Purpose of the visit

Experimental study in screened environment the microwave properties of hybrid Josephson heterostructures with antiferromagnetic interlayer in connection with the recently observed giant magneto-oscillations of their critical current.

Description of the work carried out during the visit

Coexistence of superconducting and magnetic ordering in solids is of great interest for fundamental physical studies and electronic applications. At the interfaces between superconducting and magnetic materials superconducting and magnetic order parameters may interact resulting in interplay between superconducting and magnetic ordering [1]. Recently group from IRE RAS has reported [2, 3] on studies of $Nb/Au/Ca_{1-x}Sr_xCuO_2/YBa_2Cu_3O_{7-\delta}$ heterostructures with antiferromagnetic interlayer ($Ca_{1-x}Sr_xCuO_2$). Epitaxial thin films of $YBa_2Cu_3O_{7-\delta}$ and $Ca_{1-x}Sr_xCuO_2$ were grown by laser ablation on $NdGaO_3$ substrates. $Ca_{1-x}Sr_xCuO_2$ (x=0.15 or 0.5) interlayer films were approximately d=20, 50 and 75-100 nm thick. Preliminary measurements showed increase of superconducting current in these heterostructures in comparison with the case of $Nb/Au/YBa_2Cu_3O_{7-\delta}$ junctions without antiferromagnetic layer. Also was found that the critical current is very sensitive to external magnetic field, which could be explained by a theory [4] of giant magneto-oscillations of critical current in Josephson junction with antiferromagnetic barrier: $I_C(H) \approx I_C^0 (\frac{2}{\pi\beta M_S})^{1/2} \left|\cos(\beta M_S - \frac{\pi}{4})\right|$ (I_C^0 - critical current at zero field, β>>1 - parameter defined by thickness and energy spectrum of AF layer, $0<M_S<1$ is a parameter of antiferromagnetic ordering which depends on external magnetic field. Note, this is an additional physical mechanism to the usual magnetic flux dependence of I_C. At the same time it's well known that Josephson junctions driven far from equilibrium at microwave frequencies may demonstrate noticeable deviations of high frequency dynamical characteristics predicted by RSJ-model. In this connection a set of measurements of I-V characteristics under irradiation of electromagnetic field, along with the dc controlled applied H-field has been carried out. Experimental variables were microwave frequency f=45 GHz or 70 GHz with power controlled by precision attenuator in the range of α=0÷70 dB. Precisely measured by cooled HEMT amplifier high frequency noise emission has been used for heterostructures characterization as well.

Description of the main results obtained

Fig. 1 demonstrates a family of experimental I-V curves for a heterostructure with d=100 nm thick AF interlayer. For reason of good impedance matching with the cooled HEMT amplifier measurements were over 2-point, resulted in a series resistance of order of few mΩ. RSJ type autonomous I-V curves were registered without excess current. Integer Shapiro steps demonstrated behaviour usual for RSJ model. Very similar results were obtained for other samples. Fig.2 shows the 1st fundamental Shapiro step amplitude dependence and "textbook" maximal amplitude of I_1 for a sample with the same x and d - as on Fig.1, but with a different size. At the same time, half-integer Shapiro steps were registered which are seen for intermediate power levels in Fig.1. Note, appearance of half-integer Shapiro steps did not depend on variation of magnetic field. However, application of magnetic field sometimes resulted in a flux trapping and undesired distortions of I-V curves. Long lasting stable (against flux trapping) states were

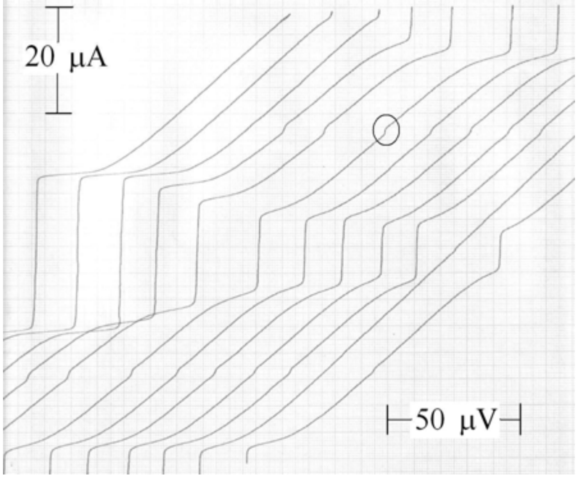

Fig.1. I-V curves for a heterostructure N1 with dimensions 40x40 μm², x=0.5, d=100 nm. f= 45.5 GHz, T=4.2K, B=0. Curves are shifted by V with power. A circle points half-integer Shapiro step.

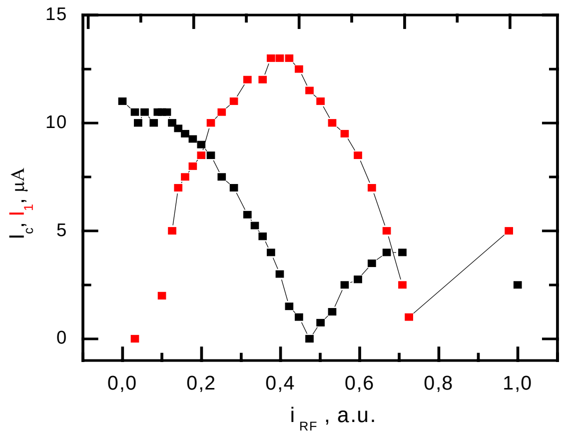

Fig.2. Critical current I_C and 1st Shapiro step amplitudes vs. microwave current i_{RF} at f=45.5 GHz for heterostructure N2 with 50x50 μm², x=0.5, d=100 nm, R_N=1.8 Ω. B=+19,4 μT has been applied to maximize the $I_C(i_{RF}=0)$.

more frequently observed for samples with smaller dimensions. Fig.3 shows well enough repeatable I-V curve for 20x20 μm² heterostructure under magnetic field where Fiske-like steps are seen. In order to register voltage position of the steps we used dependences (see Fig.3) of background thermal noise variation caused by changing of mismatch factor between heterostructure and the measuring amplifier. Distances between minima were ΔV=60 μV, giving an estimate for Swihart velocity of order c/250. The corresponding magnetic field dependence of critical current I_C is shown in Fig.4. A case of a flux trapping is also demonstrated in the inset, where I_C amplitudes are plotted under influence of microwave field at f=70 GHz.

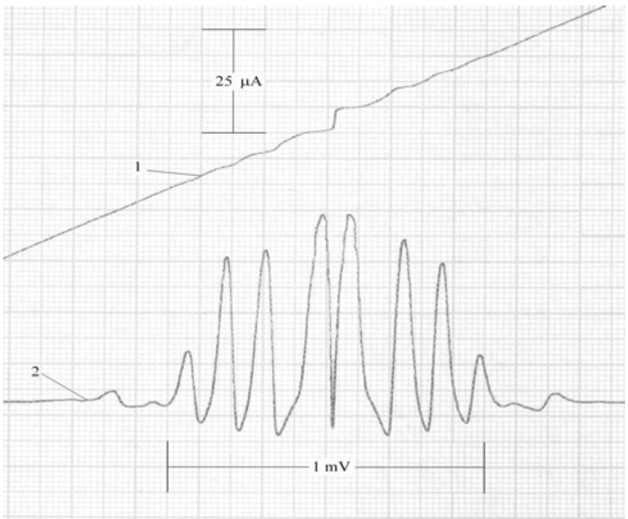

Fig.3. Magnetic field induced current steps on I-V curve (1) and background thermal noise (2) oscillations caused by change in impedance mismatch factor for heterostructure N3 with x=0.5, d=100 nm, S=20x20 μm², max I_C=7.6 μA, R_N=15 Ω at T=4.2K, B= -18.5 μT.

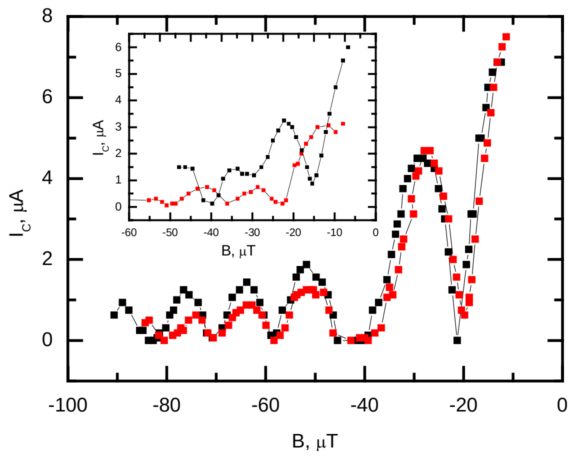

Fig. 4. Magnetic field dependence of critical current I_C for heterostructure N3. A typical difference between two runs is shown. Black points run correspond to the case shown on Fig.3. Inset shows distortion of $I_C(B)$ caused by a trapped flux (black points), red curve – when signal at f=70 GHz was applied.

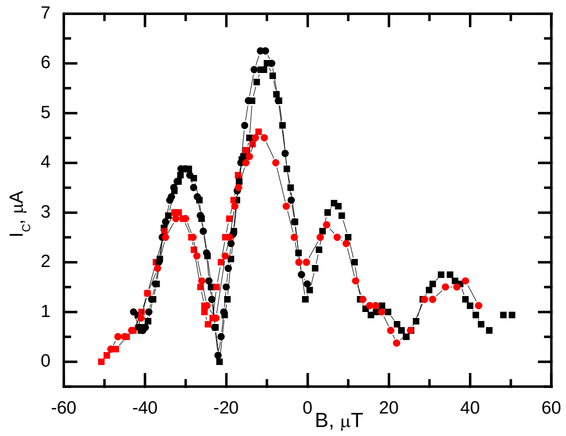

Fig. 5. Magnetic field dependence of critical current I_C for heterostructure N3. Black curves – two runs without microwave field. Red curves: under 70 GHz signal with power, corresponded to maximum of 1st Shapiro step.

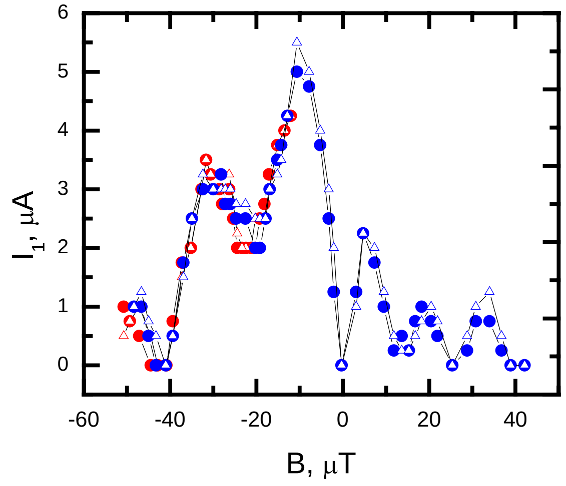

Fig. 6. Three independent runs for magnetic field dependences of the 1st Shapiro step amplitude for heterostructure N3 at the same experimental conditions as in Fig.5. Open symbols – right hand step (positive bias), filled symbols – left hand step (negative bias).

Magnetic field dependences of critical current I_C and the 1st Shapiro steps are shown in Fig.5 and Fig.6, correspondingly. Data in these figures indicate on very symmetric I_1 amplitudes at positive and negative biasing and at the same time asymmetric $I_C(B)$ and $I_1(B)$ waveforms. Note, maxI_C in Fig.5 is somewhat smaller than one registered before (Fig.4). Magnetic field dependences of critical current and Shapiro step amplitudes in Josephson junction was analyzed in [5] using RSJ model approach for two cases: current biasing and voltage biasing. Our case was current biasing at dc and near to current biasing at microwaves.

References:

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- Future collaboration with host institution

Long lasting collaboration between groups from DTU FYS and IREE RAS was already established many years ago. That significantly helps to minimize terms of technical and administrative preparations for specific measurements, planned for this project. In this connection we look optimistic for our future collaboration in the field of studies of novel interesting Josephson structures which will be designed and fabricated in IREE RAS and then experimentally investigated at DTU FYS.

- Projected publications/articles resulting or to result from your grant

New results along with the data, obtained in IREE RAS before visiting DTU, are currently analysed and discussed for preparation of a journal paper, as well for presentation to relevant international conferences/workshops.