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Evidence for a two-band behavior of MgB_2 from point-contact and tunneling spectroscopy

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Abstract

The break-junction tunneling has been systematically investigated in MgB_2. Two types of the break-junction contacts have been exploited on the same samples, which demonstrated tunnel contact like (SIS) and point contact like (SnS) behavior. Both of them have shown the existence of the two distinct energy gaps. We have also observed peculiarities on the $I(V)$-characteristics related to Leggett's collective mode assisted tunneling.
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The discovery [1] of superconductivity in MgB_2 has attracted considerable attention. The existence of a significant B isotope effect [2] strongly suggested a well-known phonon mediated BCS superconductivity mechanism. On the other hand, theoretical calculations [3–5] as well as experimental observations (see Ref. [6] for a review of experiments) have led to the conclusion that MgB_2 belongs to the class of multi-band superconductors. It was found [3–5] that the Fermi surface consists of two tubular networks arising from three-dimensional π bonding and antibonding bands, and two nearly cylindrical sheets from the two-dimensional σ-bands. Usually, these actually four bands are considered as two effective bands. The superconductivity arises from strong electron-phonon coupling in the 2D σ-bands. The main source of the superconductivity behavior of the π-electrons is their interband coupling to σ-electrons. As a result, there are two distinct energy gaps. The 2D band shows a large gap, $\Delta_\sigma \sim 7-8$ meV, whereas the 3D band has a small gap $\Delta_\pi \sim 2-3$ meV, both closing at the same critical temperature $T_c = 39$ K.

Multi-band superconductors have been studied intensively since the appearance of the original theoretical works [7,8]. One of the most intriguing contributions has been done by Leggett [9]. He has shown that a specific type of collective excitations can exist in two-gap superconductors, which corresponds to small fluctuations of the relative phase of two superconducting condensates. However, these collective excitations have been never observed experimentally in conventional superconductors. The discovery of the two band superconductivity in MgB_2 has renewed the

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interest in Leggett's modes [10–12] and some other phenomena related to the existence of several different superconducting condensate phases [13,14].

A theoretical investigation of the multi-band model for tunneling in MgB_2 junction was done recently [15]. It was shown that there is a possibility to observe either one or two gaps in the tunneling spectra of MgB_2, depending on the tunneling direction, barrier type and impurity concentration. A number of tunneling measurements has been performed on MgB_2 giving evidence of the two-gap behavior (see Ref. [16] and references therein).

In the present investigation the current–voltage characteristics (CVC) of more than 150 break-junctions in polycrystalline MgB_2 samples have been studied in the temperature range $4.2\ \mathrm{K} \leq T \leq T_c$. The break-junction technique allows changing the junction properties during the measurements, so that the tunneling contact like (SIS) and point contact like (SnS) behavior could be investigated on the same sample.

We have used three sets of MgB_2 polycrystalline samples in this investigation. For BBS and KV series the onset of the resistive transition was $T_{c,\mathrm{onset}} = 40.5$ K with the width ~0.3 K. For a BG series the onset of the resistive transition was $T_{c,\mathrm{onset}} = 39$ K with a much wider width ~10 K. A local critical temperature T_c in submicron MgB_2 break junctions has been determined from the temperature dependence of a superconducting gap $\Delta(T)$. For break junctions in BBS- and KV-samples a local critical temperature T_c varied in between 35 and 40.5 K. For junctions in BG-samples a local T_c changed from 22.5 to 36 K.

Fig. 1(a) represents CVCs of a MgB_2 break-junction demonstrating two types of behavior discussed above. One of them corresponds to a typical tunneling junction of the SIS type (curves 1 and 1′) with the DC Josephson current and a gap feature at the bias voltage $V_g = 2\Delta/e$. The other one (curves 2 and 2′) corresponds to a point contact of the SnS type. The main features of the CVCs of such point contacts comprise an excess current and a subharmonic gap structure (SGS), showing sharp dips of a differential conductance $\mathrm{d}I/\mathrm{d}V$ at bias voltages:

$$V = \frac{2\Delta}{en}, \quad \text{with } n = 1, 2... \tag{1}$$

Usually these SGS are explained by multiple Andreev reflections at the SN-interfaces [17]. This type of behavior has been observed many times for conventional superconductors [17] and also for high-T_c superconductors [17,18]. The CVCs of SIS- and SnS-contacts shown on the Fig. 1(a) demonstrate clearly only a small gap $\Delta_\pi = 1.8$ meV. We would like to emphasize that the values of the gap obtained from the differential conductance $\mathrm{d}I(V)/\mathrm{d}V$ in the tunneling regime and from the SGS in the point contact regime coincide very well.

The results presented in Fig. 1(b) show the existence of two gaps: the large gap $\Delta_\sigma = 7.6 \pm 0.4$ meV and the small

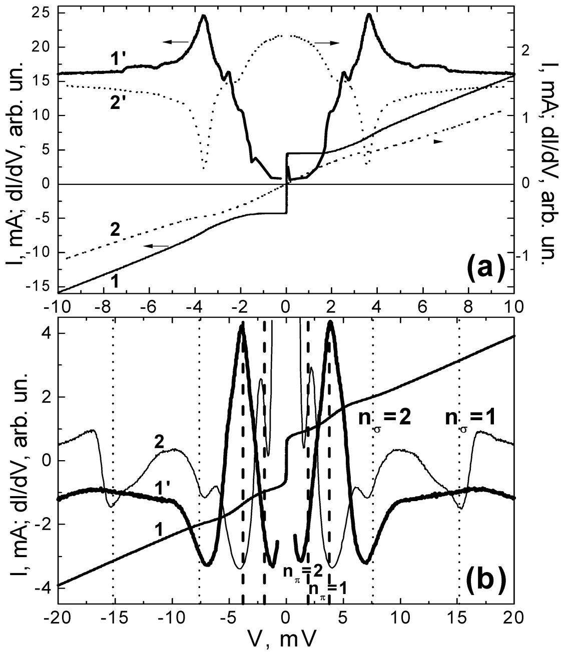

Fig. 1. (a) Small-gap structures ($\Delta_\pi = 1.8$ meV) in the $I(V)$- and $\mathrm{d}I/\mathrm{d}V$-characteristics of a MgB_2 break junction in the tunneling regime (curves 1, 1′) and point-contact regime (curves 2, 2′, SGS comprises $\mathrm{d}I/\mathrm{d}V$-dips at bias voltages $V_n = \pm 2\Delta_\pi/en$ with $n_\pi = 1$ and $n_\pi = 2$) at $T = 4.2$ K (BBS series). (b) Two-gap structures ($\Delta_\sigma = (7.6 \pm 0.4)$ meV, $\Delta_\pi = (1.9 \pm 0.1)$ meV) in the $I(V)$- and $\mathrm{d}I/\mathrm{d}V$-characteristics of a MgB_2 break junction in the tunneling regime (curves 1, 1′) and point-contact regime ($2 - \mathrm{d}I/\mathrm{d}V$) at $T = 4.2$ K (BBS series).

gap $\Delta_\pi = 1.9 \pm 0.1$ meV. In the point contact regime there is a series of dips for $n = 1$ and 2 for both gaps. We would like to mention here that the values of the gaps and their temperature dependence can be observed much easier using the point contacts due to a small width of these dips.

The temperature dependences of both gaps shown in Fig. 2(a) were obtained namely from CVCs of point contacts. The temperature dependence of a large gap $\Delta_\sigma(T)$ is qualitatively close to the BCS type but the ratio $2\Delta_\sigma/kT_c = 5.3$ surpasses the BCS value: 3.52. The temperature dependence of a small gap $\Delta_\pi(T)$ can be different for different junctions. In all cases $\Delta_\pi(T)$ deviates significantly from the BCS type behavior which could be the result of the 'intrinsic proximity' effect ('proximity' effect in k-space). However, both gaps (Δ_σ and Δ_π) close at one and the same critical temperature $T_c = 34.5$ K.

We have found that the typical values of a characteristic voltage $V_c = I_c R_n$ for the investigated MgB_2 Josephson junctions lie within the range 3.0–6.0 mV in good agreement with the theoretical predictions [15]. This result supports indirectly the validity of the two-gap model for MgB_2.

We would like now to discuss shortly some unexpected findings of our investigations. For some of MgB_2-break

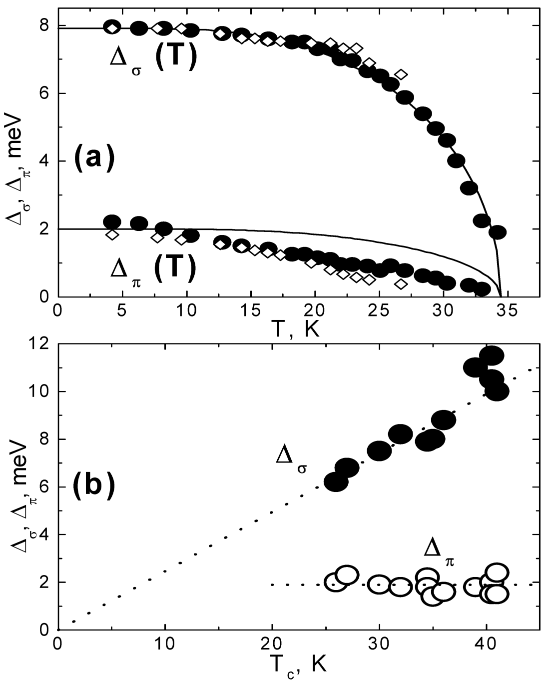

Fig. 2. (a) Evolution of superconducting gaps Δ_σ and Δ_π with the temperature for two MgB_2 SnS contacts ($T_c = 34.5$ K, $2\Delta_\sigma/kT_c = 5.3$, KR series). Solid lines—BCS-type $\Delta(T)$. (b) Variation of the gaps Δ_σ and Δ_π with the critical temperature T_c for the investigated MgB_2 SnS contacts ($T = 4.2$ K).

junctions with a local critical temperature $T_c \cong 37-40.5$ K we have observed the values of a large gap Δ_σ, which exceeded significantly the theoretical estimations [3–5]. Both in tunneling and point-contact regimes we have obtained the values of the large gap of the order $\Delta_\sigma \cong 9 - 11$ meV which leads to the ratio $2\Delta_\sigma/kT_c \cong 5.6 - 6.3$. The large gap of the same order has been also observed using Andreev spectroscopy by Li et al. [19] and by Takasaki et al. [20] on SIS junctions. It can indicate that a much stronger electron–phonon interaction may exist in the 2D Fermi sheets than was previously anticipated.

While investigating SnS contacts with different local T_c we have found that only a large 2D gap Δ_σ scaled with T_c (Fig. 2(b)). At the same time a small 3D gap Δ_π showed no reasonable tendency to change in the range $25\text{ K} \le T_c \le 40.5$ K.

Another and even more unexpected result is shown in Fig. 3. We have observed CVCs of stacks of SIS MgB_2 junctions (with up to five SIS contacts in a stack). The normalized CVCs show clearly the existence of two gaps for all stacks. Moreover, the large gap feature in these CVCs is increasingly pronounced with the increasing number of SIS contacts in a stack. Until recently, such phenomenon has been observed only in cuprate high-T_c superconductors and it was related to the intrinsic Josephson effect (IJE) between the superconducting blocks of CuO_2-planes in c-direction

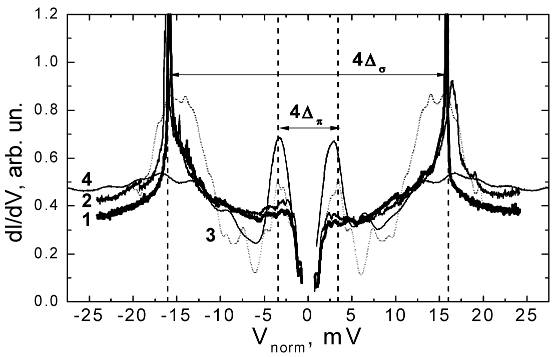

Fig. 3. Two-gap structures in the normalized dI/dV-characteristics of SIS MgB_2 contacts ($T = 4.2$ K, $\Delta_\sigma = 8$ meV, $\Delta_\pi = 1.7$ meV): 1, 2—stacks of 5 SIS contacts, 3—a stack of 2 SIS contacts, 4—a single SIS contact.

[21–23]. The same results have been obtained also for MgB_2 break junctions in the point contact regime. We have registered CVCs of stacks of SnS Andreev contacts (up to six SnS contacts in a stack) with sharp SGS corresponding to Δ_σ and Δ_π. Earlier subharmonic gap structures with strong interference pattern have been reported for stacks of SnS contacts in Bi-2201 (intrinsic multiple Andreev reflections effect (IMARE)) [24]. We believe that these effects are related to the layered structure of MgB_2 and to the existence in boron planes of two-dimensional σ-bands, which have a weak interband coupling with three-dimensional π-bands. It should be noted that an observation of two-gap structures in the CVCs of stacks of SIS or SnS contacts proves a two-gap superconductivity to be an essentially intrinsic property of MgB_2.

As we have mentioned above, multi-band superconductors can possess some special collective excitations due to different values of the order parameter phases in different bands. The existence of such collective modes has been predicted by Leggett [9] and discussed in detail recently in the paper [11] where the expression for the energy ω_0 of this mode has been presented:

$$\omega_0^2 = 4\Delta_1\Delta_2\frac{\lambda_{12}+\lambda_{21}}{\lambda_{11}\lambda_{22}-\lambda_{12}\lambda_{21}}, \tag{2}$$

This formula coincides in fact with that of obtained by Leggett [9]. The values λ_{12} and λ_{21} give the interband coupling between electrons from different bands, λ_{11} and λ_{22} are the intraband coupling constants and Δ_1, Δ_2 are corresponding energy gaps. Using the values of these parameters, obtained in the first-principle calculations [3, 25], the authors of the paper [11] have estimated the plasma mode energy for MgB_2: $6.5 \le \omega_0 \le 8.9$ meV. As it was pointed out in the work [11], to be experimentally observable a Leggett's mode should have the value of ω_0 smaller than twice the smallest gap $2\Delta_1$. Taking into account that $\Delta_1 \cong 2$ meV in MgB_2 they concluded that it is unlikely that this mode could be observed. Nevertheless, we have clearly observed the manifestation of this mode with the energy $\omega_0 \cong 4$ meV in the CVCs of MgB_2 Josephson junctions at $T < T_c$.

The resonance coupling of the AC Josephson current with some other excitations existing inside the contacts have been observed many times. The theory of such phenomenon for the interaction with electromagnetic waves has been developed in Ref. [26]. The coupling of the AC Josephson current with the optical phonons has been studied theoretically in Refs. [27,28]. The latter effect was observed experimentally in Bi-2212 break junctions in the phonon frequency range up to 20 THz [29] and in Bi-2212 mesa structures at frequencies up to 6 THz [21,22,28]. In short, the resonance coupling leads to an enhancement of the DC current flowing through a contact when a bias voltage V_{res} matches the energy of the corresponding excitations. As it was shown in Ref. [26], the resonance coupling can exist also between different harmonics of the AC Josephson current and corresponding excitations. When the discussed peculiarities become important the general expression for a voltage V_{res} may be written as:

$$V_{res} = \frac{n}{m}\frac{\omega_0}{2e}, \tag{3}$$

where n and m are the integer numbers. These peculiarities should be more pronounced in the dI/dV-characteristics.

For several investigated MgB_2 break-junctions we have observed a series of such peculiarities related to the Leggett's mode as it is shown in Fig. 4. We can find features corresponding the following values of n and m : 3/2, 1/1, 1/2, 1/3. The value of the energy of Leggett's mode is of the order $\omega_0 \cong 4$ meV. The form of the CVCs peculiarities shown in Fig. 4 is very similar to that observed in the phonon-assisted tunneling [27–29].

As is well known [30] the resonance coupling with excitations can be also observed in SnS Andreev contacts. In particular, when applying external microwave field to the contact one can register several sets of subharmonic gap structures at bias voltages [30]:

$$V_{n,m} = \frac{2\Delta + m\omega_0}{en}, \tag{4}$$

where ω_0 is a photon energy. In the present investigation we have repeatedly observed in the CVCs of MgB_2 SnS-contacts a reproducible SGS of the type (4) without any external microwave field (Fig. 5). In this case the traditional threshold energy 2Δ could be replaced by $(2\Delta + m\omega_0)$ due to a resonant emission of m Leggett's plasmons in the process of multiple Andreev reflections. From SGS corresponding to the large gap Δ_σ (Fig. 5) we have derived the excitation energy $\omega_0 \cong 4$ meV which could be also a manifestation of the existence of a low-frequency Leggett's plasma mode in a two-gap MgB_2 superconductor.

In general, peculiarities of the same type could also appear due to an interaction of the AC Josephson current with phonons [27–29] or electromagnetic waves [31]. Nevertheless, we believe that the peculiarities observed in the present investigation are related namely to the Leggett's collective excitations. There are a few 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 Josephson current and low-energy acoustic phonons as well as electromagnetic waves 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 resonator systems.

In conclusion, we have observed manifestations of the two-gap behavior of the MgB_2 including the existence of the Leggett's collective mode. We have observed also some unexpected features of the tunneling CVCs. Those are the

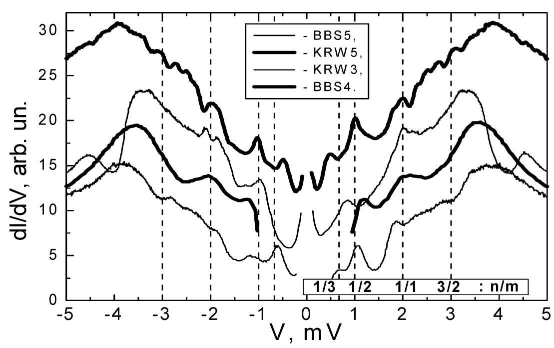

Fig. 4. A fine structure in the dI/dV-characteristics of four different SIS MgB_2 Josephson junctions caused by coupling of the AC Josephson current to a Leggett's plasma mode with the energy $\omega_0 = 4$ meV ($T = 4.2$ K). Dotted lines correspond to the bias voltage $V_{res} = n\omega_0/m2e$ with $n/m = 3/2$, 1/1, 1/2, 1/3.

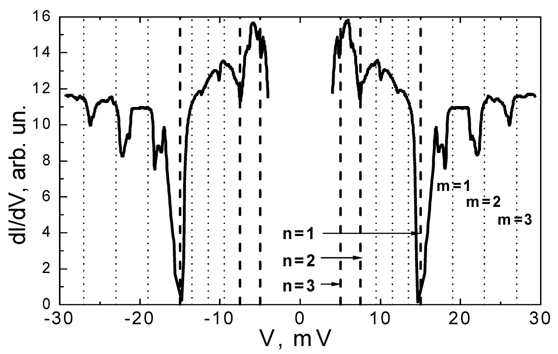

Fig. 5. A subharmonic σ-gap structure with 'satellites' in the d$I(V)$/dV-characteristic of an SnS MgB_2 contact (samp. KRW4, $T = 4.2$ K, $\Delta_\sigma = 7.5$ meV). This type of structure at bias voltages $V_{n,m} = (2\Delta_\sigma + m\omega_0)/en$ could be caused by a resonant emission of m Leggett's plasmons with the energy $\omega_0 = 4$ meV in the process of multiple Andreev reflections (dotted lines—$m = 1, 2, 3$, dashed lines—$m = 0$, $n = 1, 2, 3$).

existence of high values of the energy gap Δ_σ exceeding the theoretical predictions, the IJE and the IMARE similar to that observed in high-T_c superconducting cuprates.

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