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ELECTRON TUNNELLING OF GaAs-Pb JUNCTIONS UNDER HIGH PRESSURE

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Résumé. — Par effet tunnel sur des barrières de Schottky GaAs-Pb, on a étudié la déformation de la bande de conduction et la variation de l'énergie du phonon LO du GaAs, ainsi que la température critique, la bande d'énergie interdite et les énergies caractéristiques de phonons d'un film supraconducteur de plomb en fonction de la pression jusqu'à 30 kbar. On a établi une corrélation entre la variation des différents paramètres supraconducteurs.

Abstract. — The conduction band distortion and LO phonon energy of GaAs, the transition temperature, the energy gap and the phonon energies in superconducting lead film, have been measured at pressures up to 30 kbar by electron tunnelling through Schottky barriers.

The change of the superconducting tunnelling density of states of strong coupling superconductors can be studied successfully by using Schottky barriers as the first tunnelling electrode up to very high pressures [1]. (In fact, the conventional metal-oxide-metal junctions have been used, up to now, for pressures not greater than 14 kbar [2].) However, due to the strong variation of the background tunnelling resistance, the density of states of both electrodes must be considered simultaneously.

In this letter, we report on a study of GaAs-Pb junctions at hydrostatic pressures up to 30 kbar. We have investigated, by the electron tunnelling method, the effect of pressure on the superconducting critical temperature T_c , the energy gap $\Delta(0)$ and the TA and LA energies phonons of Pb.

The junctions were made on a n type GaAs single crystal, oriented along the [111] axis, doped with Te ($N_d = 5.6 \times 10^{18}$ impurities cm^{-3}). The surface of the GaAs is chemically polished according to the procedure described by Guétin and Schreder [3]. After introduction into a high vacuum system the surface is bombarded by 50 eV Ar ions (the ions current is about 10^{11} ions cm^{-2}) and is not annealed afterwards. Next, the Pb film is evaporated, under a pressure below 10^{-9} torr. Its thickness is 1 μm and a typical area of a Pb dot is 1 mm^2 .

The sample is immersed in the teflon pressure cell filled with the pressure transmitting fluid (isopentane

and isoamelic alcohol mixture). The hydrostatic pressure system is a double stage steel bomb delivering a pressure between 0 to 35 kbar in a range of temperature between 2 K and room temperature [4]. The high pressure stage uses a teflon cell which acts as an automatic pressure seal. The pressure is measured using the resistance variation of a manganin gauge placed inside the teflon cell : precision of the experimental pressure data is ± 0.5 kbar.

Figure 1 gives the variation of the tunnelling resistance dV/dI at zero bias *versus* the applied pressure P at 300 K, for several junctions. The increase of the resistance with P can be described by two linear variations which show a nearly exponential variation in each domain. The behaviour between 0 to 20 kbar can be explained in terms of the barrier height variation ; the slope $d(dV/dI)/dP$ is identical to values reported for GaAs junctions prepared on a cleaved surface [5]. At 20 kbar, a slope difference appears. The Aspnes model for the GaAs conduction band shows that the inversion of the low-energy valleys Γ_L and Γ_X of the conduction band appears respectively above 25 kbar and 40 kbar [6]. The same result was found by Pitt and Lees [7]. So the second domain in figure 1 is probably due to the limitation of $\mu_F(000)$, the Fermi degeneracy in the central direction, by the upper valley L which gives a transfer, in GaAs, of electrons from the Γ to the L minima. Attempts made to obtain the second inversion gap at higher pressures have not been convincing.

The energy of the LO phonon of GaAs varies

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FIG. 1. — Pressure dependence of $(dV)/(dI)$ at null bias at 300 K, for several functions.

linearly with pressure as shown in figure 2. The slope $d\omega_{LO}/dP$ is $(7.0 \pm 0.2) 10^{-5}$ meV/kbar and the experimental data points are in good agreement with previously reported results [5].

The variation of T_c and $\Delta(0)$ with pressure are shown in figure 3. T_c was determined by the first departure of the zero bias tunnelling conductance from its normal state value. $\Delta(0)$ was calculated from the tunnelling conductance using standard techniques [8]. The pressure dependence of $\Delta(0)$ and T_c

FIG. 2. — Pressure dependence of the zone centre optical phonon energy of GaAs. (□) are for the reference [5].

FIG. 3. — Critical temperature (curve a) and energy gap (curve b) versus pressure for superconducting lead.

can be described by straight lines whose slopes are given in table I. The ratio $2\Delta(0)/k_B T_c$ which decreases

TABLE I

Pressure dependence of some superconductive parameters measured by tunnelling effect on Pb

X	$dX/dP \times 10^6$		$d \log X/dP \times 10^6 \text{ bar}^{-1}$		$d \log X/d \ln V$	
	our results	previous results	our results	previous results	our results	previous results
T_c (K)	$-35.5 \pm 0.2 \text{ K bar}^{-1}$	-36.1 K bar^{-1} [11]	-5.55 ± 0.1	-5.27 ± 0.1 [10]		
$\Delta(0)$ (meV)	$-13.2 \pm 0.1 \text{ meV bar}^{-1}$	$-12.25 \pm 0.15 \text{ meV bar}^{-1}$ [2] $-12.2 \pm 0.1 \text{ meV bar}^{-1}$ [5]	-11.53	-8.6 ± 0.5 [2]		
ω_{TA} (meV)	$22.5 \pm 0.5 \text{ meV bar}^{-1}$	$33 \pm 0.4 \text{ meV bar}^{-1}$ [2] $45 \pm 0.6 \text{ meV bar}^{-1}$ [9]	4.75	7.28 ± 1 [2] 5.3 [11]	2.19	2.6 [12]
ω_{LA} (meV)	$49 \pm 0.5 \text{ meV bar}^{-1}$	$64 \pm 0.4 \text{ meV bar}^{-1}$ [2] $60 \pm 0.6 \text{ meV bar}^{-1}$ [9]	5.46	7.5 ± 0.5 [2] 7.05 ± 0.7 [11]	2.51	3.4 [12]

with pressure from 4.50 at $P = 0$ to 3.78 at 30 kbar indicates a weakening of the electron phonon coupling term. The variations of the energies of phonons, obtained from the second harmonic tunnelling characteristics, are shown in figure 4. In table I we noted the slopes of the best straight line fits with these data and the corresponding Grüneisen constant γ , calculated with a bulk modulus equal to 4.6×10^5 bar [13]. The origin of these lines at $P = 0$ are the values found by McMillan and Rowell [8]. The Grüneisen values obtained for the phonon energies are smaller in our measurement than the values determined by Franck and Keeler [12]. But these previous experiments have been performed at a pressure lower than ours ($P \sim 3$ kbar) and it is reasonable to assume a change of the force constants of the atomic interactions with pressure.

FIG. 4. — Phonons energies TA and LA versus pressure for superconducting lead. The inset is a second harmonic characteristic indicating the measured extrema.

Although a direct measurement of the pressure effects on superconductivity can be performed from the tunnelling density of states using the McMillan program [8], the strong variation of the background tunnelling conductance for Schottky barriers does not yet allow us to use it. Consequently, in order to make an estimate for the pressure dependence of the transition temperature, we have solved the Eliashberg equations [8] for different variations of $\alpha^2(\omega) F(\omega)$, the electron-phonon spectral function.

According to Allen and Dynes [14], T_c is given by :

$$T_c = \frac{\langle \omega \rangle}{1.20} \exp - \frac{1.04(1 + \lambda)}{\lambda - \mu^*(1 + 0.62 \lambda)}.$$

The electron-phonon coupling constant is λ ; $\langle \omega \rangle$ is a frequency average on $\alpha^2(\omega) F(\omega)$ and μ^* the Coulomb pseudo-potential. The pressure effect is induced in the phonon density of states by assuming that the shift of $\alpha^2 F$ to higher energies is given by the following formula [13] :

$$\alpha^2(\beta\omega) F(\beta\omega) \sim \frac{1}{\beta^2} \alpha_0^2(\omega) F_0(\omega)$$

where $\alpha_0^2(\omega) F_0(\omega)$ is the phonon density of states at $P = 0$. The experimental β value for a given pressure is obtained from the measured shift in energy of the phonon structure (Fig. 4). The pressure dependence of μ^* is considered to be small and is neglected [13] : we take the constant value $\mu^* = 0.13$. Table II gives the transition temperatures obtained following this procedure. It appears that the theoretical values of T_c are systematically lower than the experimental ones but the calculated slope

$$\frac{dT_c}{dP} = (-33.3 \pm 0.5) 10^6 \text{ K bar}^{-1}$$

agrees very well with our experimental determination.

We have also given in table II the theoretical value of the scaling factor $\beta = 1 - (\Delta V/V) \bar{\gamma}$ where $\bar{\gamma}$ is an average value of the Grüneisen parameter for all the phonons : $\bar{\gamma}$ is chosen equal to 2.85 for Pb [13] and the variation of $\Delta V/V$ with pressure is given by Miller *et al.* [15].

TABLE II

Calculated transition temperatures for different pressures and comparison of β parameter with theoretical estimates

P kbar	$\Delta(0)$ meV exp.	β exp.	β theor.	$\langle \omega \rangle$ meV	λ	T_c theor.
0	1.41	1	1	5.21	1.57	6.54
10	1.27	1.051	1.063	5.48	1.39	6.23
20	1.125	1.131	1.139	5.91	1.29	5.96
25	1.05	1.160	1.142	6.06	1.23	5.74
30	1	1.173	1.168	6.137	1.19	5.55

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