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Photon-assisted tunneling in normal-metal point contacts

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It is shown experimentally that the response of normal-metal point contacts at low temperatures to radiation starts to deviate from classical detection when the frequency approaches the Debye frequency. The high-frequency response can be described with the photon-assisted tunneling (PAT) theory. This implies the first observation of the PAT effect in a nonlinear element where no superconductor is involved.

Understanding the interaction of radiation with nonlinear electrical devices such as tunneling junctions and point contacts is of great fundamental importance. This is, moreover, of interest because these nonlinear devices are commonly used in high-frequency applications. In the simplest approach, the high-frequency response is straightforwardly described in terms of rectification. It is well known that the superconducting devices require a more fundamental treatment: either their response is governed by the Josephson effect[1] or by the photon-assisted tunneling (PAT) effect.[2] Although it was recognized on theoretical grounds that the PAT effect should hold for a general class of tunneling devices,[3] up to now it was intimately connected to superconducting tunneling junctions.

In the present work, it is shown experimentally that the PAT effect applies to the high-frequency response of the normal-metal point contact at low temperatures. This observation in a device where no superconductor is involved is the first experimental indication for the general applicability of the effect. In addition, the thorough microscopic understanding of the normal-metal point contact[4] allows an easy physical interpretation for the occurrence of the effect. Reversely, the high-frequency response can be viewed as a new and independent probe of the processes taking place in the point-contact problem, fully supporting the existing picture.[4] Moreover, a rigorous derivation of the PAT effect in case of a normal-metal point contact has recently become available.[5]

The current-voltage characteristic of a point contact with contact diameter a small compared to the electron mean free path l (inelastic scattering) is nonlinear.[4] Under the condition $l \gtrsim a$ the electrons are accelerated to an energy eV after traversing the contact when a voltage is applied (e is the electron charge). The energy dependence of l, caused by the energy dependence of electron-phonon scattering, is reflected in the resistance of the contact. A crucial parameter in the point-contact problem, therefore, is the mean free path, or equivalently, the scattering time τ ($l = v_F\tau$, v_F Fermi velocity). The scattering time is expected to govern the high-frequency response of the point contact. The high-frequency response of the point contact was previously investigated in the classical regime $\omega\tau < 1$ (ω is the frequency).[6] The results could be interpreted in terms of a simple rectification model. For the present work, the measurements are extended to a higher-frequency range, where the classical model turns out to be invalid.

The experimental technique is the same as that used before.[6] An adjustable copper-copper point contact is located at the end of a lightpipe in a liquid-helium Dewar. The lightpipe is irradiated by a far-infrared laser. The thin wire which forms one part of the contact functions as an antenna and generates alternating current across the contact at the laser frequency. Because of the nonlinear characteristics, the ac currents generate a dc voltage, which is recorded as a function of applied bias voltage. Phase sensitive detection is used by chopping the laser beam at 560 Hz.

The typical experimental results are displayed in Fig. 1. The upper curve in Fig. 1(a) is the second derivative (d^2V/dI^2) of the contact, obtained by current modulation techniques. It represents a typical point contact spectrum,[4] the main peak corresponding to the Debye frequency ω_D. The lower curve in Fig. 1(a) shows the laser-induced voltage $V_{\rm dc}$ as a function of bias voltage for a laser frequency of 525 GHz. $V_{\rm dc}$ is accurately proportional to d^2V/dI^2. This can easily be explained if the contact is considered as a classical rectifier in the small signal limit, assuming the current is modulated as $I = I_0 + i_0\cos(\omega t)$.[6] I is the total current through the contact, I_0 the dc bias current, i_0 the amplitude of the laser-induced current, and ω the angular laser frequency.

The upper curve in Fig. 1(b) again shows the second derivative of another point contact. The lower curve displays the laser response of the same contact, but now for a laser frequency of 2523 GHz. In contrast to the previous case, now $V_{\rm dc}$ is no longer proportional to d^2V/dI^2; instead a considerable broadening occurs. Note also that the structure near zero bias voltage has disappeared. The data were taken at sufficiently low power levels, so that broadening due to overmodulation can be ruled out. A dc d^2V/dI^2 characteristic as shown in Fig. 1, was recorded immediately before and after the laser data were taken to enable a comparison of dc and high-frequency data, all taken on the same contact. A broadening of the laser-induced signal was consistently observed at the higher frequency only. This ensures that the broadening is not of accidental origin. Moreover, the broadening is well outside the range of typical variations from contact to contact. The dashed line in Fig. 1 is a fit, which makes use of the PAT expression:[2]

$$I_{\rm dc}^{\rm rad}(V_0) = \sum_{n=-\infty}^{\infty} J_n^2(\alpha) I(V_0 + n(\hbar\omega/e)) \ . \qquad (1)$$

$I_{\rm dc}^{\rm rad}(V_0)$ is the dc current at dc bias voltage V_0 when radiation is applied. $I(V)$ is the current-voltage characteristic without radiation. It is assumed that the contact is voltage driven and the voltage varies as $V = V_0 + V_1\cos(\omega t)$. J_n are

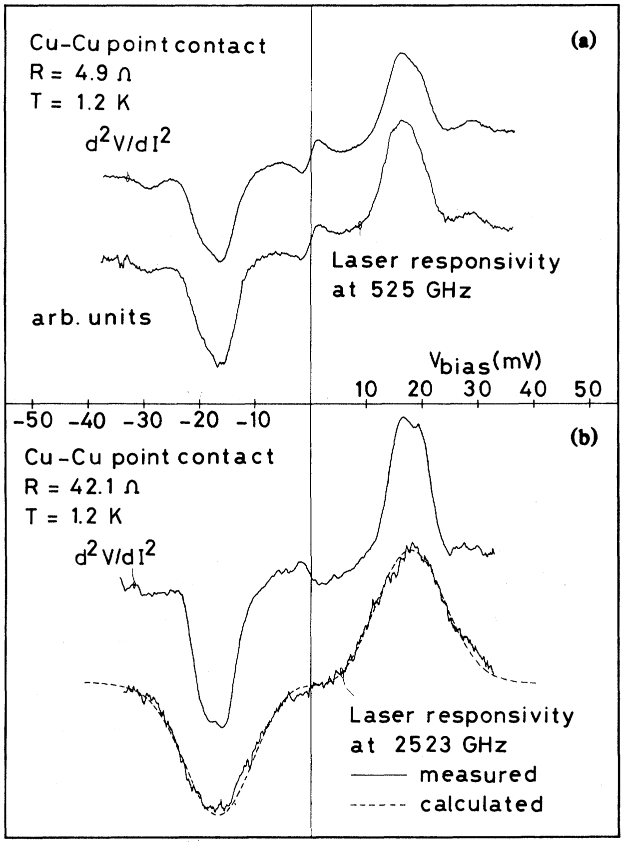

FIG. 1. (a) $d^2V/dI^2(V)$ and laser-induced signal ($V_{\rm dc}$) as a function of bias voltage for a Cu-Cu contact. The laser frequency is 525 GHz and is relatively low ($\hbar\omega/e \sim 2$ mV). (b) As above, but for a different actual contact. The laser frequency is 2523 GHz and the value $\hbar\omega/e$ ($\sim$ 10.5 mV) is now comparable to the width of the d^2V/dI^2 signal. The dashed curve is a calculated result in the low power limit and has used the measured d^2V/dI^2 characteristic without radiation.

the ordinary Bessel functions of order n and $\alpha \equiv eV_1/\hbar\omega$ ($\hbar\omega$ photon energy). For the fit in Fig. 1, the measured $I(V)$ curve was used (by numerically integrating the derivatives). Equation (1) was used in the limit of small α so that the shape of the curve does not depend on power level. The amplitude of the calculated curve was adjusted to coincide with the measured curve. In this way, an excellent fit to the data is obtained. The characteristic periodic pattern expected according to (1) is not observed since this would require higher frequencies and power levels. In the present experimental setup, coupling efficiency rapidly deteriorates for higher frequencies, while the power required increases with frequency (to keep α constant). At low power levels, expression (1) implies that the original structure is smeared out over a voltage range equal to $\hbar\omega/e$.

The standard treatment of the point-contact problem is in terms of Boltzmann transport equations.[4] This theory is only applicable for the quasistatic case $\omega\tau < 1$. Using a Green's function technique, Omel'yanchuk and Tuluzov[5] derived the same expression for the point-contact nonlinearities as obtained with the Boltzmann theory under quasistatic conditions $\omega\tau < 1$. Moreover, for arbitrary frequency they arrived at the result (1).

Equation (1) reduces to the classical high-frequency case, when the $I(V)$ curve changes slowly on a voltage scale large compared to $\hbar\omega/e$ (Ref. 7) (2 mV at 525 GHz, 10 mV at 2523 GHz). For the present point contact, the typical voltage scale is given by the peak width in Fig. 1 which is of the order of $\hbar\omega_D/e$ ($\sim$ 17 mV see Fig. 1) (ω_D: Debye frequency). Therefore, the phenomenological condition to observe high-frequency effects, based upon Eq. (1), is equivalent to $\omega \gtrsim \omega_D$ or $\omega\tau > 1$ (τ is in the order of ω_D^{-1} for electrons of energy $\sim\hbar\omega_D$ interacting with phonons).

Equation (1) has been independently derived for several specific cases. It was originally developed for superconducting tunneling junctions.[2] It has, furthermore, been found to apply for general single-particle tunneling junctions,[3] a specific type of normal-metal tunneling junction,[8] normal-metal–superconductor point contacts,[9] and recently for the normal-metal point contact.[5] Experimentally, it has up to now been extensively observed in superconducting tunneling devices (e.g., Ref. 10) and in normal-metal–superconductor point contacts.[11] This work reports the first observation in a normal-metal device. The common feature in all these devices is that there is an abrupt change in Fermi level of eV between both electrodes. It is interesting to note that in some practical, normal-metal point-contact devices, the conditions for PAT seemed in fact to be fulfilled.[3,12] There is also a striking correspondence between an internal photoemission process known as photoinduced tunnel currents (PITC)[13] and the PAT effect. Sometimes the PITC effect is also referred to as photon-assisted tunneling.[14]

The condition for observation of the PAT effect is usually formulated as $\hbar\omega > e\Delta V$,[3] where ΔV is a characteristic voltage range over which the resistance of the contact changes. If this ΔV can be associated with some microscopic lifetime in the problem via $\hbar/\tau = e\Delta V$, then the condition becomes equivalent with $\omega\tau > 1$.

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