Electron-phonon interaction and nonlinear transport phenomena in solid Hg point-contacts

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Abstract. At cryogenic temperatures the conductivity of Hg point-contacts was studied in both the superconducting and normal state. An original method of fabricating the Hg-based point-contacts directly in liquid ⁴He was proposed, which guaranteed creation of small-size high-purity ballistic contacts. The resistance of the contacts as well as the current-voltage characteristics along with the voltage dependence of their first and second derivatives were experimentally investigated at 1.5 K. We analyze such characteristics of the contacts as Josephson critical current, excess current, energy gap and the nonlinear part of conductivity caused by electron-phonon interaction (EPI). The point-contact EPI function $g_{pc}(\omega)$ for Hg was reconstructed and integral parameters of EPI were calculated. The $g_{pc}(\omega)$ was then used as an approximation to the phonon density of states for estimations of the thermodynamic characteristics in Hg. Finally we discuss the results of our calculations of non-linear conductivity caused by manifestation of the frequency dependence of the energy gap function in the elastic current component through the contact.

1. Introduction
Among all metallic elements, the record-breaking value of the electron-phonon interaction (EPI) constant belongs to the crystalline mercury [1]. The latter stimulates interest to this metal, which is the type one superconductor, and can be considered as a valuable model object for the spectroscopy of phonons. Up to now, despite apparent experimental possibilities, reliable information on the EPI spectrum and the phonon density of states (PDOS) in solid mercury has been limited to only few publications [2,3], where the Eliashberg EPI function obtained by means of the tunneling effect in superconducting state and the PDOS reconstructed from neutron scattering data were presented. Here we introduce our results of studying the EPI in crystalline mercury in normal and superconducting state by means of the point-contact spectroscopy [4] at low temperatures.

2. Experiment
Electrical characteristics of the point-contacts Hg/Hg and heterocontacts Hg/normal-metal were studied in both normal and superconducting state of the mercury-electrode. All the measurements were carried out at as low temperature as 1.5 – 2 K, when, in particular, the value of the superconducting
energy gap parameter in Hg was close to its theoretically expected limit at $T = 0$. If necessary the superconductivity of the mercury-electrodes was suppressed by an external magnetic field.

The small-size point-contacts were fabricated directly in liquid Helium between two mercury coatings deposited at room temperature by exposing of the suitable substrate-electrodes to a mercury bath prior rapid cooling inside a cryostat. In the course of the fabrication the bulk electrodes initially touched one another by their side surfaces. Then a subsequent small shift in the plane of the mechanical contact was performed to create every time a new point-contact [4]. We exploit also an original newly developed fabrication method based on twisting of two mercury-coated wires or thin foil stripes [5]. Prior to mercury deposition the surface of the electrodes was chemically or electro-chemically polished. The thickness of the mercury coating layer ranged 5-20 µm. It was determined by different independent methods like an optical microscopy, weight analysis, etc., which provided well-agreed results. It is important to note that for all the electrodes employed the thickness of the mercury layer was much greater than the diameter of the effective phonon-generation volume, and also the average electron mean-free path. Thus, such coatings can be regarded as bulk mercury-electrodes.

The static resistance $R_0$ at zero bias voltage in the normal state of the point-contacts was measured, which usually averaged several Ohms. In addition to the current-voltage characteristics (IVC) $I(V)$, their first derivatives $dV/dI(V) = R(V)$, where $R(V)$ is the differential resistance, and second derivatives $d^2V/dI^2(V)$ were recorded for the normal and superconducting state of the mercury-electrode. The standard modulation technique was employed.

In the case of the superconducting Hg/Hg point-contacts the Josephson critical current $I_c$ and the superconducting gap parameter $2\Delta$ were defined experimentally while for the contacts Hg/normal-metal we analyzed the voltage dependence of the excess current $I_{exc}(V) = \text{sign}(V) [I(V) - V/R_{st}(V)]$, where $R_{st}(V)$ is the static resistance of the point-contact in the normal state.

3. Results and discussion
The reconstruction of the point-contact EPI function $g_{pc}(\omega)$ in the normal state of Hg/Hg contacts, when the nonlinearities of the IVC were predominantly caused by inelastic processes of EPI, was performed following the approach described in [4]. Graphical representation of the $g_{pc}(\omega)$ is given at figure 1. along with the Eliashberg EPI function $g(\omega)$, which was obtained from tunnelling data [2].

![Figure 1](image.png)

**Figure 1.** Point-contact EPI function $g_{pc}(\omega)$ for Hg (solid line) and Eliashberg EPI function $g(\omega)$ [2] (dashed line). The thermal smearing, which corresponds to $T = 1.5$ K, has been applied to $g(\omega)$ (dots) for better comparison with the point-contact experimental data.
The existing discrepancy in the EPI functions can be quite reasonably explained by influence of the point-contact form-factor on the \( g_{pc}(\omega) \). However, it is very significant that the mean phonon frequencies \( < \omega > = 3.3 \text{ meV} \) and \( < \omega^2 >^{1/2} = 4.2 \text{ meV} \), which were calculated for the \( g_{pc}(\omega) \), match precisely the known tunnelling results \([2]\). Moreover, the value of the EPI constant \( \lambda = 1.60 \) from \([2]\) is very close to our estimation \( \lambda_{pc} = 1.55 \) made in the isotropic square dispersion law approximation, which is adequate in the given case for great majority of \( sp \)-metals \([6]\).

Being normalized to unity the \( g_{pc}(\omega) \) function can afford a good approximation to the PDOS in calculations of thermodynamic properties of the solid mercury. In particular, we estimated the low-temperature limit of the calorimetric Debye temperature as 73 K. The last-mentioned corresponds well to known calorimetric data.

The gap parameter \( 2\Delta = 1.60 \text{ meV} \) at \( T = 1.5 K \) was obtained by means of a direct experimental method using clearly-pronounced sub-harmonic gap peculiarities at the IVC-derivatives of the superconducting Hg/Hg point-contacts, which are related to the processes of the multiple Andreev reflection in the contact region \([7]\). The above parameter is in a reasonable agreement with the zero-temperature value \( 2\Delta_0 = 1.60 \text{ meV} \) \([8]\).

In order to determine values of the Josephson critical current \( I_c \) in superconducting Hg point-contacts and the excess current \( I_{exc} \) for the heterocontacts with a mercury-electrode we made readings of the currents at voltages corresponding to \( 6\Delta_0 \) and \( 3\Delta_0 \) respectively. It was defined experimentally that at \( T = 1.5 K \), which is far below the critical temperature \( T_c = 4.19 \text{ K} \) for mercury, the numerical values of products \( p_c = I_c R_0 / \Delta_0 = 3.0 \) and \( p_{exc} = I_{exc} e R_0 / \Delta_0 = 2.5 \) at voltages \( V > 2\Delta_0 / e \) were close to the theoretically expected figures \( p_c = 3.14, \ p_{exc} = 2.67 \) at \( T = 0 \) in the clean-contact limit (see table 3 in \([4]\)). We found that for our best-quality Hg/Cu heterocontacts the values of \( I_{exc} e R_0 / \Delta_0 \) were asymptotic to \( 4/3 \), which was the estimated limit for the clean ballistic superconductor/normal-metal point-contact \([4]\). This is a convincing proof of the ballistic behavior of carriers inside the contact region.

The theory \([9]\) predicts the non-linear behavior of the differential conductivity of the superconductor/normal-metal point-contacts comprising a superconductor with the strong EPI. Such nonlinearities are associated with the inelastic current component, which is modulated by the strong energy dependence of the complex superconducting gap function \( \Delta(\omega) \), and can reach a few percent of the \( R_0 \). The first and the second derivatives of the IVC for the Hg/normal-metal contact were calculated using the tabulated data \([8]\) on the real and imaginary parts of the complex \( \Delta(\omega) \) function for Hg. The calculation revealed a maximum of the differential conductivity located at the energy of the main peak in the EPI spectrum of mercury. The experimentally recorded nonlinearity at the second IVC derivative reproduces the shape of the calculated peak. Further experimental study of such point-contacts perhaps requires somewhat better separation of the elastic and inelastic terms in the contact conductivity. For this reason the CuBe-brass was selected as an ultimate material for the normal electrodes. The short average electron mean-free path in this alloy makes it possible to suppress the contribution from the inelastic processes of EPI to the point-contact resistance and purify this way the nonlinearities caused by manifestation of the frequency dependence of the gap function in the elastic current component through the contact. It should be noticed that in our test experiments with the normal Hg/CuBe-brass point-contacts the inelastic EPI did not contribute noticeable nonlinear terms to the IVC second derivatives. While carrying out the same sort experiments with the brass/brass contacts the derivatives were presented by monotonous curves.

4. Conclusion

We have developed the technology of creation of the point-contacts with mercury-coated electrodes. Our experimental studies and subsequent analysis revealed that good-quality pure ballistic point contacts can be routinely fabricated using a range of different type metallic substrates. The EPI point-contact function and integral parameters of the EPI spectrum were obtained. Point-contacts with a superconducting electrode can provide additional source of experimental data for reconstruction of the spectral EPI function in strong-coupled superconductors.
References

[1] Wolf E L 1985 *Principles of electron tunnelling spectroscopy* New York, Oxford Univ. press; Oxford, Clarendon press

[2] Hubin W N and Grinsberg D M 1969 *Phys. Rev.* **188** 716

[3] Kamitakahara W M, Smith H G and Wakabayashi N 1977 *Ferroelectrics* **16** 111

[4] Khotkevich A V and Yanson I K 1995 *Atlas of point-contact spectra of electron-phonon interaction in metals* Kluwer Academic Publishers, Boston-Dordrecht-London

[5] Fisun V V, Khotkevich A V, Alexandrov Yu L and Kamarchuk G V 2008 Patent UA 29170 Ukraine

[6] Khotkevich A V 1990 *Abstr. Doct. Habil. Thesis* Inst. Low Temp. Phys & Eng., Kharkiv

[7] Najdyuk Yu G and Yanson I K 2004 *Point-contact spectroscopy* Springer, New York

[8] Rowell J M, McMillan W L and Dynes R C 1973 *Prepr. Bell Labs* Murray Hill, NJ

[9] Omelyanchuk A N, Beloborod’ko E I and Kulik I O 1988 *Sov. J. Low Temp. Phys.* **14** 630