Tunneling through a controllable vacuum gap

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We report on the first successful tunneling experiment with an externally and reproducibly adjustable vacuum gap. The observation of vacuum tunneling is established by the exponential dependence of the tunneling resistance on the width of the gap. The experimental setup allows for simultaneous investigation and treatment of the tunnel electrode surfaces.

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The concept of tunneling in solid-state physics first appeared in context with tunneling into vacuum or through a vacuum barrier.[1] On the other hand, tunneling as a spectroscopic tool was developed exclusively for solid tunnel barriers.[2] Experiments using vacuum tunnel barriers, although often attempted, have been unsuccessful mainly because of vibration problems. This is rather regrettable, since the interest in vacuum tunnel barriers is evident: conceptually most simple barrier, free access to the electrodes for other investigations of physical and chemical processes, e.g., in connection with inelastic tunneling spectroscopy.[3] The possibility of vacuum tunneling opens an interesting and challenging new area of surface investigations.

We have now performed an experiment demonstrating the feasibility of vacuum tunneling with modest means. The main purpose of the experiment is not to observe vacuum tunneling *per se*, but to achieve it in a configuration which allows simultaneously spacially resolved tunneling spectroscopy and other surface spectroscopic methods.

A crucial point for the experiment is the suppression of vibrations, mainly responsible for the failure of previous vacuum-tunneling experiments. This requires excellent mechanical decoupling of the tunneling unit from its surroundings. This was achieved by soft suspension of a compact tunneling unit, shown schematically in Fig. 1, with low current electrical positioning of the tunneling electrodes. The vacuum-tunneling junction consists essentially of a platinum plate Pt and a tungsten tip W. The tungsten tip is fixed to a support A, which can travel in a semicontinuous fashion in any direction on the bench B. The driving mechanism of this support is similar to the one published elsewhere.[4] It consists essentially of a piezoplate PP, resting with three metal feet (only two, F_1 and F_2, are shown in Fig. 1) on a metal plate MP, insulated from each other by a high dielectric-constant material D. The feet can glide freely on the dielectric, or are clamped in place by applying a voltage between them and the metal plate. Elongation and contraction of the piezo with an appropriate clamping sequence of the feet allows movements of the support A on the bench in any direction in steps down to 100 Å. Fine control of the electrode distance s (z direction) and relative x-y position of the electrodes is achieved by the piezodrive P, to which the platinum plate is fixed. The piezodrive, made of commercial piezoceramics (Philips PXE 5), allows movements in any direction up to some thousand angstroms with a sensitivity of about 2 Å/V. Thus, the tunnel electrodes are positioned with practically no mechanical contact except for the 0.06 mm diameter electrical leads.

The whole tunneling unit is protected against vibrations in two steps. The building vibrations are eliminated by installing the vacuum chamber on a heavy stone bench floating on inflated rubber tubes. The internal vibrations of the whole system are filtered out by *static* magnetic levitation of the tunneling unit, an excellent filter for high-frequency ($\nu < 0$ Hz) vibrations. For this purpose, the tunneling unit is mounted on strong permanent magnets M levitating on a superconducting bowl of lead, Pb, superinsulated and cooled directly by liquid He. A normal conducting sheet R between the lead and the magnets acts as an efficient eddy-current damper. For levitation, we did not make use of the Meissner effect, since trapped flux stiffens the mechanical coupling between the superconductor and the tunneling unit. Instead, the unit was lowered onto the lead bowl after cooling the latter to liquid-He temperature, and decoupled from the lowering mechanism after levitation. The mechanical decoupling also ensured thermal decoupling, and room-temperature radiation kept the tunneling unit just a few degrees below room temperature.

The present preliminary experimental setup allowed vacuum down to about 10^{-6} Torr, with the superconductor cooled to He temperature. This is by no means adequate to obtain clean surfaces but they were found to be sufficiently stable to perform measurements. The work function ϕ, sensitive to contamination,[5] does not change noticeably over tens of minutes. Since no provision has yet been made for independent cleaning of the electrodes, we employed a self-cleaning procedure. After approaching tip and plate until contact, 10 Vpp at 10 kHz were applied to the fine-control piezoplate, leading to some type of ultrasonic cleaning of both tip and

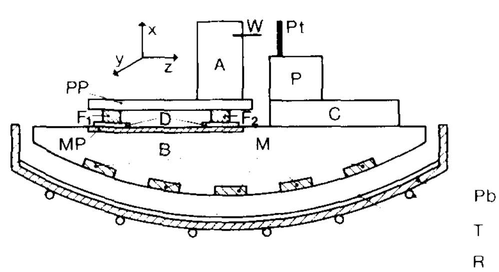

FIG. 1. Schematic of the tunneling unit and magnetic levitation system. Components and operation are described in the text. Liquid-He circulating in the tubes T cools the lead bowl Pb, which is thermally shielded by Al-coated mylar foils (not shown).

plate. After repeated cleaning, $d[(\ln R(s)]/ds$, a measure of the work function [see Eq. (1)], no longer changes appreciably.

Some typical curves for the tunnel resistance $R(s)$ are shown in Fig. 2. The tunnel resistance was measured with a constant voltage of 60 mV of either polarity which is sufficiently small to avoid field emission. Theory[1] predicts an exponential dependence of the tunnel resistance $R(s)$,

$$R(s) \alpha \exp(A\phi^{1/2}s), \quad (1)$$

where the constant A is given by $(4\pi/h)(2m)^{1/2}$ with m the electron mass in the barrier. Using the free electron mass, $A = 1.025\ \text{eV}^{-1/2}\ \text{Å}^{-1}$, $d(\ln R)/ds \approx \phi^{1/2}$. Prior to self-cleaning, the distance dependence of $R(s)$ is weak and nonexponential, but already after the first cleaning step, the expected exponential behavior of $R(s)$ is observed. Curves A, B, and C were obtained with moderate vacuum, curve A after the first cleaning step ($\phi \approx 0.6$ eV). Further cleaning did not lead to substantially higher values of ϕ (curves B and C, $\phi \approx 0.7$ eV). Thus, contamination of the electrodes still appears to be mainly responsible for the observed value of ϕ. In better vacuum ($\approx 10^{-6}$ Torr), a value of $\phi \approx 3.2$ eV, closer to that expected for clean Pt and W surfaces $[(\phi_{\text{clean}} = \frac{1}{2}(\phi_{\text{Pt}} + \phi_{\text{W}}) \approx 5\ \text{eV}]$, could be reached (curves D and E).

These measurements yield the first continuous exponential distance dependence of the tunnel current, in a single tunnel junction, over four orders of magnitude (the resistance range is solely limited by the electronics used). An

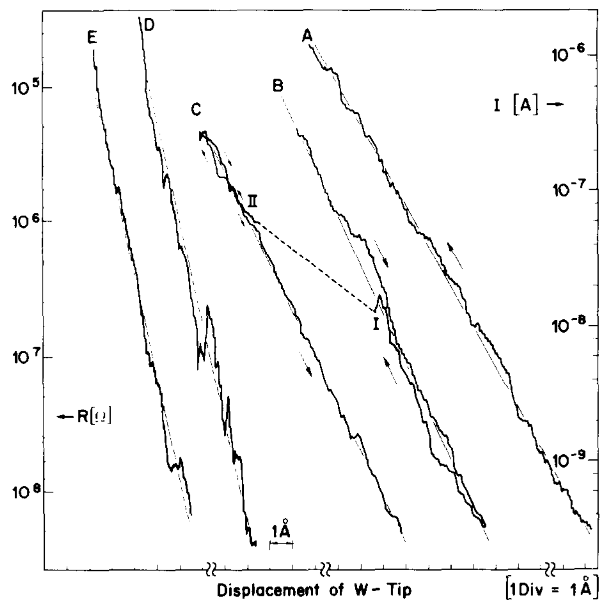

FIG. 2. Tunnel resistance and current vs displacement of Pt plate for different surface conditions as described in the text. The displacement origin is arbitrary for each curve (except for curves B and C with the same origin). The sweep rate was approximately 1 Å/s. Work functions $\phi = 0.6$ eV and 0.7 eV are derived from curves A, B, and C, respectively. The instability which occurred while scanning B and resulted in a jump from point I to II is attributed to the release of thermal stress in the unit. After this, the tunnel unit remained stable within 0.2 Å as shown by curve C. After repeated cleaning and in slightly better vacuum, the steepness of curves D and E resulted in $\phi = 3.2$ eV.

exponential $R(s)$ was previously inferred from comparing different junctions.[6,7] However, solid-state barriers are not expected to be homogeneous in width and height on a microscopic scale, and tunneling will occur dominantly at the weakest points (smallest widths and lowest heights). At present, there is no way to determine such an effective tunnel distance. Therefore, the exponential dependence of a tunnel resistance on some measured average barrier thickness appears rather fortuitous. Indeed, the assumed exponential $R(s)$ dependence was even used to construct a model for an inhomogeneous barrier.[7] In contrast, the displacement of the W tip in our experiment is equal to the variation of the *effective* tunnel distance.

Such an exponential distance dependence of $R(s)$ should only be observed for a *tunnel* current. Tunneling merely through a contamination layer can be ruled out on several grounds. Firstly, deformation of a hard contamination layer like tungsten oxide on varying the width of the tunnel gap would result in nonreproducible and hysteretic $R(s)$ curves. Secondly, the cleaning process increased the work function. This could not be caused by simply narrowing a compact contamination layer between the electrodes. Thirdly, existing data in metal-insulator-metal tunnel junctions[6] yield at best values of $d(\ln R)/ds \approx 0.8$ eV. Thus, a barrier height of a contamination layer of 3.2 eV appears very unlikely. Therefore, we conclude that the dependence of the tunnel resistance is really due to the varying width of a vacuum gap, and that the remaining contamination of the electrodes simply reduced the effective barrier height to various degrees. Vacuum tunneling might have been observed in some previous[8] experiments, but real experimental evidence was lacking. Neither an exponential distance dependence nor any appropriate work function has been observed in these experiments, both mandatory for excluding the existence of Ohmic or point contacts or tunneling through contamination layers.

The present experiment was performed close to room temperature and at moderate vacuum. At low temperatures, better mechanical stability is expected since thermal stress release and thermal expansion become less bothersome. Ultrahigh vacuum conditions allow better-defined surfaces (cleanliness, well-defined coverage). Since field ionization of molecules in the barrier did not contribute noticeably to the tunnel current even in moderate vacuum, vacuum tunneling should become an interesting tool for studies of coverage processes like growth of oxidation layers and inelastic tunneling spectroscopy. Such investigations with improved mechanical stability of the tunnel unit are the main goal of experiments in progress.

In summary, we have shown that vacuum tunneling with externally controllable tunnel distance is technically feasible, even at room temperature and nonultrahigh vacuum conditions. This investigation is the first step towards the development of scanning tunneling microscopy, where the surface is scanned by a tunnel current and should open the door to a new area of surface studies.

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Possibility of effect of electric charge on the stability of current-carrying high-field superconductors

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The charge-diffusion length λ_Q^* in the flux-pinned superconducting region near the interface between the pinned region and dissipative region is estimated from published experimental data on the minimum current I_r for *SN*-boundary propagation in Nb-Ti composite conductors. The estimation gives $\lambda_Q^* \simeq 3.2$–$3.9\ \mu$m irrespective of the variety of conductor shape and structure, applied magnetic field, and cooling conditions. This result reveals the possibility that the gap depression by the accumulated charge at the interface with a flux-depinning effect is the determining factor in the dynamics of the *SN* boundary in composite superconductors.

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Stabilization of superconductor wires and magnets is an important problem in the high-field application of superconductivity. The magnetic instability characterized by the sudden *SN* transition[1] in magnetized superconductors has been believed to be a phenomenon described only by magnetic field dynamics and thermal conditions. Kantrowitz and Steckly[2] provided a model for estimating the stabilization condition of superconductors embedded in a copper matrix. They assumed that (i) *SN* transition takes place uniformly in the superconductor and that (ii) the superconductivity is determined by the temperature rise of the wire given by dissipation and heat-transfer relations. Actual *SN* transition is thought to begin from a localized normal region. Considering the heat transfer along the conductor length, and specifying the cooling characteristics of liquid helium, Maddock *et al.*[3] improved the transition theory. Dressner[4] and Willig[5] investigated the propagation characteristics of the *SN* boundary considering heat-balance equations constructed on revised Madock theory. They tried to fit their calculation to observed characteristics by adjusting values for heat parameters. Today we still lack a good theory which can describe *a priori* the dynamics of *SN* boundaries.

In this letter we propose a model with a new feature in which the gap depression by the accumulation of electric charge and the following flux-depinning effect are considered to be the dominant factor in determining the motion of the *SN* boundary. Consider a boundary between the *S* and *N* states in a superconductor as shown in Fig. 1(a), where current is flowing in the *x* direction. Dolan and Jackel[6] have experimentally demonstrated that there appears to be a potential discrepancy in the transition region between the normal-electron potential (Fermi level) $e\phi$ and the superelectron potential $e\phi_p$. The existence of the discrepancy $e\delta\phi = e(\phi - \phi_p)$ brings about the unbalance of excitation energy between electron and hold excitation. The energy gap Δ

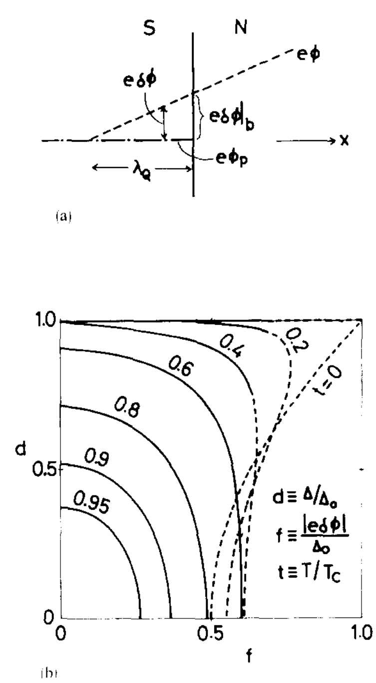

FIG. 1. (a) Potential discrepancy $\delta\phi = \phi - \phi_p$ between the Fermi level ϕ and pair level ϕ_p at a *SN* boundary in a current-carrying superconductor. (b) Dependence of energy gap on the potential discrepancy.

