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THz detectors using surface Josephson plasma waves in layered superconductors

Sergey Savel'ev [a,b], Valery Yampol'skii [a,c], Franco Nori [a,d,*]

[a] Frontier Research System, The Institute of Physical and Chemical Research, DML, FRS, RIKEN 2-1 Hirosawa, Wako-shi, Saitama, 351-0198, Japan
[b] Department of Physics, Loughborough University, Loughborough LE11 3TU, United Kingdom
[c] A. Ya. Usikov Institute for Radiophysics and Electronics, NASU, 61085 Kharkov, Ukraine
[d] Department of Physics and MCTP, The University of Michigan, Ann Arbor, MI 48109-1040, USA

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Abstract

We describe a proposal for THz detectors based on the excitation of surface waves, in layered superconductors, at frequencies lower than the Josephson plasma frequency ω_J. These waves propagate along the vacuum-superconductor interface and are attenuated in both transverse directions out of the surface (i.e., towards the superconductor and towards the vacuum). The surface Josephson plasma waves are also important for the complete suppression of the specular reflection from a sample (Wood's anomalies, used for gratings) and produce a huge enhancement of the wave absorption, which can be used for the detection of THz waves.

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1. Introduction

High temperature $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) and $Tl_2Ba_2CaCu_2O_{8+\delta}$ (Tl-2212) superconductors have a layered structure of superconducting CuO_2 planes with Josephson coupling between them. This structure allows propagating electromagnetic waves, called Josephson plasma waves (JPW) [1–3], through the layers. These waves attract considerable interest because of their Terahertz frequency range. During the last decade there have been many attempts to push THz science and technology forward [4] because of many important applications in physics, astronomy, chemistry, biology and medicine.

The unusual optical properties of layered superconductors, including reflectivity and transmissivity, caused by the JPW excitation were studied in, e.g., Refs. [1,5,6]. In particular, Ref. [5] demonstrated that the spectrum of JPW consists of two branches due to a peculiar effect [7] of dynamical breaking of charge neutrality.

All previous works on this problem have focused on running waves in the frequency range *above* the gap of the JPW spectrum, i.e., above the Josephson plasma frequency $\omega > \omega_J$. A similar gapped spectrum also appears in solid state plasmas [8]. In such situations the presence of the sample boundary can produce a new branch of the wave spectrum inside the gap, i.e., a surface plasmon [8,9]. In general, surface waves play a very important role in many fundamental resonant phenomena, such as the "Wood anomalies" in the reflectivity [9,10] and transmissivity [11] of periodically corrugated metal and semiconducting samples, and are employed in many devices. Therefore, it is important to know if surface waves can exist in layered superconductors.

* Corresponding author. Address: Frontier Research System, The Institute of Physical and Chemical Research, DML, FRS, RIKEN 2-1 Hirosawa, Wako-shi, Saitama, 351-0198, Japan. Tel.: +8148 462 1111x3322; fax: +8148 467 9650.
E-mail address: nori@umich.edu (F. Nori).

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Here, we briefly summarize the results related to surface Josephson plasma waves obtained in [12] and discuss several promising applications. We show that *surface* Josephson plasma waves can propagate along the surface between the superconductor and the vacuum in a wide frequency range below $\omega_{\rm J}$. We present the dispersion relation for these waves and discuss ways to excite them. We show that these surface waves play an important role in the absorption and reflection of electromagnetic waves, including their resonance dependence on the incident angle θ. The studied resonant absorbability could be experimentally observed by measurement of the surface impedance of a sample or dc resistivity. The predicted phenomena [12] are potentially useful for designing THz detectors and improving THz grating arrays.

2. Surface waves

We consider a semi-infinite layered superconductor in the geometry shown in the right-bottom inset of Fig. 1. The crystallographic *ab*-plane coincides with the *xy*-plane and the *c*-axis is along the *z*-axis. Superconducting layers are numbered by the integer $l \geqslant 0$.

We consider a surface p-wave with the electric, $\vec{E} = \{E_x, 0, E_z\}$, and magnetic, $\vec{H} = \{0, H, 0\}$, fields damped away from the interface $z = 0$,

$$H, E_x, E_z \propto \exp(-\mathrm{i}\omega t + \mathrm{i}qx - klD) \tag{1}$$

inside a layered superconductor, $z < 0$, and

$$H^{\rm vac}, E_x^{\rm vac}, E_z^{\rm vac} \propto \exp(-\mathrm{i}\omega t + \mathrm{i}qx - k_{\rm vac}z), \tag{2}$$

in vacuum, for $z > 0$ and $q > \omega/c$. Here D is the spatial period of the layered structure.

Inside the layered superconductor, where $z < 0$, the gauge invariant phase difference is described by a set of coupled sine-Gordon equations [13]. The effect of breaking charge neutrality [7], which is crucial for our analysis, is taken into account in these equations. Substituting the wave (1) into the coupled sine-Gordon equations, we obtain the implicit relation for the damped-wave transverse wave vector $k(q,\omega)$

$$\frac{\omega^2}{\omega_{\rm J}^2} = 1 + \frac{\lambda_c^2 q^2}{1 - (4\lambda_{ab}^2/D^2)\sinh^2[k(q,\omega)D/2]} - 4\alpha\sinh^2[k(q,\omega)D/2]. \tag{3}$$

Here $\lambda_{\rm ab}$ is the London penetration depth in the z-direction, $\omega_{\rm J} = \sqrt{8\pi eDJ_{\rm c}/\hbar\varepsilon}$ is the Josephson plasma frequency determined by the maximum Josephson current $J_{\rm c}$ and dielectric constant ε, $\lambda_{\rm c}^2 = c^2/\omega_{\rm J}^2\varepsilon$. The constant α characterizing the effect of breaking charge neutrality was estimated, e.g., in Ref. [5], $\alpha \sim 0.05$–0.1 for Bi-2212 or Tl-2212 crystals.

The dispersion relation $q(\omega)$ for the surface waves can be obtained by joining fields in a superconductor and vacuum at the sample surface via appropriate boundary conditions. After doing this, we obtain the dispersion relation for two branches of the surface wave corresponding to two solutions of Eq. (3). For $(1 - \omega/\omega_{\rm J}) \gg \sqrt{\alpha/\varepsilon}D/\lambda_{\rm ab} \approx 5 \cdot 10^{-4}$, this spectrum can be written as

$$Q_-(\Omega) = \Omega;$$
$$Q_+(\Omega) = \Omega(1 + \beta^2\Omega^2\Gamma_\Omega \times \{1 + 2\Gamma_\Omega[1 - (1 + \Gamma_\Omega^{-1})^{1/2}]\})^{1/2} \tag{4}$$

for two branches "$\mp$". Here we introduce the dimensionless variables: $Q = cq/\omega_{\rm J}$, $\Omega = \omega/\omega_{\rm J}$, $\beta = 2\lambda_{\rm ab}^2\omega_J/cD$, and $\Gamma_\Omega = (1 - \Omega^2)/4\alpha$. The value of the parameter β for Bi-2212 is about 1.4. The spectra Eqs. (4) are shown in Fig. 1. Both branches merge in a narrow frequency region below $\omega_{\rm J}$, i.e., $(1 - \Omega) \sim (\alpha/\varepsilon)^{1/2}(D/\lambda_{\rm ab})$.

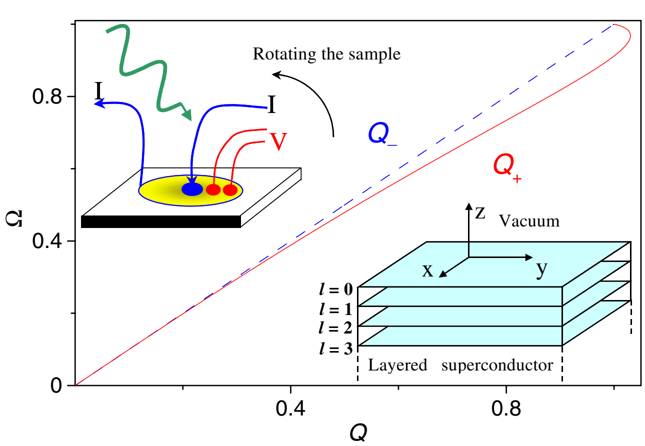

Fig. 1. (Color online) Spectra of the surface Josephson plasma waves $Q_\mp$ for the parameters $\alpha = 0.1$, and $\beta = 1.4$, standard for Bi-2212. Left top inset: the simplest design for the THz detector involves a spatially modulated Bi-2212 sample fixed on a precisely rotated holder and attached to electrical contacts to measure its resistance. The right bottom inset shows the sample geometry used.

3. How to excite surface waves

One of the ways to excite surface Josephson plasma waves is via externally applied electromagnetic waves on a sample having spatially modulated parameters. Thus, we consider a weak modulation of the maximum current density $J_{\rm c}$. This can result in the modulation of $\omega_{\rm J}$. For simplicity, we assume that

$$\omega_{\rm J}^2(x) = \omega_{\rm J}^2\left[1 + 2\mu\cos\left(\frac{2\pi x}{a}\right)\right], \quad \mu \ll 1, \tag{5}$$

where a is a spatial period.

An electromagnetic wave with $\omega < \omega_{\rm J}$, incident at an angle θ with respect to the sample surface, generates modes having longitudinal wave vectors $q_m = \omega\sin\theta/c + 2\pi m/a$, with integer m. Almost all of these modes for $m \neq 0$ are weak, because $\mu \ll 1$. However, one of these modes (e.g., for $m = 1$) can be excited with large amplitude at resonance, i.e., when the wave vector $q_1 = (\omega/c)\sin\theta + 2\pi/a$

is close to the wave vector $q_+ = \omega_J Q_+(\Omega)/c$ of the surface wave (4). This corresponds to the incident angle θ close to the resonance angle θ_0 defined by

$$\Omega \sin\,\theta_0 + \frac{2\pi c}{a\omega_J} = Q_+(\Omega). \quad (6)$$

Because of this resonance, the amplitude of the wave with $q = q_1$ can be of the same order, or even higher than, the amplitude of the incident wave. In resonance, the mode with $q = q_1$ is actually the surface Josephson plasma wave discussed above.

The resonance in the absorption can be observed by measuring the dependence of the surface impedance on the angle θ. Alternatively, the peak in absorption produces a temperature increase, resulting in a sharp increase of the DC resistance or even the transition of the sample to the normal state at $\theta = \theta_0$.

4. THz detectors

The excitation of the Josephson plasma waves could be potentially useful for the *design of THz detectors*, an important current goal of many labs worldwide. The simplest design could be a spatially modulated Bi-2212 sample fixed on a precisely rotated holder and attached by contacts to measure its resistance (see Fig. 1, left top inset). Spatial modulations in the sample could be fabricated by either using ion irradiation of the sample covered by periodically modulated mask [14], or even mechanically [15]. When rotating the sample, the incident THz radiation can produce a surface wave at certain angles. This results in a strong enhancement of absorption associated with increasing of temperature in the sample and, thus, its resistance. The relative positions of the resonance peaks (the set of angles) allows to calculate *the angle and the frequency of the incident THz radiation*, while the relative heights of the resistance peaks can be used to estimate *the intensity of the incident radiation.*

Another promising application of the THz surface Josephson plasma waves could be an improvement of grating arrays, which is one of the usual applications of the Wood's anomalies associated with the resonant excitations of surface waves.

5. Conclusions

We have derived the properties of surface Josephson plasma waves in layered superconductors, and obtained their dispersion relation. The absorption of incident electromagnetic waves can strongly increase at certain incident angles, due to the resonant generation of our predicted surface waves. We propose ways to experimentally observe the surface Josephson plasma waves and their application to new designs of THz detectors.

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