Power dissipation in metal-vacuum-metal tunnel junctions

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Abstract. We report on the mutual relationship between the current-voltage (I-V) and power-voltage (P-V) characteristics in metal-vacuum-metal tunnel junctions (TJs). Performed studies of power redistribution between individual electrodes of TJ have shown good correlation of measured P-V curves with ones numerically derived from I-V characteristics. This supports our earlier proposal that careful studies of power dissipation in individual electrodes of TJ by tunneling calorimetry could be a source of similar spectroscopic information as that derived from I-V characteristics. Moreover, we advert to the possibility to extend the tunneling calorimetry for detection of energy emission processes due to charge tunneling, what represents a base for development of qualitatively new scanning probe microscopy techniques.

1. Introduction

An interesting consequence of charge carriers tunneling in metal-insulator-metal tunnel structures is voltage-dependent redistribution of the dissipated power between the individual TJ electrodes [1, 2]. The self-heating in the Coulomb-blockade electrometer due to electron tunneling at very low temperatures can lead to a significant rise in the electron temperature, producing an appreciable change in the electrometer characteristics [2]. On the other hand, (normal-)metal-insulator-superconductor (NIS) and SINIS tunnel structures that can be used to manipulate the Fermi–Dirac distribution of electrons in the normal electrode in order to cool them well below the lattice temperature [3–5]. However, an important technical problem in studies of electron refrigeration in NIS-based structures, as well as in thermoelectric studies of TJs in general, represents a parasitic thermal coupling between TJ electrodes due to a solid-state tunnel barrier.

Recently we reported a qualitatively new approach to the power dissipation (and other thermoelectric properties) studies in TJs [6]. The experimental setup, assigned as the calorimetric tunneling experiment (CTE), utilizing the tunneling between a “tip” and a “sample” through a vacuum tunnel barrier by means of the scanning tunneling microscopy (as depicted in Fig. 1a), eliminates the problem of thermal coupling between the TJ electrodes. Because the sample is installed on the platform of the semiadiabatic calorimeter, the CTE enables an exact determination of the power dissipated in the sample due to the tunneling. In the special case when both TJ electrodes (the “tip” and the “sample”) are from the same material, the CTE allows an exact determination of the power redistribution between the TJ electrodes [6].
Figure 1. Schematic depiction of the CTE (a) and the energy scheme of metal-insulator-metal TJ at external bias voltage $V$ (b). Elastic electron tunneling process at the energy $E$, marked by an arrow, is followed by inelastic processes accompanied by emission of quasiparticles with total energy $E$ and $eV - E$ in the positive and negative electrode, respectively. Both electrodes are from the same metal with the output work $\phi$.

The process of power dissipation in metal-insulator-metal tunnel structure can be understood based on the energy diagram in Fig. 1b. The net tunnel current $I$ through the barrier can be expressed in the form

$$I = e \int_{-\infty}^{+\infty} n(E) dE,$$  \hspace{1cm} (1)

where $e$ is the charge of electron and $n(E)$ is the number of electrons tunneled per one second at the energy $E$, counted from the Fermi level of the positive electrode. As a consequence of the elastic electron tunneling at energy $E$, after passing the barrier the electron appears in an excited state with an excess energy $E$ (in the positive electrode). Subsequently, the electron is brought into the equilibrium state via inelastic process(es), generating non-equilibrium quasiparticles with the total energy $E$. On the other hand, an empty state (non-equilibrium hole) is created in the negative electrode, which has to be filled by the electron(s) from higher energy level(s), what is connected with inelastic electron process(es) of the total energy $eV - E$. Thus, based on the Eq. (1) and considering that the energy of all inelastic electron processes in both TJ electrodes will be as a result converted to heat, the power dissipated in the positive and negative electrode, $P^+$ and $P^-$, respectively, can be expressed by

$$P^+ = \int_{-\infty}^{+\infty} En(E) dE$$ \hspace{1cm} (2)

$$P^- = \int_{-\infty}^{+\infty} (eV - E)n(E) dE.$$ \hspace{1cm} (3)

The total power dissipated in the TJ is then given by

$$P^+ + P^- = VI.$$ \hspace{1cm} (4)

As follows from the Eqs. (1), (2) and (3), there is a clear relationship between the current-voltage ($I$-$V$) and power-voltage ($P$-$V$) characteristics. The purpose of the presented work is a direct experimental verification of this relationship.
2. Experiment
The studies of power dissipation were performed at 0.5 K in a commercial Oxford Instruments $^3$He refrigerator. The experimental setup for the tunneling calorimetry was the same as one of the CTE described before [6], however, the Lake Shore CERNOX CX-1050 thermometer was used instead of bare chip Ge–thermometer. The heat power generated in the sample due to the tunnel current was derived from the increase of the calorimeter platform temperature for positively- and negatively-biased sample. The $I$-$V$ dependence of the TJ was measured by means of the scanning tunneling spectroscopy approach (at a fixed tip – sample distance). The tip and the sample were prepared from the same gold based alloy Au$_{0.7}$Cu$_{0.16}$Ag$_{0.14}$.

3. Results and discussion
A representative $I$-$V$ characteristic of the TJ for $|V| < 0.6$ V is shown in Fig 2a. In accordance with the model for the metal-insulator-metal type of TJ [7], if the applied bias voltage is not too high, the $I$-$V$ dependence is adequately described by

$$I(V) = \alpha V + \gamma V^3,$$

where $\alpha$ and $\gamma$ are constants [7]. The analysis of the data shown in Fig. 2a in accordance with the regression model given by Eq. (5) yields $\alpha = 1.97$ nA/V and $\gamma = 1.44$ nA/V$^3$.

The $P$-$V$ dependences for both TJ electrodes measured at the constant tunnel current $I_t = 10$ nA are depicted in Fig. 2b. The curves show the expected behavior; at low-voltage limit the power is redistributed symmetrically, while the redistribution becomes asymmetric at higher voltage. The total power dissipated in the TJ is equal to $VI_t$, indicating that all energy of inelastic processes is converted to the heat. At sufficiently low temperatures one can consider $n(E) = 0$ for $E < 0$ and $E > eV$, what enables a simple calculation of $P$-$V$ curves from $I$-$V$ ones. Based on equations (1), (2) and (3) it can be easily shown that in TJs with $I$-$V$ dependence expressed by Eq. (5) the power $P^+$ and $P^-$, dissipated in the positive and negative TJ electrode, respectively, are given by

$$P^+ = \frac{\alpha V^2}{2} + \frac{3\gamma V^4}{4},$$

$$P^- = \frac{\alpha V^2}{2} + \frac{\gamma V^4}{4}.$$
The power-voltage dependencies given by Eqs. (6) and (7) correspond to the TJs with fixed tip–sample distance. As in our experiments the tunnel current \( I_t \) was kept constant, the experimentally measured power dissipated in the positively- and negatively-biased sample, \( P_m^+ \) and \( P_m^- \), can be expressed by \( P_m^+(V) = P^+(V)I_t/I(V) \) and \( P_m^-(V) = P^-(V)I_t/I(V) \), respectively, where \( I(V) \), \( P^+(V) \) and \( P^-(V) \) are given by Eqs. (5), (6) and (7). Calculated \( P_m^+(V) \) and \( P_m^-(V) \) dependencies (using the parameters \( \alpha = 1.97 \, \text{nA/V} \), \( \gamma = 1.44 \, \text{nA/V}^3 \) and \( I_t = 10 \, \text{nA} \)), shown in the Fig. 2b, reveal good agreement with the experimental data.

The presented results support our earlier proposal that if there is no energy escape from the tunnel structure, the careful studies of power dissipation processes in the individual electrodes of TJ can be a source of similar spectroscopic information as that derived from \( I-V \) characteristics [6,8]. However, even more advantageous applications of the tunneling calorimetry can be proposed for situations, where tunneling process is accompanied by an energy emission (e.g. light emission); in such cases Eq. (4) is not longer valid. The realization of the tip holder as a system with another calorimeter (see Fig. 1a) should enable to measure the power dissipation in both TJ electrodes simultaneously and to detect the decrease of total power generated in the TJ electrodes (as an indication of the “missing power” not converted to the heat). Moreover, using a 3-D piezo transducer, the system can be extended to a scanning probe microscopy (SPM) type technique capable to visualize intensity of energy emission due to electron tunneling between the tip and the studied surface. Such method could represent an alternative approach for studies of photon emission due to charge tunneling, for instance, a “classic” optical approach for detection of photons in the STM studies of luminescence from the metallic quantum wells caused by the tunneling current (see e.g. [9]) could be replaced by the tunneling calorimetry.

4. Summary

Our studies of current-voltage and power dissipation characteristics in vacuum-barrier TJs have shown a good agreement between the \( P-V \) characteristics obtained by the tunneling calorimetry and those numerically derived from \( I-V \) curves for both, positively- and negatively-biased TJ electrode. This supports our earlier proposal that if there is no energy escape from the tunnel structure, careful tunneling calorimetry studies of the power dissipation processes in the individual electrodes of the TJ can be a source of similar spectroscopic information as that derived from the \( I-V \) characteristics. We have also pointed out that even more advantageous applications for the tunneling calorimetry can be found in the field of detection of energy emission due to the tunnel current, and the principle of the original SPM type technique has been sketched.

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