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Effect of High Pressure on the Energy Gap of Indium and Thallium Superconducting Films

By

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The effect of high pressure (up to 15000 atm) on the energy gap of In and Tl superconducting films was investigated by the tunnel effect on superconductor–barrier–superconductor systems. As directly found in the experiments, the In values $2\,\Delta/kT_c$ indicate a reduction of the electron–phonon interaction under pressure for this metal. In the range up to 8 katm the value $2\,\Delta/kT_c$ for Tl remained constant within the experimental error and was found to be 3.64 ± 0.06.

Методом туннельного эффекта на системах сверхпроводник–барьер–сверхпроводник изучалось влияние высоких (до 15000 атм) давлений на энергетическую щель сверхпроводящих пленок In и Tl. Непосредственно найденные в экспериментах значения $2\,\Delta/kT_c$ для индия указывают на ослабление электрон-фононного взаимодействия под давлением для этого металла. Для таллия в области давлений до 8 катм в пределах погрешности эксперимента величина $2\,\Delta/kT_c$ оставалась постоянной и составляла $3{,}64 \pm 0{,}06$.

1. Introduction

The central part of microscopic theory of superconductivity [1] is the presence of an energy gap in the spectrum of elementary excitations:

$$\Delta = \frac{\hbar\,\omega}{\sinh\left(\frac{1}{N\,V}\right)}\,, \tag{1}$$

where ω and V are cut-off frequency and interaction strength, respectively, N is the state density on the Fermi surface. In this theory the energy gap is coupled with the critical temperature by the universal relation

$$\frac{2\,\Delta}{kT_c} = 3.528\,. \tag{2}$$

This value characterizes the electron–phonon interaction strength which differs for real superconductors from 3.528, reaching a maximum value of 4.6 for Hg [2].

It is interesting to investigate the influence of different factors on $2\,\Delta/kT_c$ for one crystal modification. In this respect high pressures as a method are most perspective.

In all investigations concerning pressure influence on superconductivity main attention is given to the change of the critical temperature T_c and critical magnetic field H_c [3]. In [4] it was considered that $2\,\Delta/kT_c$ does not change with pressure.

One of the direct experimental methods for the study of the energy gap in superconductors is the electron tunnelling technique. Possibilities of this finest instrument allowed to find out a change of $2\,\Delta/kT_c$ with pressure at first for Pb [5] and then less for Sn [6].

This paper presents results on tunnelling investigations of the energy gap in In and Tl under pressure.

2. Experimental Technique

2.1 Samples

As is known [7] the best gaps can be obtained on superconductor–barrier–superconductor tunnel systems. This made superconducting diodes useful for investigations under pressure. Of all systems investigated the best are pairs prepared on Al base, i.e. an Al–Al_2O_3 superconductor.

Al–I–In and Al–I–Tl samples were prepared by deposition in high (1×10^{-6} Torr) vacuum on a cooled (up to 80 to 100 °K) glass slide 4×16 mm². There were three junctions on one slide, each $1_{Al}\times0.5_{In,\,Tl}$ mm² (Fig. 1). To avoid edge effects films were deposited through stencils supported by an electromagnet. Junction quality in the sense of fitness for their use in pressure measurements much depended on condensation and oxidation conditions of the Al film. Aluminium was sprayed from a tungsten U-vaporizer. During deposition the vacuum did not become worse due to preliminary long annealing (up to vacuum restoration) of the vaporizer and the hinge. Oxidation took place in the atmosphere of dry air at a pressure of 0.2 Torr for 5 min. Sample preparation was controlled by film and junction resistance measurements both during deposition and subsequent heating up to room temperatures. Junctions with resistance 50 to 100 Ω were chosen. Al–I–Tl samples were covered with Si monoxide of about 1 μm thickness. In and Tl film thickness was determined by Linnick's microinterferometer MII-4 and was equal to (1000 ± 100) Å. For Tl films $\frac{R_{300}}{R_{4.2}} = 14$ to 18.

Al films had resistivities of 4000 to 6400 Ω mm², and their initial critical temperature varied from 1.65 to 2 °K.

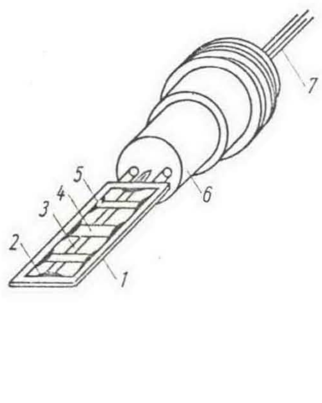

Fig. 1. Tunnel sample and obturator. 1 Sample holder made of getinax, 2 indium contacts, 3 Al film, 4 In and Tl films, 5 cover glass, 6 obturator, 7 electrical wires

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2.2 High pressure technique

A high pressure bomb with kerosene–oil mixture [8] was used in all investigations. Pressure was created at room temperature and controlled by a hydraulic pressure manometer. Here an almost linear change of tunnel junction resistance (e.g. for $R(0) = 100\ \Omega$, $\mathrm{d}R/\mathrm{d}p = 6\ \Omega$/katm) was a reliable indication. Sensitivity of junction resistance to pressures gave the possibility of rejecting samples before immersing into liquid helium. The final pressure in the bomb at low temperatures was calculated from T_c changes of an In wire [9]:

$$T_c = 4.36\times10^{-5}\,p + 5.2\times10^{-10}\,p^2.$$

20 electrical conductors were introduced into the obturator, this allowed measurements to be carried out simultaneously, by means of a 4-probe system, of the critical temperature of films, the In wire, and corresponding tunnel characteristics.

2.3 Cryogenics and measuring apparatus

Low temperature measurements were carried out in a metal cryostat where it was possible to get temperatures from 4.2 to 1.15 °K. The bomb with samples was in liquid helium.

During the experiments the voltage–current characteristic was measured both at constant voltage and constant current conditions. Depending on the condition $\mathrm{d}I/\mathrm{d}U$ or $(\mathrm{d}U/\mathrm{d}I)$–$U$ at a modulation frequency of 383 Hz were plotted.

All tunnel characteristics were recorded automatically on a X–Y coordinate EPP-09-type register. Constant voltage at a sample was measured by a high-ohmic potentiometer to within $\approx 1\ \mu$V during recording.

3. Results and Discussion

Indium: After preparation Al–I–In samples were annealed for some days at room temperature. The critical temperature of In films practically did not differ from T_c for massive pure indium. The halfwidth of the superconducting junction did not exceed 0.01 °K for all pressures. Table 1 gives the change of critical temperature for the film which is found to be

$$\frac{\mathrm{d}T_c}{\mathrm{d}p} = -\,(3.65 \pm 0.15)\times10^{-5}\,\frac{°\mathrm{K}}{\mathrm{atm}},$$

Table 1

T_c and $2\,\Delta$ of indium under pressure

p (katm)	T_c (∓ 0.01 °K)	$t = \frac{T}{T_c}$	$2\,\Delta(p,t)$ (∓ 0.01 meV)	$2\,\Delta/kT_c$ (p,t)	$2\,\Delta(p,0)$ (meV)	$2\,\Delta/kT_c$ $(p,0)$
0	3.42	0.342	1.090	3.69	1.09	3.69
5	3.23	0.36	1.01	3.63	1.02	3.66
7	3.15	0,372	0.982	3.62	0.99	3.64
7.9	3.13	0.374	0.974	3.61	0.98	3.64
10.5	3.03	0.387	0.930	3.57	0.94	3.60
14	2.91	0.4	0.880	3.51	0.89	3.55

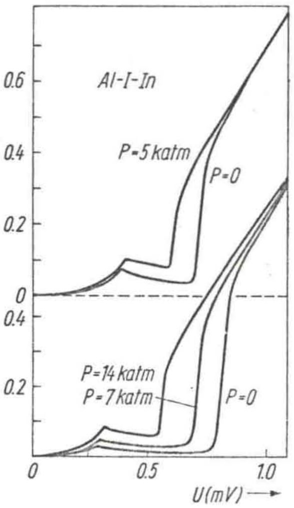


Fig. 2. Current–voltage characteristics of Al–I–In samples at different pressures. $T = (1.17 \pm 0.02)$ °K; normalized units are along the I-axis

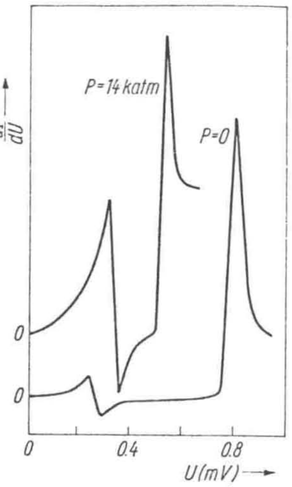


Fig. 3. $\mathrm{d}I/\mathrm{d}U$–U characteristics of Al–I–In samples at different pressures. $T = (1.16 \pm 0.02)$ °K

where the error does not include the inaccuracy in pressure measurement. Such T_c change of In films with pressure excellently coincides with Berman, Brandt, and Ginzburg's measurements [10] on massive indium.

Fig. 2 shows voltage–current characteristics for two Al–I–In samples plotted at different pressures. The energy gap was defined from the maxima of the $(\mathrm{d}I/\mathrm{d}U)$–$U$ characteristics (Fig. 3).

Fig. 4 shows the result of high pressure influence on the energy gap of indium. For comparison the $2\,\Delta(p) = 3.69\,kT_c$ line is drawn which in fact corresponds to the critical temperature change. The gap values obtained by extrapolating $2\Delta(T)$ to $T = 0$ °K are also included in Table 1. From experiments it is found

$$\frac{\mathrm{d}\,2\,\Delta}{\mathrm{d}p} = -\,(1.43 \pm 0.13) \times 10^{-5}\,\frac{\mathrm{meV}}{\mathrm{atm}}\,.$$

The energy gap of In at zero pressure, $2\,\Delta(0.0) = (3.69 \pm 0.04)\,kT_c$, is in good agreement with data obtained from precision measurements of critical field curves [11], where the coefficient defining a deviation from the parabola was found to be

$$a_{\mathrm{In}} = 2\,\pi\,\gamma\,\frac{T_c^2}{H_0^2} = 0.985 \qquad (3)$$

where

$$\gamma = \frac{2}{3}\pi^2\,k^2\,N\,. \qquad (4)$$

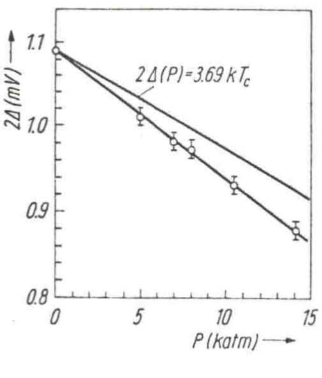
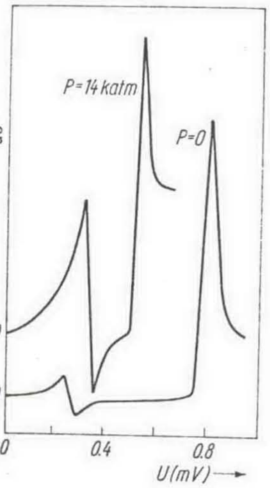


Fig. 4. Change of the superconducting indium energy gap under pressure. o experimental points



…3. dI/dU–U characteristics of Al–I–In samples at different pressures. $T = (1.16 \pm 0.02)$ °K

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$$\gamma = \frac{2}{3}\pi^2 k^2 N\,. \tag{4}$$

… superconducting indium energy gap under pressure. o experimental points

On the basis of the thermodynamic relation [1]

$$\Delta = k\sqrt{\frac{\pi}{6\gamma}}\, H_0 \tag{5}$$

using (3) we have

$$\frac{\Delta}{kT_c} = 1.82\, a^{-\frac{1}{2}}\,. \tag{6}$$

Then from our experiments it follows that the parameter a increases with pressure from 0.985 to 1.04 ($p = 14$ katm), i.e. it approaches the BCS case. Experimenta points $\Delta h = h - (1 - t^2)$ given in [10] for indium clearly show a tendency to the above mentioned increase of a with pressure (see Fig. 6 in [10]). In principle on the basis of (5) one may estimate the change of state density N with pressure. Using our gap data and those of $H_0(p)$ from [10], the state density seems to decrease by no more than 2% at 14 katm.

Thallium: Because of quick oxidation of Tl films Al–I–Tl samples were charged in the bomb immediately after preparation, and control measurement at small pressure were carried out after some compression cycles. After such a procedure the film critical temperature was (2.38 ± 0.01) °K at zero pressure. The energy gap here is $2\Delta(0.0) = (0.75 \pm 0.01)$ meV $= (3.65 \pm 0.06)\, kT_c$, that is in good agreement with Clark's recent measurements [12].

In the small pressure range (2000 to 4000 atm) the anomalous change of critical temperature typical of massive pure Tl [13] was not observed. The critical temperature linearly decreased up to (2.34 ± 0.01) °K at $p = 8$ katm being in qualitative agreement with Gey's data [14] on the dependence of T_c of pure Tl on residual resistance produced by plastic deformation at different pressures.

Fig. 5 shows I–U characteristics for Al–I–Tl at different pressures. The gap value obtained at 8 katm, $2\Delta(8.0) = (0.73 \pm 0.01)$ meV $= (3.64 \pm 0.06)\, kT_c$, shows rather weak dependence in this pressure range. However, this does not exclude the possibility that $2\Delta/kT_c$ changes for thallium at higher pressures. Work in this direction is in progress.

The main result of gap tunnelling measurements in superconductors under pressure is that the effect of $2\Delta/kT_c$ decrease initially discovered on Pb, which is a representative of superconductors with strong electron–phonon interaction, shows different dependence on superconductors with intermediate coupling: In, Sn, and perhaps Tl. This circumstance makes theoretical investigations necessary to obtain a relation connecting the gap

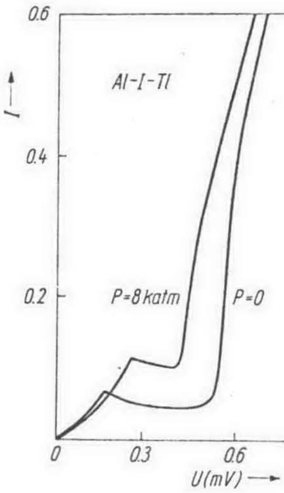

Fig. 5. Voltage–current characteristics of Al–I–Tl samples at different pressures. $T = (1.16 \pm 0.02)$ °K; normalized units are along the I-axis

and critical temperature, taking account of the real energy spectrum of a superconductor, in a manner proposed by Geilikman and Kresin [15], when explaining anomalous superconductor properties.

In conclusion we note that in all our experiments $\mathrm{d}T_c/\mathrm{d}p$ of superfine aluminium films was always larger than for massive material [16] and varied from 3 to 4×10^{-5} °K/atm for different films.[1])

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