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HOW TO MEASURE THE COOPER PAIR MASS USING PLASMON IN LOW-DIMENSIONAL SUPERCONDUCTOR STRUCTURES *

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ABSTRACT

The creation of the Cooper pair mass–spectroscopy is suggested. The plasmons in low–dimensional superconductor structures (layers or wires in dielectric background) are theoretically considered to that purpose. The Cooper pair mass m^* can be determined by measurements of the Doppler shift of the plasmon frequency when a direct current is applied through the superconductor. The plasmons with frequency ω lower than the superconducting gap $2\,\Delta$ can be detected by the same fare–infrared (FIR) absorption technique and grating couplings used previously for investigation of two–dimension $(2\,D)$ plasmons in semiconductor microstructures.

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In view of the experimental inaccessibility of m^*, we can assign it an arbitrary value, and it is probably most convenient to choose twice the mass of the free electron. (This arbitrariness was emphasized by de Gennes, who suggested that one could equally well take the mass of the sun!)

Michael Tinkham, 1975.

Introduction. The effective mass of the quasi-particles connected with the dynamic equation of quasi-momentum is one of the most important basic ideas in condensed matter physics. In the physics of superconductivity the mass of the "superconducting electron" m^* i.e. the Cooper pair mass was introduced by brethren London [1] as early as in 1935. At the present renaissance in physics of the superconductivity the knowledge of the Cooper pair mass can give an important information for the mechanism of the high-T_c superconductivity. Instead this however, the Cooper pair mass is an outlaw-notion still for several generations physicist.

And anyhow, what is the value of m^* for InO_x or $Y_1Ba_2Cu_3O_{7-\delta}$, is this generally a reasonable question? - "I can say nothing intelligible, we don't know in reality their density" was an answer [2]. The aim of the present paper is the rehabilitation of m^* by suggestion an experimental method for the measurement of the volume density of the Cooper pairs n and as a consequence m^*.

Really at known volume current density $j=e^* n v_{dr}$ the determination of n is possible if we know the drift velocity v_{dr}. But how to measure the velocity of a fluid of identical quantum particles? How paint several Cooper pairs in green to trace his motion? - Such marker can be performed by some quantum excitation of the coherent superconducting state. We suppose that the plasmon in thin low-dimensional superconductors can be used as such marker.

Method. Our starting point is the well known dispersion equation of the 2D plasmon (for an introduction see, for example, the review [3])

$$\omega^2 = 2\pi n^{2D} e^{*2} q/\varepsilon m^*, \tag{1}$$

where: $q=2\pi/a_{gr}$ is the 2D wave vector of the plasmon fixed by the grating constant a_{gr} (see Fig.1), d is the thickness of the superconducting layer, $n^{2D}=dn$ is the number of Cooper pair per unit area and ε is the dielectric permeability of the bulk insulator around the layer. This formula is in law if: $T \ll T_c$, $\hbar\omega \ll 2\Delta(0)$, $2\pi/q \gg \xi(0)$, $\omega/q \ll c/\eta$, $d \ll \lambda$, where T is the temperature, c is the light velocity, $\xi(0)$ is the Ginzburg-Landau GL coherence length for $T=0$, and $\eta=\sqrt{\varepsilon}$. The plasmon dispersion relation is a simple consequence of the London electrodynamic applicable for low frequencies $\omega < 2\Delta$. Plasmons for superconducting systems was predicted for thin filaments [4,5], thin layers and Josephson arrays [6,7], and even for arbitrary dimension [8], but since this moment there are not experimental investigations. The plasmon dispersion relation can be also expressed by the experimentally measurable kinetic inductance [9]

$$L = 4\pi\lambda^2/d = m^* c^2/e^{*2} n^{2D} \qquad \text{for } d \ll \lambda,$$

$$\omega^2 = 2\pi c^2 q/L\varepsilon. \tag{2}$$

Let us mention that in the used gaussian system L has dimension of length (1nH=1cm).

If the thin superconducting layer is spaced at distance D from a bulk superconductor as is shown in Fig.1 the plasmon dispersion become acoustic [3]

$$\omega = v_{ac} q, \qquad v_{ac} = (4\pi D/\varepsilon L)^{1/2} = (c/\eta\lambda)(Dd)^{1/2}, \tag{3}$$

for $\omega \ll 2\Delta$, $v_{ac} \ll c/\eta$, $D \ll a_{gr}$. The plasma frequency is in this case (3) $(D/a_{gr})^{1/2}$ time lower than in the $D \gg a_{gr}$ case (1,2). The bulk superconductor causes also a homogeneous distribution of the surface current in the plane of the superconducting layer. The returning of the current back trough the bulk superconductor as is shown in Fig.1 is necessary for homogenization of the 2D surface current j^{2D} in the plane of the layer. The weak parallel to the grating magnetic field $B_y=4\pi j^{2D}/c$ in the insulator layer between the superconductors can be closed by U-shape insulated superconducting cowering of the bottom of the microstructure. In this case the 2D current will be extremely homogeneous.

The considered polaritons are in meV region (for high-T_c superconductors) and can be investigated by the same FIR technique used previously for investigations of the 2D plasmons in 2D electron gas in semiconductors. Only the plasma resonances will be extremely sharp due to absence of ohmic dissipation for $k_B T$, $\hbar\omega \ll 2\Delta(0)$ when there are no thermally excited normal carriers.

The dispersion relations (1-3) are written in the coordinate system in witch the Cooper pairs are unmoving. In case of applied surface current $j^{2D}=dj=e^* n^{2D} v_{dr}$ perpendicular to the grating the drift velocity of the charge carriers causes a Doppler shift $\Delta\omega=v_{dr}q$ of the frequency ω of the plasma resonance. As a consequence the Doppler shift of the plasmons running in opposite directions $q=\pm 2\pi/a_{gr}$ gives the doublet splitting of the plasmon resonance with the frequency difference $2\Delta\omega=4\pi v_{dr}/a_{gr}$. Of course for the observation of this splitting the plasmon life-time τ must be large enough $\Delta\omega\tau \gg 1$, as is shown in Fig.2. At low temperatures the main mechanism of the plasmon decay will be probably the acoustic wave emission in the bulk dielectric medium.

The predicted effect is unfortunately very small and can be observed only in high-technology superconducting microstructures unthinkable in London's time. The relatively changing of the frequency of the acoustic plasmon (3), for example, is small even for drift velocities v_{dr} comparable with the the critical velocity $v_c \cong \hbar/m^* \xi(0)\pi$ which creates the decay of Cooper pairs:

$$\Delta\omega/\omega \ll v_c/v_{ac} \cong \eta(m_e/m^*) \left[\delta/\xi(0)\right] \left[\lambda/(Dd)^{1/2}\right] \gg 1/N,\ \mathrm{Im}\varepsilon/\mathrm{Re}\varepsilon. \quad (4)$$

Here m_e and $\delta=\hbar/m_e c$ are the mass and the Compton length of the free electron. This inequality gives the same restriction $\delta/\xi(0)\simeq10^{-4}$ for the homogeneity of the layer thickness, the surface current, dielectric losses, the experimental resolution, and also for the minimal number of the superconducting grating strips N.

The Cooper pair density is unchanged by the drift when the current density is much smaller than the critical current [10] $j_c=H_c/4\pi\lambda$ (H_c is the thermodynamic critical field). The measurement of the Doppler splitting $2\Delta\omega$ gives the drift velocity $\upsilon_{dr}=a_{gr}\Delta\omega/2\pi$. In case of the absence of screening by a bulk superconductor the distribution of 2D current density is homogeneous if the width w of the superconducting strip is $\ll$ than the 2D screening length L. This $a_{gr}\ll w\ll 4\pi\lambda^2/d$ condition can be reach only for extremely thin layers. In this condition the 2D current density $j^{2D}=I/w$ can be expressed by experimentally measured current I through the "source-drain" electrodes of the shown in Fig.1 microstructure. For simultaneously measured current density $j=j^{2D}/d$ we can determine the volume density of the Cooper pairs $n=j/e^*\upsilon_{dr}$. The Cooper pair mass can be expressed then by $m^*=4\pi ne^{*2}\lambda^2/c^2$. However more natural way is: 1)determination of $n^{2D}=j^{2D}/e^*\upsilon_{dr}$ 2) expression L from plasmon dispersion relation, from (3) for example, $L=4\pi Dq^2/\varepsilon\omega^2$ 3) and at the end the determination of $m^*=e^{*2}Ln^{2D}/c^2$. The 2D plasmons can be used in principle for the determination of the penetration depth also.

If the grating period is much bigger than the superconducting strip width $a_{gr}\gg w$ the plasmon become one-dimensional 1D

$$\omega = (c/\lambda\eta)(A/2\pi)^{1/2}\Big[\ln(1/qw)\Big]q,$$

where A(=wd for the considered microstructure) is the cross section area of the 1D superconductor. Further lowering of the plasmon frequency can be reach if a thin superconducting wire is separated from a bulk superconductor by by a thin insulator layer with thickness $D \ll a_{gr}$. In this case the logarithm must be replaced by a constant of order of unit, and the 1D plasmon dispersion is purely acoustic.

The suggested method is not even in smallest degree controversial. The Doppler shift of the plasmons in low-dimensional superconductors is considered as an important ingredient of the supposed solid state two-stream instability [11]. An appropriate layered superconducting microstructure can be prepared by contemporary technology for growing of thin high-T_c layers [9] and even superlattices [12] with d=12Å. The development of the Cooper pair mass-spectroscopy can be expected in the near future. On account of this we will describe the renormalization of m^* by disorder for the conventional dirty alloys.

The Pippard-Landau theory. Let us write the kinetic energy of the Cooper pairs in the spirit of the GL theory [13]

$$E_{kin} = \int\int d^3x\ d^3y \left[\left(-i\hbar\nabla_x - e^*\mathbf{A}(\mathbf{x})\right)\psi(\mathbf{x})\right]^* \cdot \left(\overleftrightarrow{\mathbf{K}}(\mathbf{x}-\mathbf{y})/2m^*_{pure}\right) \cdot \left(-i\hbar\nabla_y - e^*\mathbf{A}(\mathbf{y})\right)\psi(\mathbf{y}), \qquad (5)$$

where: $\mathbf{x},\mathbf{y}$ are displacement vectors, $\mathbf{A}$ is the vector potential, m^*_{pure} is the Cooper pair mass for the clean material and ψ is the GL superconducting wave function [13]. The comparison of the current density given in this theory by the variational derivative

$$\mathbf{j}(\mathbf{x})/c = -\delta E_{kin}/\delta\mathbf{A}(\mathbf{x}) \qquad (6)$$

with the well known formula of the Pippard nonlocal electrodynamic [14] fixes the kernel

$$\overleftrightarrow{\mathbf{K}}(\mathbf{R}) = (3/4\pi\xi_o)\ (\mathbf{R}\otimes\mathbf{R}/R^4)\exp(-R/\xi_p), \qquad (7)$$

$$1/\xi_p = 1/\xi_o + 1/l, \qquad R=|\mathbf{R}|,$$

where ξ_o is the Pippard coherence length for pure metal. Within several per cent accuracy $\xi_o=\xi(0)$ for pure isotropic metals.

Probably the most direct confirmation of this unification of the GL and Pippard theory gives the experiment [15] on fluctuational diamagnetic moment M_{fl} in a external magnetic field H just at the critical temperature T_c. The corresponding state law for $M_{fl}(T_c,H)$ is a reflection of the existing of a kernel $\overleftrightarrow{K}$ general for the all isotropic conventional superconductors.

For smooth space changes of the wave function ψ the local GL approximation of the kernel by Dirac δ-function $\overleftrightarrow{K}(\mathbf{R})=(\xi_p/\xi_0)\delta(\mathbf{R})1_{3\times 3}$ gives the renormalization of the Cooper pair mass by the disorder c.f.[16]

$$m^*_{dirty} = (1+\xi_0/l)m^*_{pure}. \tag{8}$$

The BCS theory gives temperature dependent multipliers of order of unit which are omitted in this formula. The main properties of the post-BCS dirty alloy theory such as increasing of the upper critical magnetic field H_{c2}, the GL parameter $\varkappa$, and Ginzburg number Gi with the disorder $1/l$ can be well explained in framework of the presented nonlocal phenomenological theory.

Qualitatively the increasing of $m^*\propto\rho$ proportional to the electric resistivity continues even in strong scattering limit. For the 100Å thin disordered InO_x films [14] the Kosterlitz-Thouless (KT) transition temperature T_{KT} is considerably below the GL one T_c, i.e. $(T_c-T_{KT})\simeq T_c$. Then the number of Cooper pairs per unite area at T_{KT} has the same order as the surface density n_e of the normal electrons $n(T_{KT})\cong(1-T_{KT}/T_c)(n_e/2)\simeq n_e$.

From one hand side it is well known that electrons of every superconductor are highly degenerated $\hbar^2 n_e/2m_e \gg k_B T_c$, but from another hand side the equation for the T_{KT} [14]

$$\hbar^2 n(T_{KT})/2m^* = k_B T_{KT}/\pi \tag{9}$$

shows that after the superconducting pairing the Cooper pairs are almost a classical gas. It is seams that Cooper pair mass $m^*\gg m_e$ reach typical hadronic values for these strongly disordered films. Another question waiting for an experimental solution is: are the heavy-fermion superconductors also heavy-boson? The first step of the creation of the

Cooper pair spectroscopy will the measurement of the plasmon linewidth in a low-dimensional superconductor microstructure. We hope that understanding of the superconductivity begin with the London electrodynamic.

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Figure captions

FIG. 1. Gedanken microstructure for the measurement of the Cooper pair mass m^* (schematically not to scale): 1)thin superconducting layer 2)dielectric medium 3)bulk superconductor 4)grating strips 5-6)"source-drain" electrodes 7)current generator. The electric field E_x of the external FIR electromagnetic field is polarized perpendicularly to the grating. The weak magnetic field B_y of the drift current is parallel to the grating.

FIG. 2. Expected FIR absorption spectrum of 2D plasmons. The upper curve is the plasmon resonance absorption for zero source-drain current I. The lover curve presents the Doppler doublet splitting for large enough drift velocities v_{dr}.

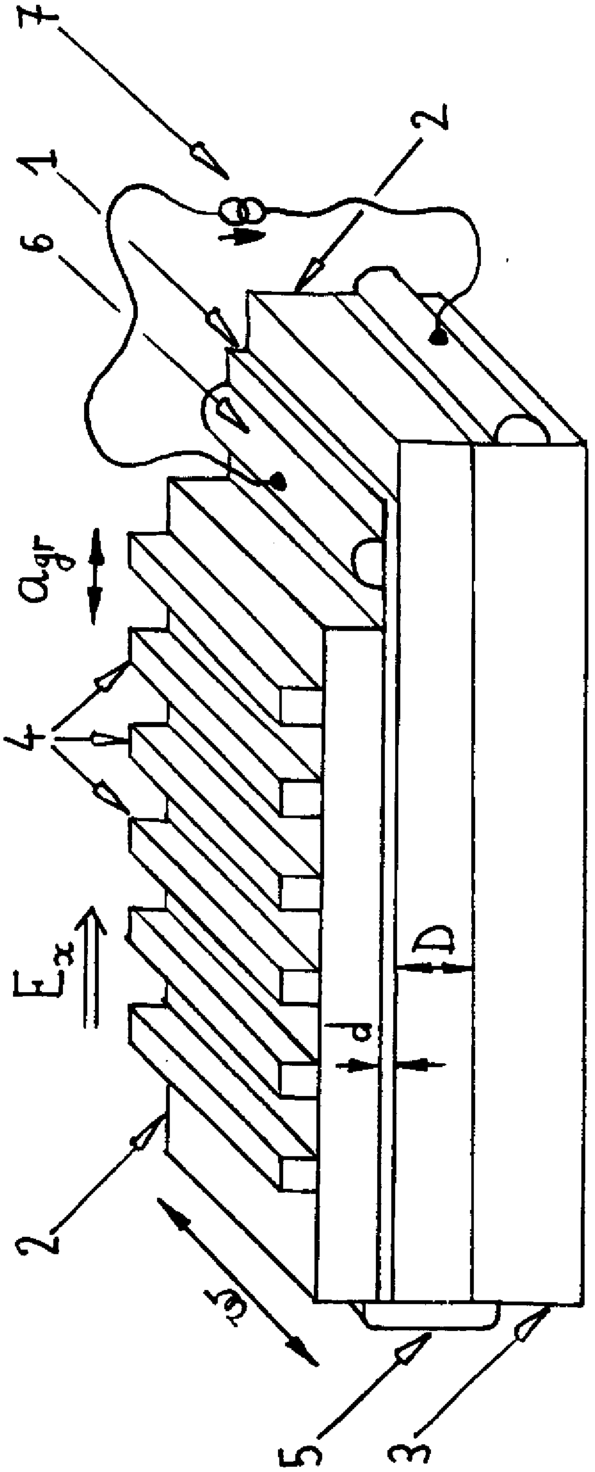

Fig.1

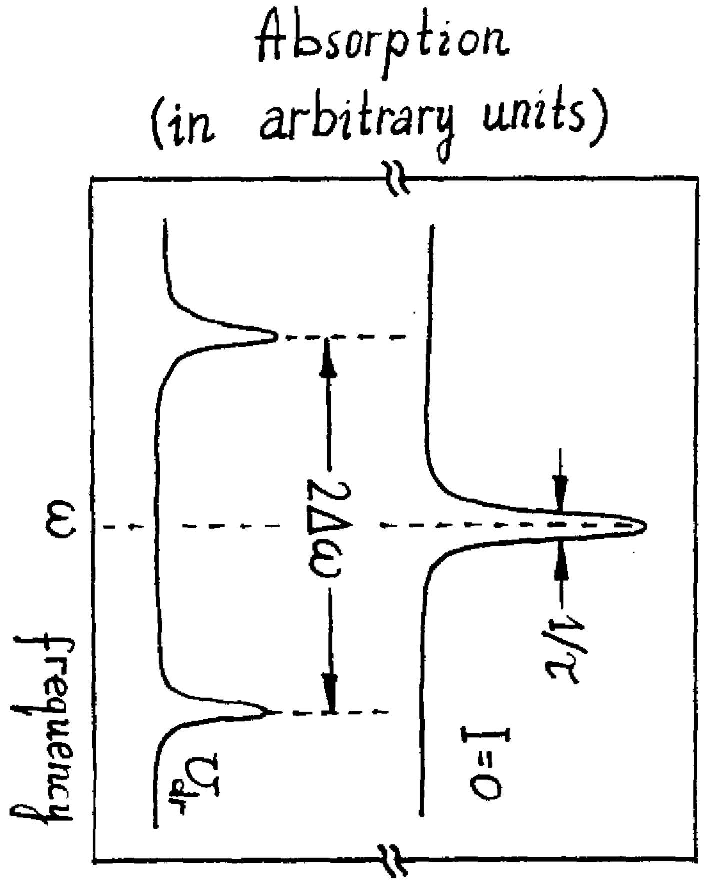

Fig.2

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