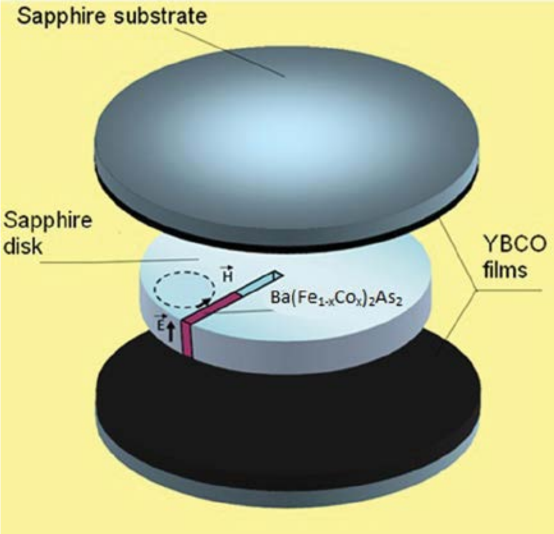

Fig. 1. (Color online) Schematics of the slotted sapphire disk resonator experiment. The sapphire disk with a single crystal of $Ba(Fe_{1-x}Co_x)_2As_2$ placed in the slot is sandwiched between superconducting $YBa_2Cu_3O_7$ film end plates. Whispering gallery mode excitation at a *Ka* band frequency (35 to 40 GHz) produces an electric field *E* parallel to the conducting plane of the sample, enabling measurements of in-plane surface impedance.

C. *Tunneling Current Calculations in Junctions of d-Wave Superconductors in Presence of Charge Density Waves*

Prof. Dr. Sci. (in Physics and Mathematics), Alexander Gabovich, Institute of Physics of the Ukrainian National Academy of Sciences, alexander.gabovich@gmail.com

The stationary Josephson tunnel current I_c was calculated by Alexander Gabovich (Institute of Physics of the Ukrainian National Academy of Sciences) for junctions made of superconductors partially gapped by biaxial or unidirectional charge density waves (CDW) and possessing a superconducting order parameter of d-wave symmetry. Specific calculations were carried out for symmetric junctions between two identical CDW superconducting electrodes and non-symmetric ones composed of a CDW superconductor and a conventional isotropic s-wave superconductor. The directionality of tunneling was made allowance for. In all studied cases, the dependences of I_c on the angle γ between the chosen crystal direction and the normal to the junction plane were found to be significantly influenced by CDW. It was shown, in particular, that the d-wave driven periodicity of $I_c(\gamma)$ in the CDW-free case is transformed into double-period beatings depending on the parameters of the system. The results of calculation testify that the orientation-dependent patterns $I_c(\gamma)$ measured for CDW superconductors allow the CDW configuration (unidirectional or checkerboard) and the symmetry of superconducting parameter to be determined. It was shown that when CDW are absent or weak, there exists an approximate proportionality between $I_c(x)$ and the product of superconducting energy gaps $\Delta(x)$ and $\Delta(x')$ to the left and to the right of the tunnel barrier. Here, x is either the reduced temperature, T/T_c, where T_c is the critical temperature of the superconducting transition, or one of the parameters characterizing the combined CDW superconducting phase. However, provided a high directionality of tunneling, CDWs may violate the law of corresponding states. The proposed method is an additional one to detect CDWs in cuprates along with the measurements of $I_c(\gamma)$ dependences.

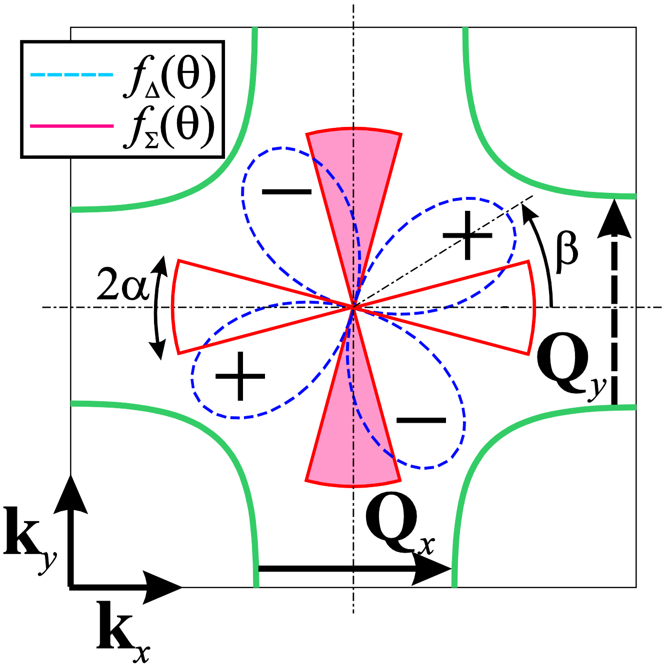

Fig. 1. Schematic diagram of the two-dimensional Fermi surface appropriate to cuprates and angular profiles of the *d*-wave superconducting, $f_\Delta(\theta)$, and dielectric, $f_\Sigma(\theta)$, order parameters. Charge-density waves (CDWs) are described by two, $\mathbf{Q}_x$ and $\mathbf{Q}_y$, or one, $\mathbf{Q}_x$, CDW vectors. The corresponding CDW configuration function $f_\Sigma(\theta)$ possesses either two or one (non-tinted), respectively, sector pairs. 2α is a CDW sector opening, and β is a mismatch angle between superconducting lobes and CDW sectors.

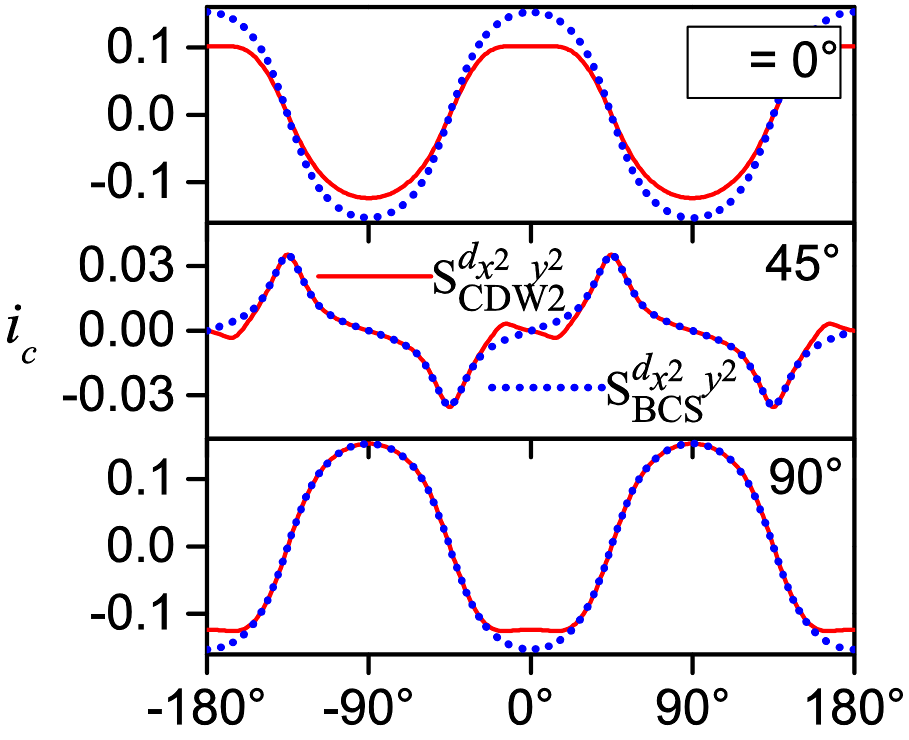

Fig. 2. Dependences $i_c(\gamma)$ for symmetrical superconducting-CDW$_2$ and symmetrical-d-BCS junctions for the CDWS superconductor and its *d*-wave BCS counterpart and various γ' angles. Here i_c is the normalized Josephson current, γ

and γ' are the angles between the left-hand-side and right-hand-side crystal lattices and the normal to the junction plane.

D. *Proximity Effect Theory for Inhomogeneous Iron-based Superconductors*

Dr. Sci. (in Physics and Mathematics) Mikhail A. Belogolovskii, Donetsk Institute for Physics and Engineering, National Academy of Science of Ukraine, Donetsk 83114, Ukraine, bel@fti.dn.ua

Striking difference between reasonable gap values extracted from point-contact measurements with a normal-state counter electrode and extremely small products I_cR_N inferred from Josephson-junction experiments is one of the challenge results obtained recently for novel iron-based superconductors. M. Belogolovskii suggests to attribute the unexpected suppression of the supercurrent in Josephson junctions to the presence of alternating conducting regions with antiferromagnetic metallic (AFM) and superconducting (S) orderings in the Fe-based electrodes.

Up-to-date studies of iron pnictides and selenides showed various forms of coexistence between superconductivity and magnetism. In some materials, superconductivity and incommensurate antiferromagnetism coexist at the atomic level. In other compounds, superconducting clusters appear inside an antiferromagnetic background or the two electron orderings are separated in nanometer-thick alternate layers. Although such phase separation has been observed in some cuprates as well, the essential difference between the two high-T_c families resides in the fact that undoped, parent compounds of cuprates are antiferromagnetic insulators, whereas Fe-based superconductors derive from magnetic-metal parent compounds.

M. Belogolovskii has developed a proximity-effect theory for an inhomogeneous superconductor consisting of S and AFM ultra-small regions with incoherent single-particle scattering between them. Magnetic ordering in the AFM part of the system is described by a generalised Stoner model where an itinerant-electron antiferromagnet is regarded as two identical ferromagnetic sublattices which interpenetrate so that spins on one sublattice are exactly opposed by those on the other. Through proximity effect between the superconductor and the antiferromagnetic metal, pairing correlations between electrons are delivered from superconducting regions to the AFM ones and a minigap is induced there. But, in contrast to the conventional proximity phenomenon in N/S heterogeneous systems, the density of states of an AFM layer is spin-splitted due to the presence of internal magnetic fields (similar to the well-known Meservey-Tedrow effect). As a result, in the AFM/S system, there is a single unified gap which is much smaller than that in a separated S metal. It causes strong suppression of the Josephson current which, as well known, is sensitive to the real gap value in superconducting electrodes. Unlike the Josephson effect, quasiparticle tunneling and point-contact techniques provide an information about the shape of the energy dependence of the S-layer spectrum which contains a comparatively strong feature reminding about singularity in a separated superconductor. Just this circumstance, according to M. Belogolovskii, is the origin of a striking discrepancy between the “gap values” inferred from point-contact and Josephson data. Only the latter one is the real gap in the inhomogeneous AFM/S system. Numerical simulations performed by him support this explanation.

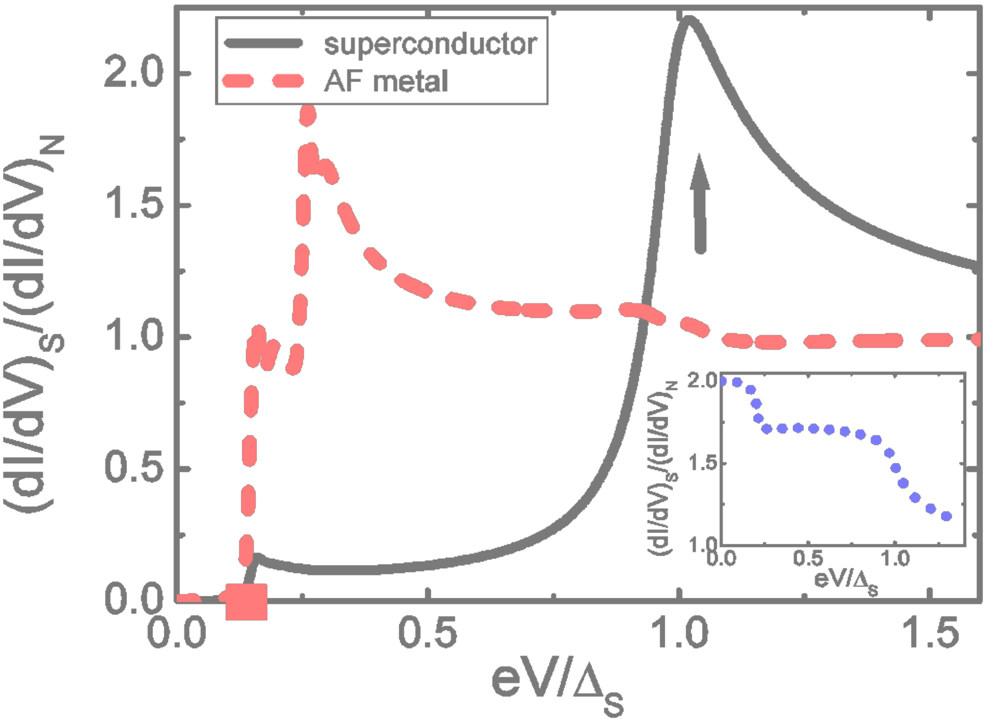

Fig. 1. Illustration of the proximity effect in a system of superconducting and antiferromagnetic metal regions with a fixed incoherent single-particle scattering between them. The main panel shows densities of quasipartice states in the two regions; the square indicates the unified gap value whereas the arrow points to the reminder of the energy gap in a separated superconductor. The inset shows an expected point-contact characteristic.

E. *Nanostructural Inhomogeneities Acting as Pinning Centers in Bulk MgB_2*

Prof. Dr. T. A. Prikhna, Corresponding Member of the National Academy of Sciences of Ukraine, Head of Department "Technologies of Superhigh Pressures, Functional Structured Ceramic Composites and Dispersed Nanomaterials" of the Institute for Superhard Materials of the National Academy of Sciences of Ukraine, 2 Avtozavodskaya Street, Kiev, 04074, Ukraine,
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The distribution of nanostructural inhomogeneities, such as areas with a high concentration of boron and impurity oxygen, plays a key role in the variation of j_c in MgB_2 materials prepared in a wide range of pressures (0.1 MPa - 2 GPa) and temperatures (600-1100 °C). The materials have 18-98% connectivity and 55-99% density. Auger and SEM studies show that with increasing manufacturing temperature oxygen enriched 15-20 nm thick nano-layers transform into distinct dispersed Mg-B-O inclusions (Fig.1). In parallel, the size of B-enriched (MgB_x, $x \geq 4$) inclusions is reduced at all pressures studied and j_c is enhanced at low and medium magnetic fields (as long as a near-MgB_2 matrix is preserved). In particular, the temperature increase at 2 GPa leads to a transformation of the $MgB_{1.2-2.7}O_{1.8-2.5}$ layers into separate grains of $MgB_{0.6-0.8}O_{0.8-0.9}$ and to a reduction of the $MgB_{11-13}O_{0.2-0.3}$ inclusions located in the MgB_2 ($MgB_{2.2-1.7}O_{0.4-0.6}$) matrix. j_c reaches about 1 MA/cm^2 at 20 K and 1 T. Boron and oxygen can enter the MgO and MgB_2 structures forming solid solutions. The contribution of point-like pinning centers to the total pinning force increases with increasing manufacturing temperature [1].

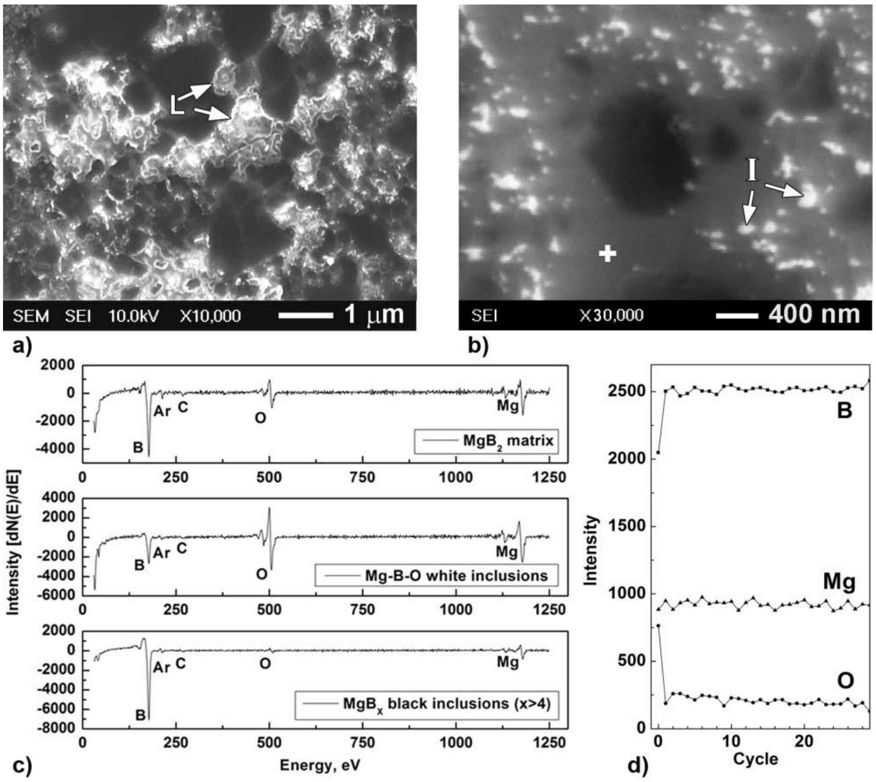

Fig. 1. (a), (b) SEM images SEI of MgB_2 materials synthesized from Mg:2B mixtures under 2 GPa, for 1 h at 800 and 1050 °C, respectively;
(c) Auger spectrum of the matrix ($MgB_{2.2-1.7}O_{0.4-0.6}$), white ($MgB_{0.6-0.8}O_{0.8-0.9}$) and black ($MgB_{11-13}O_{0.2-0.3}$) inclusions of MgB_2 from B(III), 2 GPa, 1050 °C, shown in Fig. 1b. The Ar spectrum is due to Ar gas used for etching. The C spectrum comes from C-deposition by the electron beam or from impurities in B;
(d) Depth profile of the amount of O, B and Mg in the MgB_2 matrix (at the spot marked "+" in Fig. 1b) obtained from quantitative Auger analysis and multiple etching in Ar (30 cycles for 10 s each); was analyzed to a depth of 200 -300 nm). As demonstrated in figure 1d the amount of O, B and Mg is practically unchanged indicating that oxygen was incorporated in the MgB_2 structure and formed a solid solution [1].

1. Nanostructural inhomogeneities acting as pinning centers in bulk MgB_2 with low and enhanced grain connectivity**,** T A Prikhna, M Eisterer, H W Weber, W Gawalek, V Kovylaev, M V Karpets, T V Basyk, V E Moshchil (*accepted for publication in SUST in 2014*)**.**