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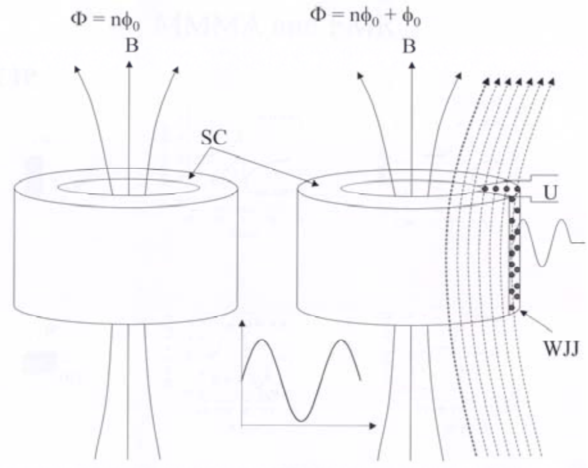
MICROWAVE ABSORPTION (MMMA) – A CONTACLESS METHOD TO STUDY SUPERCONDUCTORS AND MAGNETIC NANOSTRUCTURES

Magnetically Modulated Microwave Absorption (MMMA) is a sensitive differential method to study magnetoresistence related to the voltage fluctuation in nonhomogeneous superconducting systems with Josephson junctions (JS) and in magnetic systems exhibiting giant magnetoresistence (GMR). The MMMA method has been successfully established after the discovery of polycrystalline high temperature superconductors with high concentration of Josephson junctions. MMMA proved to be the third method besides resistivity and magnetic susceptibility measurements to determine critical temperature T_c. In magnetic nanostructures MMMA enables to determine GMR(H) and magnetization reversal.

Keywords: Josephson junction, microwave absorption, HTC nanostructure

1. INTRODUCTION

In superconductor (SC) electrons having properties of a Fermi liquid form Cooper pairs (CP) which, being bosons, below critical temperature T_c constitute a Bose-Einstein condensate (BEC). A metal in SC state displays vanished resistance. Quantum properties are displayed by a magnetic flux enclosed in a superconducting ring (Fig. 1a) in integral multiples: $\Phi = n\Phi_0$ ($\Phi_0 = h/2e = 2.067849 \cdot 10^{-15}$ Wb or V/Hz). Penetration of each flux through a weak Josephson contact (WJC) (Fig. 1b) gives rise to Josephson oscillations with a frequency $f = \Phi_0^{-1} U$, hence proportional to the voltage at the contact. Penetration of the fluxon through the ring gives microwave losses and the MMMA signal.



a) b)

Fig.1. a) superconducting ring can enclose magnetic flux Φ only in integral multiples of flux quantum Φ_0
b) penetration of a fluxon gives polarization U and electromagnetic wave emission at f_J [Hz] = 4.835941×10^{14} U[V].

Magnetic flux penetration into the network of WJC results in strong absorption of the a.c. field. An example of such a network is granular SC, YBCO. The MMMA method, due to the high sensitivity, can detect a single WJC or small (of nanoscopic size) regions in SC state.

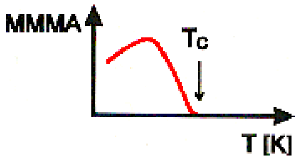


Fig.2. Josephson oscillations which appear at T_c constitute the third SC material property besides vanishing resistance and magnetic susceptibility anomaly. MMMA signal versus temperature allows determining T_c.

2. JOSEPHSON OSCILLATION – THE THIRD METHOD TO DETERMINE T_c

The most successful and a simple application of the MMMA method is for the determination of the critical temperature of superconductors (Fig. 2) [1-10]. Equation 1 will help to explain Josephson dissipation:

$$\langle U\rangle = R\,(\langle I\rangle^2 - I_C^2)^{1/2} \qquad (1)$$

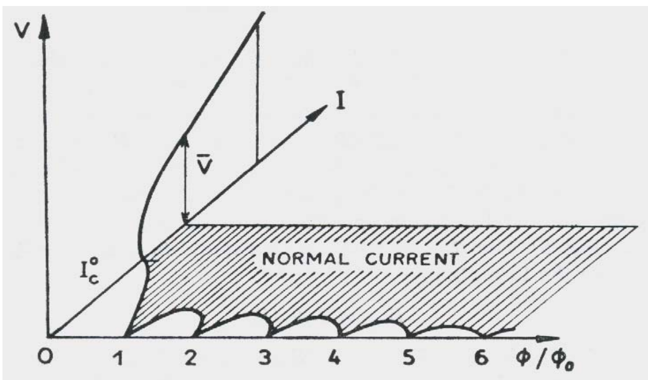


Fig. 3. Characteristics: current-voltage-magnetic field ($B = \Phi/S$, where S is the effective WJC surface).

When fluctuating current $\langle I\rangle$ in WJC exceeds a critical value I_c, $\langle U\rangle$ is the fluctuating voltage and R is resistivity of the junction. A very important characteristic is critical current dependence on the magnetic field (Fig. 3). Josephson absorption appears below T_c as a low field line with a maximum around 5 mT. This maximum corresponds to the first maximum ($n = 1$) of Josephson absorption in Fig. 3. In a polycrystalline material there is a large number of SC loops, each having a different surface S_i. Therefore, the shape of the signal comes from all loops; $B_{in} = n(\Phi_0/S_i)$. Because the amplitude for $n = 1$ is the highest, contribution from $n > 1$ has little effect on MMMA signal shape. A strong magnetic field can only shift microwave absorption.

3. MMMA SIGNAL DETECTION

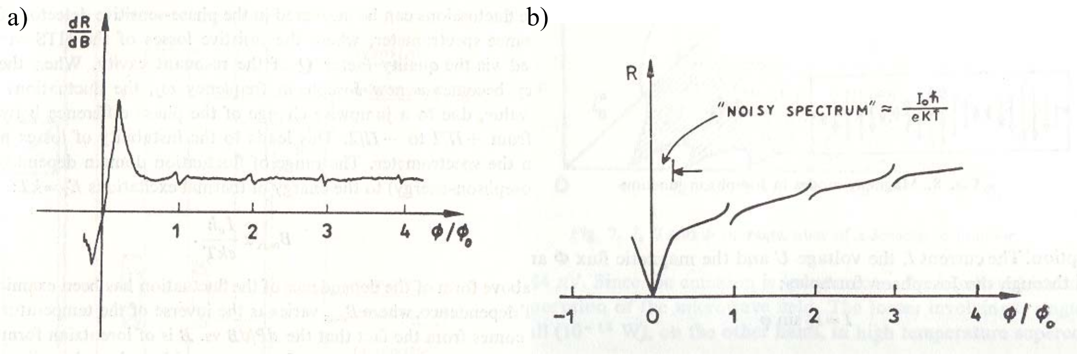


Fig. 4. Effective magnetoresistance $R(B)$ (a) and its derivative $dR(B)/dB$ (b) of SC loop with WJC.

Microwaves are coupled inductively with WJC. WJC turns from SC to normal state, absorbing power of the ac field in the ac circuit coupled to the SC loop with WJC. Recording the penetration of consecutive fluxons underlines the SQUID technique. Figure 4 shows that the MMMA signal is related to the change of magnetoresistance due to the penetration of the first fluxon ($n = 1$), whereas the SQUID effect shows penetration of successive fluxons $n\Phi_0 \leftrightarrow (n + 1)\Phi_0$. The "noisy spectrum" in Fig. 4a is the effect of quantum oscillations due to the fluctuation of SC state. The coherence of these oscillations is realized by the magnetic component of microwaves giving the MMMA signal as the derivative of magnetoresistance (Fig. 4b). There is a minimum of absorption in the middle of the MMMA signal. MMMA can be observed by means of a standard EPR spectrometer with the magnet replaced by Helmholtz coils. The second modulation of the magnetic field differentiates the signal of microwave losses. Direct $P(B)$ microwave absorption can be thermally detected. Figure 5a presents a thermally detected microwave absorption signal proportional to $P(B)$, whereas Fig. 5b shows a typical MMMA signal for YBCO ceramic for a slow sweep of the magnetic field. The shape of both signals around $B = 0$ corresponds to magnetoresistance presented in Fig. 4.

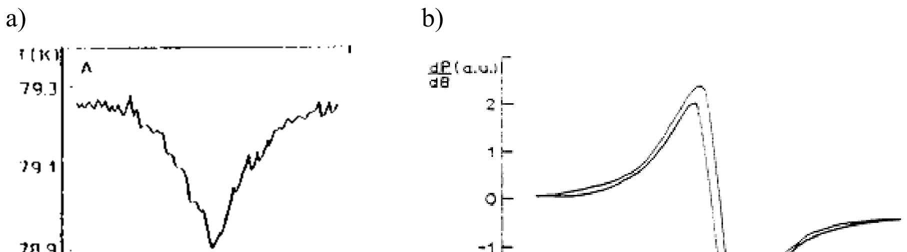


Fig. 5. Polycrystalline YBCO: a) TMDA signal ($\sim P(B)$); b) differential $dP(B)/dB$ MMMA signal.

The hysteresis obtained by fastest sweep of the magnetic field is the consequence of fluxons pinning on defects and of the heat flow between the Josephson junctions system (JJS) and the sample.

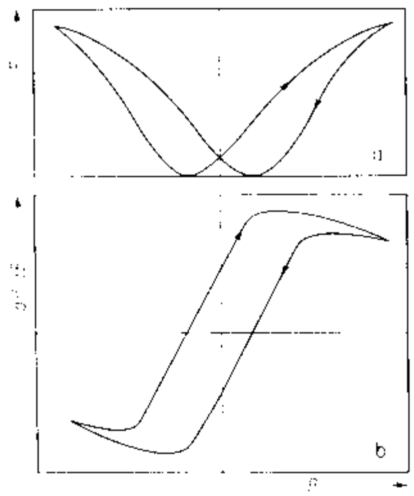


Fig. 6. Schematic microwave absorption lineshape observed without (a) and with 100 kHz modulation (b).

The MMMA signal (Fig. 6b) has two distinctive extrema at ± B_{max}, where dP/dB has the highest value. It looks like a resonance line in magnetic resonance spectroscopy; hence it is often called "the EPR line in zero magnetic field". The value of B_{max} results from the distribution of Josephson junctions in the sample. Therefore, the width of the signal does not relate to the electron relaxation process but to the heat transport between JJS and SC sample. A sweeping magnetic field with a frequency of several Hz for a microwave power of 10 mW already gives hysteresis. This hysteresis differs from a ferromagnetic one, because there is no remanent field. A MMMA signal has zero value at ± B_0. The width of the MMMA hysteresis depends of the rate of sweeping magnetic field $B(t)$ and is given by the following expression:

$$\Delta B_{hist} = a(T)\frac{dB_{\mathrm{mod}}}{dT} - \Delta B_0(B', T) \qquad (2)$$

4. EXAMPLES OF NONHOMOGENEOUS SUPERCONDUCTORS

The study of small superconducting regions dispersed in the "host" in the normal state is possible only by the contacless MMMA method. This is the only method for superconducting nano-regions below percolation threshold, and the small total volume of the superconducting phase does not allow detecting superconductivity by susceptibility measurements.

1. Superconducting nano-regions (islands) of MgB_2 in magnesium metal were obtained by first, boron ion implantation into a magnesium substrate, and then the near surface region was melted by short, intense hydrogen or argon plasma pulses. Dispersed superconducting nano-regions are schematically presented in Fig. 7. Superconducting state in such insulated islands of MgB_2 has been experimentally proven by the MMMA method with transition temperatures as high as 31K. Figure 8 shows an example of a Josephson hysteresis loop for one sample [11].

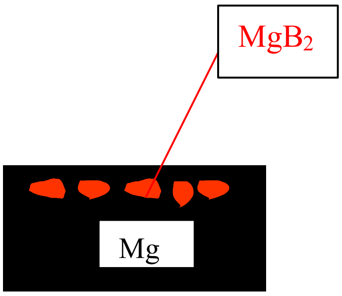


Fig. 7. Islands of SC MgB_2 obtained by boron ions implantation into magnesium.

Fig. 8. Josephson hysteresis loop for the sample in Fig. 7: MMMA signal versus magnetic field from -40G to 40G.

2. Another example of the uniqueness of the MMMA method is the study of the process of potassium intercalation into a fullerene C_{60} structure. At the beginning of the intercalation process, at the front of intercalation in fullerene grain, a new metastable superconducting phase was discovered. This phase has manifested itself in MMMA(T) dependence (Fig. 9).

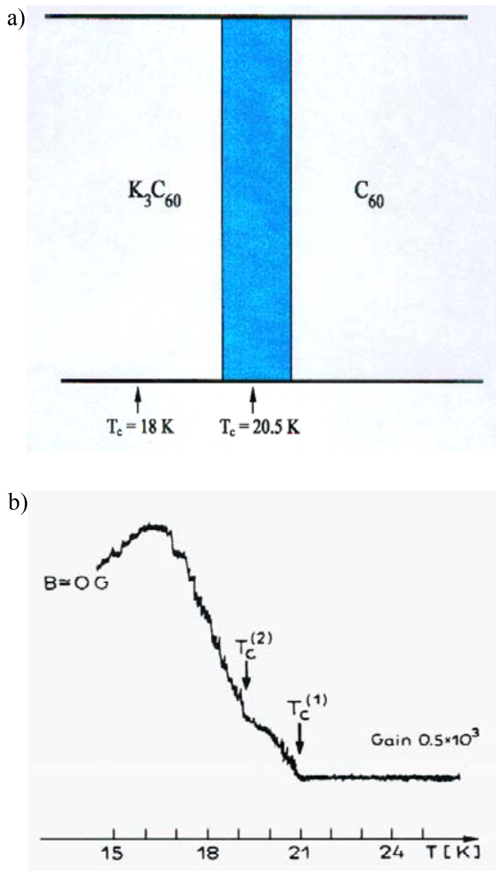


Fig. 9. At the front of potassium intercalation into C_{60} a metastable phase can be formed (a); b): MMMA signal in temperature dependence shows two T_c's; for a metastable phase and for K_3C_{60}.

3. Composite YBCO-PST contains superconducting grains of $YBa_2Cu_3O_{6.9}$ in $Pb(Sc_{0.5}Ta_{0.5}O_3)$ dielectric (Fig. 10a). By changing the concentration x of YBCO in $(YBCO)_{1-x} - PST_x$ composite it became possible to realize the transition from "underdoped" to "overdoped" state in the HTSC phase diagram. Fig. 10b shows the pressure effect on T_c for different YBCO concentrations x. The change of the sign of dT_c/dp has been predicted by theory (different scaling is presented in Fig. 11).

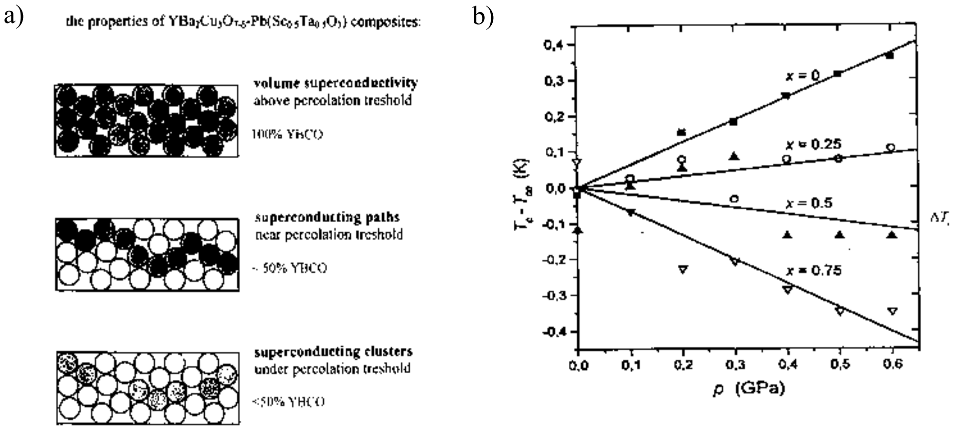


Fig. 10. Composites $(YBCO)_{1-x} - PST_x$ with different YBCO content x (a); b): the pressure coefficient changes the sign with x.

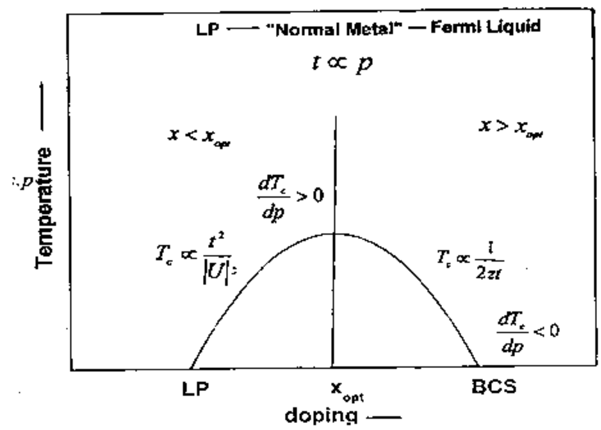
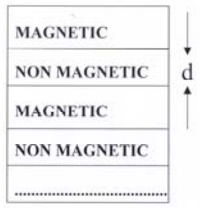


Fig. 11. Scaling of the pressure coefficient in "underdoped" and "overdoped" regions in the HTSC diagram.

5. APPLICATION OF MMMA TO STUDY GIANT MAGNETORESISTANCE

A multilayered magnetic nanostructure consisting of alternating magnetic and nonmagnetic layers has unique properties [12]. Changing the thickness of nonmagnetic layer gives either ferro- (F) or antiferromagnetic (AF) coupling in the sample. This is illustrated in Fig. 12.



$$E_{1,2} = J_1 \frac{M_1 \circ M_2}{M_1 M_2} + J_2 \left(\frac{M_1 \circ M_2}{M_1 M_2} \right)^2 = J_1 \cos\theta + J_2 \cos^2\theta$$

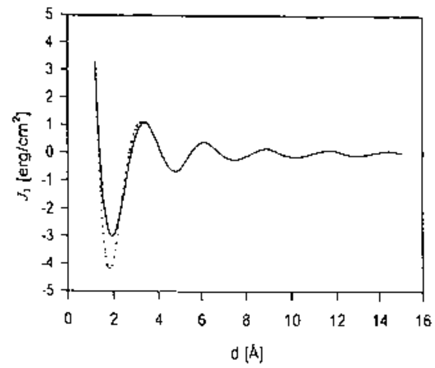
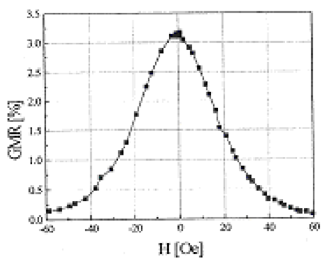


Fig. 12. In an alternating magnetic-nonmagnetic multilayer system either ferro- or antyferromagnetic coupling is possible. The sign of the exchange integral J_1 depends on d, the thickness of the nonmagnetic layer.

In a periodic magnetic structure (Fig.12; right) the exchange integral J_i oscillates with an increase of the thickness of the nonmagnetic layer. For a positive and negative J_i there are antiferromagnetic (AF) and ferromagnetic (F) couplings in the ML sample, respectively.

For AF coupling the sample exhibits high resistivity. An external magnetic field leads to a decrease of resistivity since ordering of the magnetization to F coupling opens up a channel for less-effective electron energy dissipation. This constitutes the giant magnetoresistance effect (GMR).



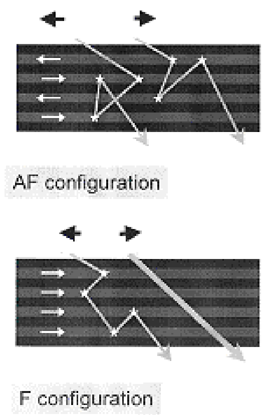
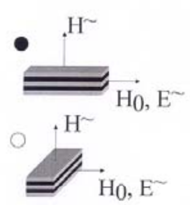


Fig. 13. Giant magnetoresistance GMR is related to the decrease of scattering for one spin orientation.

Typical GMR characteristics obtained with a conventional four-point method in current in plane configuration (CIP) are presented in Fig. 13, whereas a MMMA signal for GMR in CIP configuration is shown in Fig. 14.



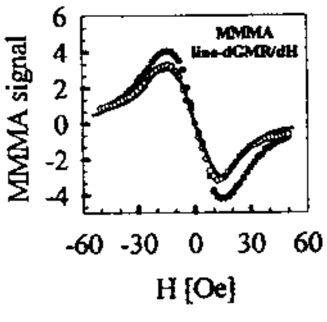


Fig. 14. MMMA and FMR signals for a *Py*/*Cu* multilayer sample for the two magnetic field configurations.

6. QUANTUM METROLOGY

Universal Josephson relation between voltage and frequency

$$U = (h/2e)\, f \tag{3}$$

is reversible. This means that a frequency of 1 Hz is related to 2.067834×10^{-15} V, whereas a voltage of 1Vcomplies with an electromagnetic field oscillation of $4.8359767(14)\times10^{14}$ Hz. If a Josephson junction is subjected to microwave radiation of 10 GHz, a voltage of approximately 21 μV will be generated. These facts give a simple definition for a standard voltage unit which has been established in metrology. The standard consists of a pile of 10^4 Josephson junctions irradiated by microwaves at 70 GHz (typically). This gives a standard voltage of 1 V.

The voltage and electric current intensity are related by universal constants with frequency. This is illustrated by the "quantum metrological triangle" in Fig. 15.

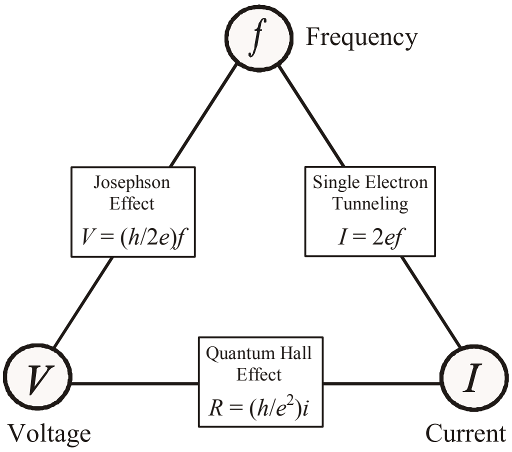


Fig. 15. The relation between voltage, intensity of the electric current and frequency defines universal constants.

The Quantum Hall effect discovered in two-dimensional electron gas shows that resistance is discretely changed; the experiment with vibrating wires proved that.

The quantum of resistance: $R_H = h/2e^2 = 12.9$ kΩ.

Bloch's oscillations showing the direct relation between current and frequency awaits experimental evidence in strongly correlated electrons systems.

7. CONCLUSION

MMMA is an effective contactless method to study fluctuations of Bose-Einstein condensate via Josephson dissipation. It opens up the possibility to extend our knowledge about spin and transport phenomena in magnetic materials.

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MIKROFALOWA ABSORPCJA (MMMA) - BEZKONTAKTOWA METODA BADAŃ NADPRZEWODNIKÓW I NANOSTRUKTUR MAGNETYCZNYCH

Streszczenie

Magnetycznie modulowana mikrofalowa absorpcja – MMMA jest czułą metodą różniczkową badania magnetooporu związanego z fluktuacjami napięcia w niejednorodnych układach nadprzewodzących ze złączami Josephsona - JS i w układach magnetycznych wykazujących gigantyczny magnetoopór –GMR. MMMA pojawiła się po odkryciu polikrystalicznych nadprzewodników wysokotemperaturowych, w których duża koncentracja złączy powoduje, ze nadprzewodnik można traktować jako system Josephsona – JJS. MMMA okazuje się trzecią metodą, obok oporności i podatności wyznaczania temperatury krytycznej T_c. W nanostrukturach magnetycznych MMMA pozwala na wyznaczenie kształtu GMR(H) oraz pola przełączania namagnesowania w punktach osobliwych pętli histerezy, w których nachylenie M(H) ma największe wartości.