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Leggett's Mode in $Mg_{1-x}Al_xB_2$

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A detailed investigation of multiband superconductivity and Leggett's mode in the $Mg_{1-x}Al_xB_2$ ($0 \leq x \leq 0.45$) system was carried out using tunneling and Andreev spectroscopy. Temperature dependences of superconducting gaps Δ_σ and Δ_π and their variation upon the degree of disorder and the Al concentration were studied. The dependence of the Leggett's mode energy ε_0 upon the values of the gaps Δ_σ and Δ_π has been derived.

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Introduction. According to a popular version [1, 2] magnesium diboride displays a two-gap superconductivity. The large gap Δ_σ corresponds to 2D charge carriers in σ-bands, while the small gap Δ_π corresponds to 3D carriers in π-bands. Both gaps close simultaneously at the critical temperature $T_c \cong 40$ K [3 – 6]. The presence of a van Hove singularity in 2D σ-bands may strongly affect the value of T_c if one shifts the Fermi level to the peak in the quasi-particle density of states through doping [7]. The quasi-particle density of states in MgB_2 has two distinctive gap singularities, which result in two independent subharmonic gap structures (SGS), corresponding to Δ_σ and Δ_π, appearing in the current-voltage characteristics of Andreev point contacts of SnS type [8 – 10]. Accordingly two-gap structures are present in the current-voltage characteristics (CVCs) of tunneling NIS and SIS junctions [3 – 6, 8 – 10].

In 1966 Leggett had predicted for two-band superconductors a collective mode resulting from small fluctuations of the relative phase of the two superconducting condensates [11]. An expression for the energy of the Leggett's mode for MgB_2 has been derived by Sharapov et al. [12]:

$$\varepsilon_0^2 = 4\Delta_\sigma\Delta_\pi[(\lambda_{12} + \lambda_{21})/(\lambda_{11}\lambda_{22} - \lambda_{12}\lambda_{21})], \qquad (1)$$

where λ_{ij} – dimensionless interband and intraband coupling constants. The Leggett's mode energy ε_0 is governed by the values of intraband coupling constants and goes to zero in case of noninteracting bands. The Leggett's mode is observable only when $\varepsilon_0 < 2\Delta_\pi$ [12].

As it was shown by Agterberg et al. [13], a Josephson junction on the basis of a two-gap superconductor can be used to detect a collective plasma mode originally proposed by Leggett [11]. A resonance enhancement of the DC current through a Josephson junction at a bias voltage V_{res} is expected when the Josephson frequency ω_J or its harmonics ($n \cdot \omega_J$) match the energy of the Leggett's mode ε_0 or its harmonics ($m \cdot \varepsilon_0$) [8, 9, 13]:

$$\varepsilon_0 = (n/m)2eV_{\text{res}}, \qquad (2)$$

where n and m are integer numbers.

In case of Andreev point contacts of the SnS type the resonant emission of Leggett's plasmons with the energy ε_0 causes the appearance of several sets of subharmonic gap structures for σ-σ channel at bias voltages [8, 9]:

$$V_{n,m} = (2\Delta_\sigma + m\varepsilon_0)/en, \qquad (3)$$

where n and m are integer numbers (m is a number of emitted Leggett's plasmons). In the present investigation we have studied peculiarities on the $dI(V)/dV$-characteristics of break junctions in $Mg_{1-x}Al_xB_2$ related to Leggett's collective mode assisted tunneling. For the first time the dependence of the excitation energy ε_0 upon the values of the large (Δ_σ) and small (Δ_π) gaps at T = 4.2 K has been derived for $Mg_{1-x}Al_xB_2$ samples with the critical temperature T_c in the range $40.5\text{ K} \leq T_c \leq 6.5\text{ K}$. The result is in a qualitative agreement with the theoretical predictions [11, 12].

Experiment. In the present investigation a study of superconducting properties of $Mg_{1-x}Al_xB_2$ polycrystalline samples has been performed. The following experimental methods were employed in our investigations:

1) Andreev spectroscopy (multiple Andreev reflections (MAR) in $Mg_{1-x}Al_xB_2$ break junctions of the SnS type),

2) tunneling spectroscopy (Josephson $Mg_{1-x}Al_xB_2$ SIS junctions). Both methods of investigation of superconducting properties of $Mg_{1-x}Al_xB_2$ involve using a break junction technique. The break-junction technique allows changing the junction properties during the measurements, so that the tunneling-contact like (SIS) and Andreev-contact like (SnS) behavior could be investigated on the same sample. A local critical temperature T_c in submicron $Mg_{1-x}Al_xB_2$ break junctions has been determined from the measured temperature dependences of superconducting gaps $\Delta_\sigma(T)$ and $\Delta_\pi(T)$.

In the CVC of $Mg_{1-x}Al_xB_2$ break-junctions (SIS type) we have observed peculiarities of the type (2) related to the Leggett's mode [8, 9, 11–13] (Fig.1). The structure is detectable only at temperatures $T < T_c$ and disappears with suppression of the Josephson current by an external magnetic field (which supports the above-mentioned version).

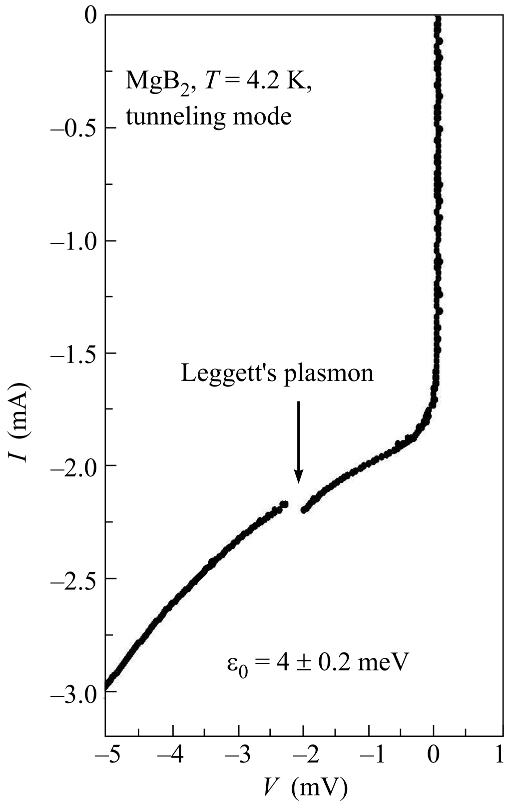

Fig.1. A fragment of the $I(V)$-characteristic of a break junction in a MgB_2 sample at $T = 4.2$ K (tunneling mode). A structure marked by an arrow is caused by coupling of the AC Josephson current to a Leggett's mode with the energy $\varepsilon_0 = 4$ meV

We have also observed a reproducible SGS of the type (3) in the CVCs of SnS (Andreev) contacts (Fig.2). In this case the traditional threshold energy $2\Delta_\sigma$ should be replaced by $(2\Delta_\sigma + m\varepsilon_0)$ due to a resonant emission of m Leggett's plasmons in the process of MAR. The energy of Leggett's mode in $Mg_{1-x}Al_xB_2$ samples was found to decrease with reduction of T_c (Fig.3, Fig.4).

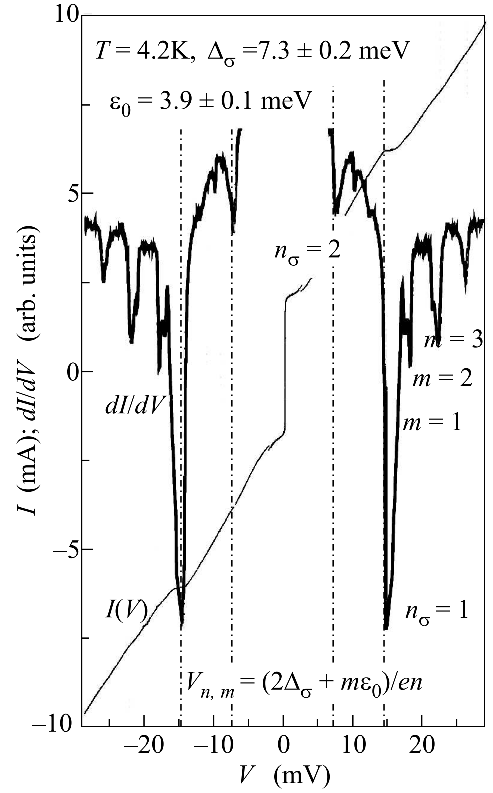

Fig.2. The SGS for a σ-σ channel at bias voltages $V_{n,m} = (2\Delta_\sigma + m\varepsilon_0)/en$ for a MgB_2 contact ($T = 4.2$ K, $\Delta_s = 7.5$ meV). "Satellites" in the SGS are caused by emission of m Leggett's plasmons with the energy $\varepsilon_0 = 3.9 \pm 0.2$ meV in the process of MAR

Discussion. Qualitatively a fine structure in the CVCs of MgB_2 Josephson junctions resembles the one in the CVCs of Bi-2212 Josephson junctions [14]. The latter is caused by the coupling of the AC Josephson current to the Raman-active optical phonons in a frequency range up to 20 THz [14, 15]. Nevertheless, we believe that the peculiarities observed in the present investigation are related namely to the Leggett's collective excitations. There are several reasons for such a conclusion. Firstly, there are no optical phonons with the energy as low as 4 meV in MgB_2. Secondly, the effective interaction between the AC Josephson current and low-energy acoustic phonons can exist only in the presence of a resonator system inside the junction. Then the observed subgap structure could appear at voltages matching the energies of resonator eigenmodes. It is very unlikely that all our break-junctions demonstrating the discussed subgap structure possess identical res-

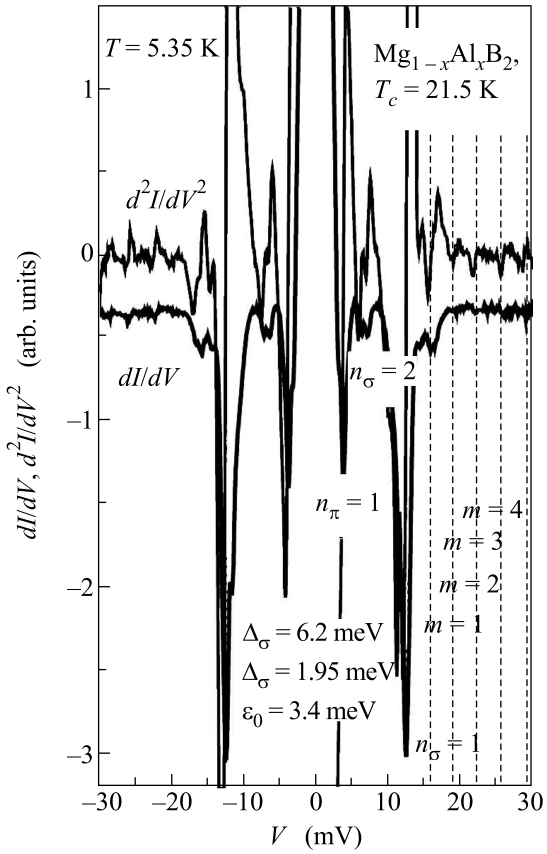

Fig.3. The SGS for a σ-σ channel for a $Mg_{1-x}Al_xB_2$ contact ($T = 4.2\,K$). "Satellites" are caused by emission of m Leggett's plasmons with the energy $\varepsilon_0 = 3.4\,meV$ ($\Delta_\sigma = 6.2\,meV$, $T_c = 21.5\,K$)

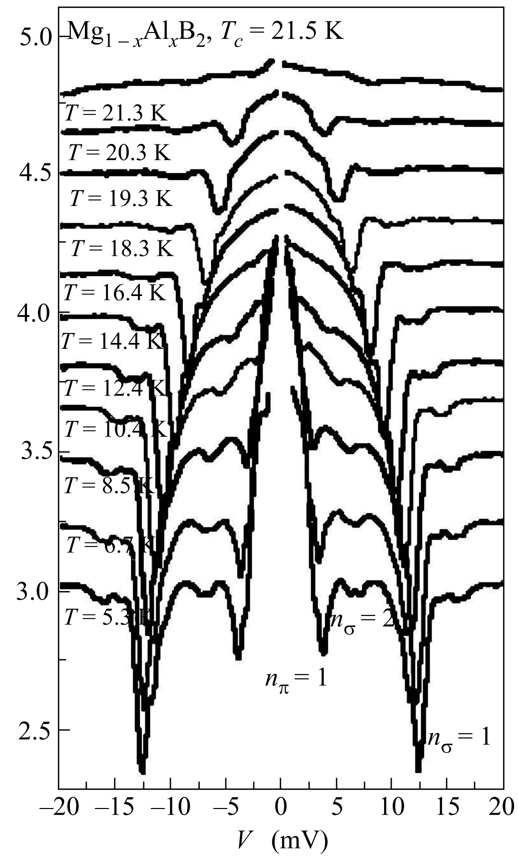

Fig.4. The SGS in dI/dV characteristics of a break junction in $Mg_{1-x}Al_xB_2$ at different temperatures ($T_c = 21.5\,K$). The SGS dips labeled n_σ (σ-bands) and n_π (π-bands) are indicated

onator systems. Finally, a fine structure in the CVCs of the investigated SIS and SnS contacts can not be caused by "depairing" of Cooper pairs in the π-condensate since for all contacts the temperature dependence of the energy of the observed mode was found much weaker than the temperature dependence of a small gap Δ_π in MgB_2.

The main parameters of the investigated $Mg_{1-x}Al_xB_2$ polycrystalline samples and MgB_2 polycrystalline samples with different level of disorder (microinclusions of MgO) are presented in Table, Fig.5 and Fig.6. An important point is that the temperature dependences $\Delta_\sigma(T)$ and $\Delta_\pi(T)$ in the $Mg_{1-x}Al_xB_2$ system are qualitatively different. The $\Delta_\sigma(T)$ dependences are close to the BCS type (Fig.4). However, the $\Delta_\pi(T)$ gap behaves in a cardinally different way (Fig.4, see also Fig.3 in [10]). The appearance of a "tail" in the $\Delta_\pi(T)$ curves is a notable evidence of a weak coupling between σ- and π-condensates (interband coupling constants $\lambda_{\sigma\pi}$ and $\lambda_{\pi\sigma}$ are by an order of magnitude smaller than intraband coupling constants $\lambda_{\sigma\sigma}$ and $\lambda_{\pi\pi}$) [16].

The dependence of the excitation energy squared ε_0^2 upon the product of the gaps $(\Delta_\sigma \cdot \Delta_\pi)$ at T = 4.2 K for $Mg_{1-x}Al_xB_2$ samples (Fig.6) is in qualitative agreement with theoretical predictions [11,12] (see Eq.(1)). The slope of the curve given by $K = 4[(\lambda_{\sigma\pi}+\lambda_{\pi\sigma})/(\lambda_{\sigma\sigma}\lambda_{\pi\pi} - \lambda_{\sigma\pi}\lambda_{\pi\sigma})] = 1 \pm 0.2$ is in agreement with the above given estimation and at the same time 3.5 times smaller than the value of K calculated from the data presented in [17]. It was shown in [18] that the decrease of T_c in $Mg_{1-x}Al_xB_2$ is mainly a result of scaling of all coupling constants λ_{ij} caused by the variation of the density of states as a function of doping, which probably leaves the value of K intact.

Conclusions. In the present investigation we have studied peculiarities on the $dI(V)/dV$-characteristics of break junctions in $Mg_{1-x}Al_xB_2$ related to Leggett's collective mode assisted tunneling. For the first time the dependence of the excitation energy ε_0 upon the values of the large (Δ_σ) and small (Δ_π) gaps at T = 4.2 K has been derived for $Mg_{1-x}Al_xB_2$ samples with the critical temperature T_c in the range $40.5\,K \le T_c \le 6.5\,K$. The

The main parameters of investigated $Mg_{1-x}Al_xB_2$ and MgB_2 samples

N^0	sample	Tc, K	ε_0, meV	Δ_σ, meV	Δ_π, meV	ε_0^2, meV^2	$\Delta_\sigma \cdot \Delta_\pi$, meV^2
$Mg_{1-x}Al_xB_2$ polycrystalline samples							
1	MBA2	6.5	1.2	1.4	0.7	1.44	0.98
2	MBA3	12	1.9	2.7	1.3	3.6	3.51
3	MBA3	14	2.5	4.2	1.7	6.25	7.14
4	MBA1	21.5 ± 0.5	3.4	6.2	1.95	11.6	12.09
MgB_2 polycrystalline samples with different level of disorder							
1	MB2D12	28 ± 2	4.5	7.0	2.4	20.2	16.8
2	KRW4	30	4.0	7.5	2.0	16.0	15.0
3	MB4	32 ± 2	4.0	8.0	2.0	16.0	16.0
4	BBSC	33	3.6 ± 0.4	8.2	2.0	13.0	16.4
5	MB7D06	40	5.0	10.1	2.1	25.0	22.26

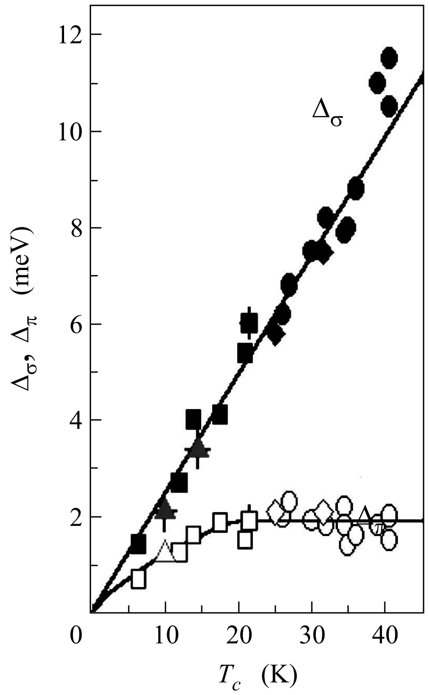

Fig.5. The Δ_σ (solid symbols) and Δ_π (open symbols) gaps as functions T_c for $Mg_{1-x}Al_xB_2$ (squares, triangles) and MgB_2 with different degree of disorder (circles, diamonds). Solid lines are drawn for convenience sake

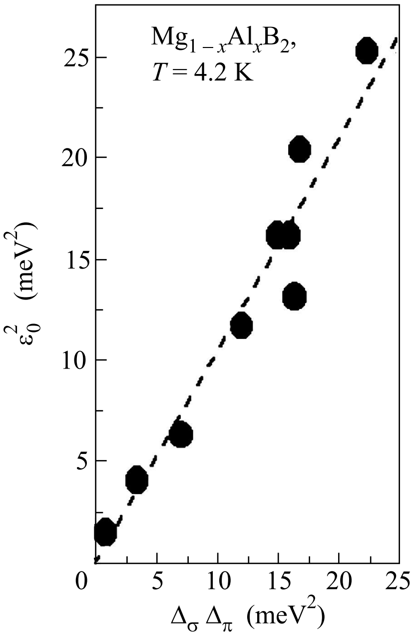

Fig.6.The dependence of the excitation energy squared ε_0^2 upon the product of the gaps $(\Delta_\sigma \Delta_\pi)$ at $T = 4.2$ K for $Mg_{1-x}Al_xB_2$ samples ($40.5\,K \le T_c \le 6.5\,K$)

result is in a qualitative agreement with the theoretical predictions [11, 12].

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