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New optoelectronic tip design for ultrafast scanning tunneling microscopy

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We have developed a scanning tunneling microscope using an optoelectronic switch that gates the tunneling tip current. The switch is fabricated within $30\ \mu\text{m}$ from the tip by photolithography and an accurate cleavage method. We demonstrate this approach by detecting picosecond electrical transients on a coplanar stripline. We have investigated the signal dependence on contact resistance and found significant differences when the tip is brought from low-ohmic contact into the tunneling regime. In this regime, the THz signal amplitude was found to depend linearly on the tunnel conductance, and disappeared when the tip was retracted. © 1996 American Vacuum Society.

I. INTRODUCTION

In recent years, great interest has arisen in the development of scanning probes through which both atomic-scale spatial resolution as well as ultrafast temporal resolution can be accomplished. These techniques will allow for the study of picosecond dynamical processes in nanometer-scale objects such as individual quantum dots or clusters, in which electronic, acoustic, or magnetic excitations are affected by the geometrical boundaries. Also, strong technological efforts are made in the development of local electrical probes for studying ultrafast submicrometer electronic devices.^{1,2} For these purposes, several methods have been introduced, based on scanning force microscopy,³ scanning near-field optical microscopy,⁴ and scanning tunneling microscopy (STM).⁵⁻⁷

An ultrafast local probe has been developed based on a STM, since this type of microscopy yields the most promising spatial resolution. Temporal resolution is achieved by gating the tip current by an optoelectronic switch. These switches are widely used in terahertz time-domain spectroscopy (see Ref. 8 and references therein). The technique has been recently demonstrated by Weiss *et al.*^{6,7} In this article, a novel tip design is introduced that is both elegant in its simplicity and has picosecond temporal performance.

II. EXPERIMENT

The tip design allows us to fabricate the switch in close proximity to the tunneling tip. This has several advantages, such as minimizing effects of signal damping and dispersion.

Also, when the roundtrip time of a signal traveling between tip and switch is smaller than the typical pulse duration, propagation effects between tip and switch leading to spurious transient reflections will become negligible. For example, a 1 ps pulse duration would require the distance between tip and switch to be less than $60\ \mu\text{m}$, assuming a propagation velocity of $0.4c$. Our method enables us to fabricate the switch within several tens of micrometers from the tip. By molecular beam epitaxy, a (100)-oriented GaAs wafer is covered with an epilayer of low-temperature-grown GaAs (LT-GaAs) having picosecond carrier lifetime necessary to attain fast switch-off times. On top of the LT-GaAs, a *single metallization pattern* of alloyed Ni-Ge-Au is deposited by standard photolithography. The repetitive pattern is aligned under 45° with the easy-cleavage (110 and $1\bar{1}0$) directions. By performing two orthogonal cleaves, we obtain a strip of metallization that runs from the very edge of the cleaved wafer to a gap, that separates the strip from the rest of the metallization (see Fig. 1). This large mesh of metallization can easily be wired to an amplifier. The $9\text{-}\mu\text{m}$ -wide gap between mesh and strip forms the switch, and the cleaved edge of the metallization forms the tunneling tip. In this manner, tips with different strip lengths between 25 and $180\ \mu\text{m}$ have been fabricated from the same mask pattern. The strip width is $15\ \mu\text{m}$. The high accuracy of the second cleave allows us to determine the strip length to within several microns in advance, and to avoid the situation in which bare GaAs would be present at the apex. The cleaved metallized apex proves to be a stable tunneling tip.

The tip is mounted above a coplanar stripline (CPS) in a

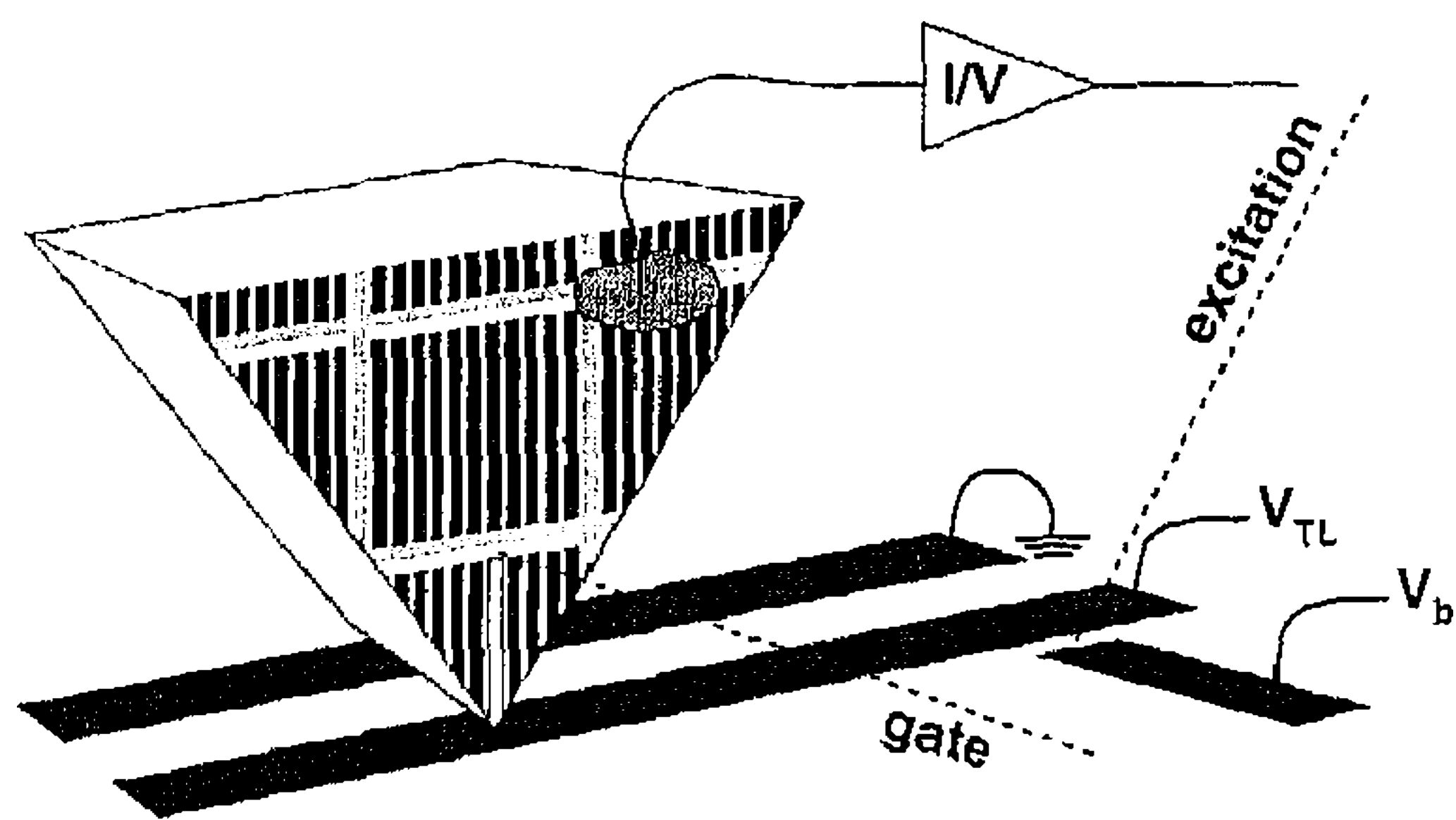


FIG. 1. Ultrafast gated tunneling tip design with integrated optoelectronic switch, above a coplanar stripline on which picosecond electrical transients are generated, by the "excitation" optical pulse. The single metallization layer has been depicted in different shades to indicate its different functions. The white strip is the tip wire. The gap between tip wire and gray mesh forms the switch. The gray mesh connects the switch to the outside. The black strips are unused.

tilted position so that the threefold symmetry axis of the tip is approximately normal to the CPS surface (see Fig. 1). The CPS consists of 50- μm -wide Al lines spaced 50 μm apart on top of an LT-GaAs covered GaAs substrate. The mesh of the tip is fed into a 100 mV/nA current-to-voltage converter connected to both a constant-current feedback system and a lock-in amplifier (LIA). The beam of a colliding-pulse mode-locked laser, providing 70 fs pulses at a 95 MHz repetition rate, is split in two. The 2 kHz chopped "excitation" beam fires a biased ($V_b = 10$ V) photoconductive switch with a 10- μm -long and 50- μm -wide gap on the transmission line. The chopping frequency lies above the cutoff frequency of the constant-current system. The second beam, the "gate" beam, passes a mechanical stage through which the time delay τ between excitation and gate pulses can be varied before it is focused onto the tip switch. The average current measured by I/V converter and LIA is recorded for different time delays.

III. RESULTS

First, we have measured the transient signal by placing a tip with 160 μm strip length in low-ohmic contact with the CPS. The exact zero delay time was determined by reversing the role of excitation and gate beams without making any modification to the optical beam paths. This measurement, shown in Fig. 2 by the solid curve, is compared to the measurement in which the signal is detected by a second sampling gate on the CPS. The pulse as detected by the sampling gate has a full width at half-maximum (FWHM) of 6.0 ps, whereas detection by the tip increases the FWHM to 8.5 ps. It was found that the tip may be placed several times in contact with the substrate before significant tip damage occurs.

Next, we will investigate the influence of the strip length on the detected signals in contact. We have performed measurements with four tips having strip lengths of 173, 50, 175, and 41 μm , in that order. We group the tips in two different categories having small and large strip lengths, respectively. The generated electrical transient has been propagated along

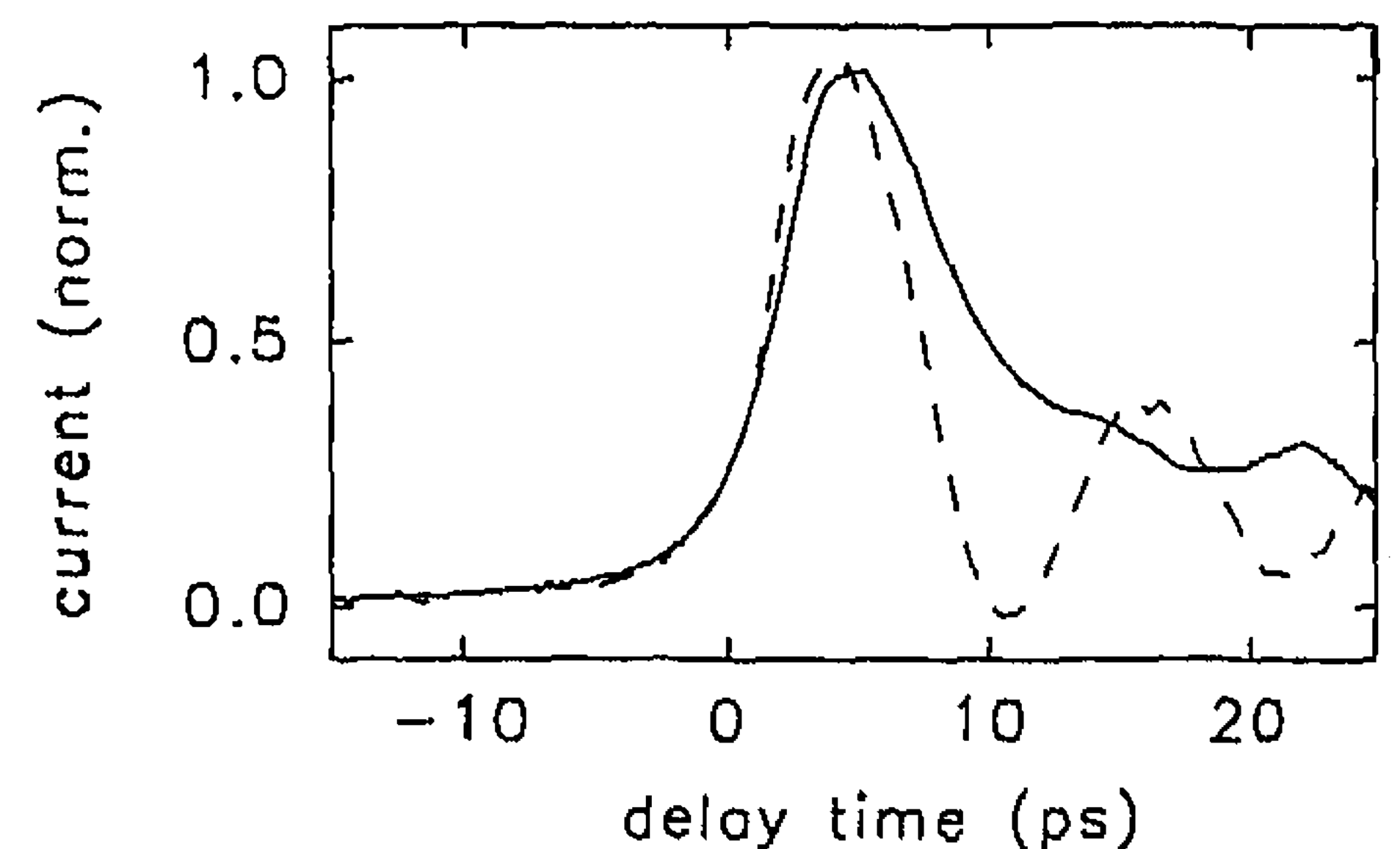


FIG. 2. Comparison between the measured transient signal, as detected by an optoelectronic switch on the coplanar stripline (dashed curve), and as detected by the ultrafast STM tip in contact with the stripline (solid). Curves have been scaled vertically. The transient has been generated by a second biased optoelectronic switch on the coplanar stripline.

the CPS up to an in-line gap in the stripline, which capacitively couples part of the signal to a second stripline. The tip is positioned on the second stripline. For each measurement, the exact zero delay time has been determined with an accuracy of 0.2 ps, and each measurement has been scaled to its maximum value at the peak. The results for four different tips are shown in Fig. 3.

A systematic difference between the measurements of long and short strip lengths is found at the leading edge of the signal peak. The edge detected by the short strip tip arrives 1 ps earlier than the edge detected by the long strip tip. After performing the four measurements shown, we have measured with the first tip again and found that the signal shape remained unchanged within 15% (long-dashed curves in Fig. 3). This variation is likely to be due to the different alignments of the optical beams and the tip position on the stripline. The measured variations between the long and short strip tips curves of Fig. 3 are larger than the uncertainty due to alignment. The 1 ps time difference may be the consequence of frequency-dependent damping or dispersion. With the presently measured pulse durations, the effects of spurious transient reflections in the strip is expected to be negligible. When future developments lead to shorter pulses ~ 1 ps, our tip design is expected to be effective in suppressing the reflections.

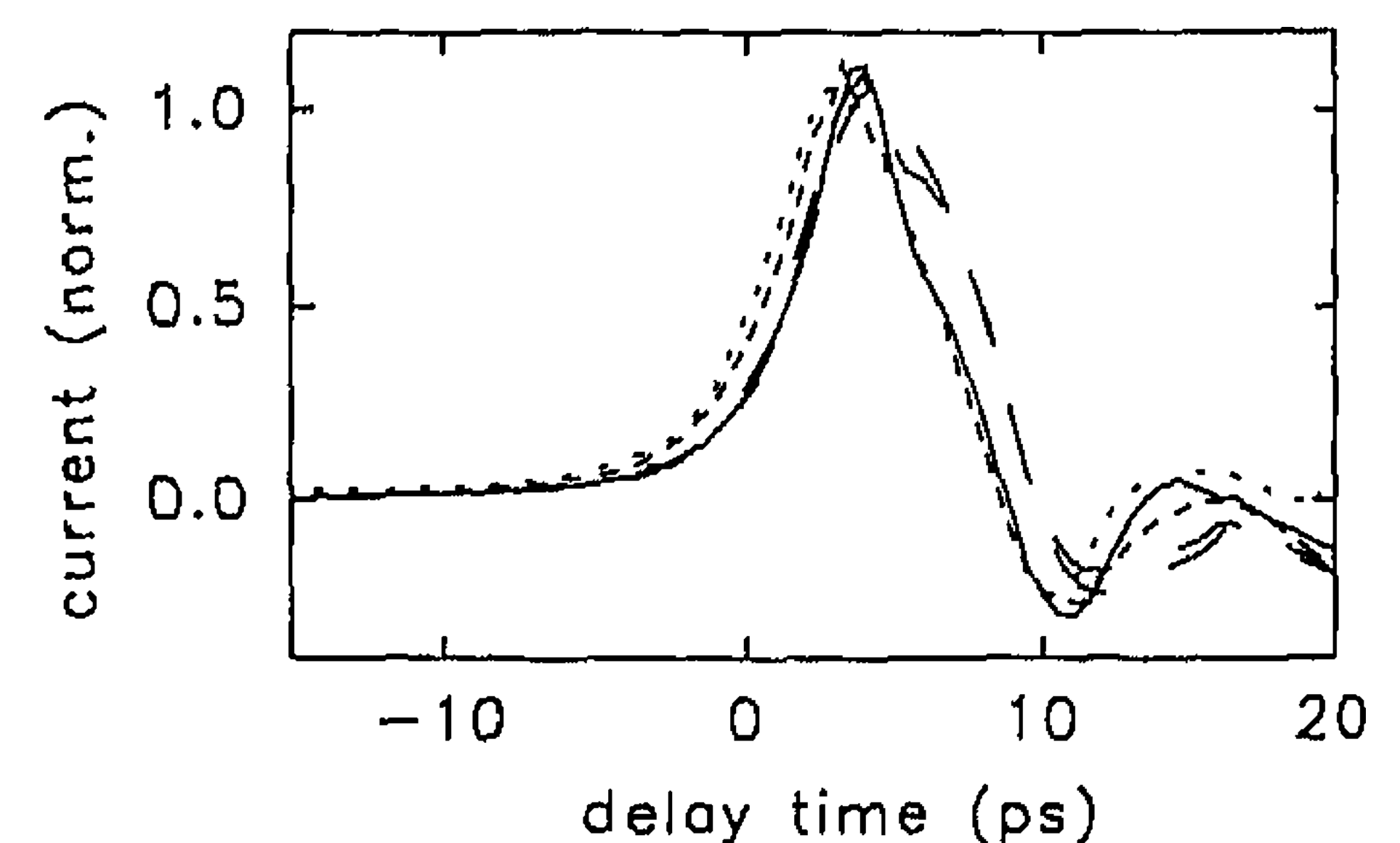


FIG. 3. Measured electrical transients for different lengths between tip apex and optoelectronic switch on the tip. Solid line: 175 μm ; long-dashed line: 173 μm ; medium-dashed line: 50 μm ; short-dashed line: 41 μm . Each curve has been independently scaled vertically. A significant 1 ps time lag of the leading edge of the pulses for long strip lengths is observed.

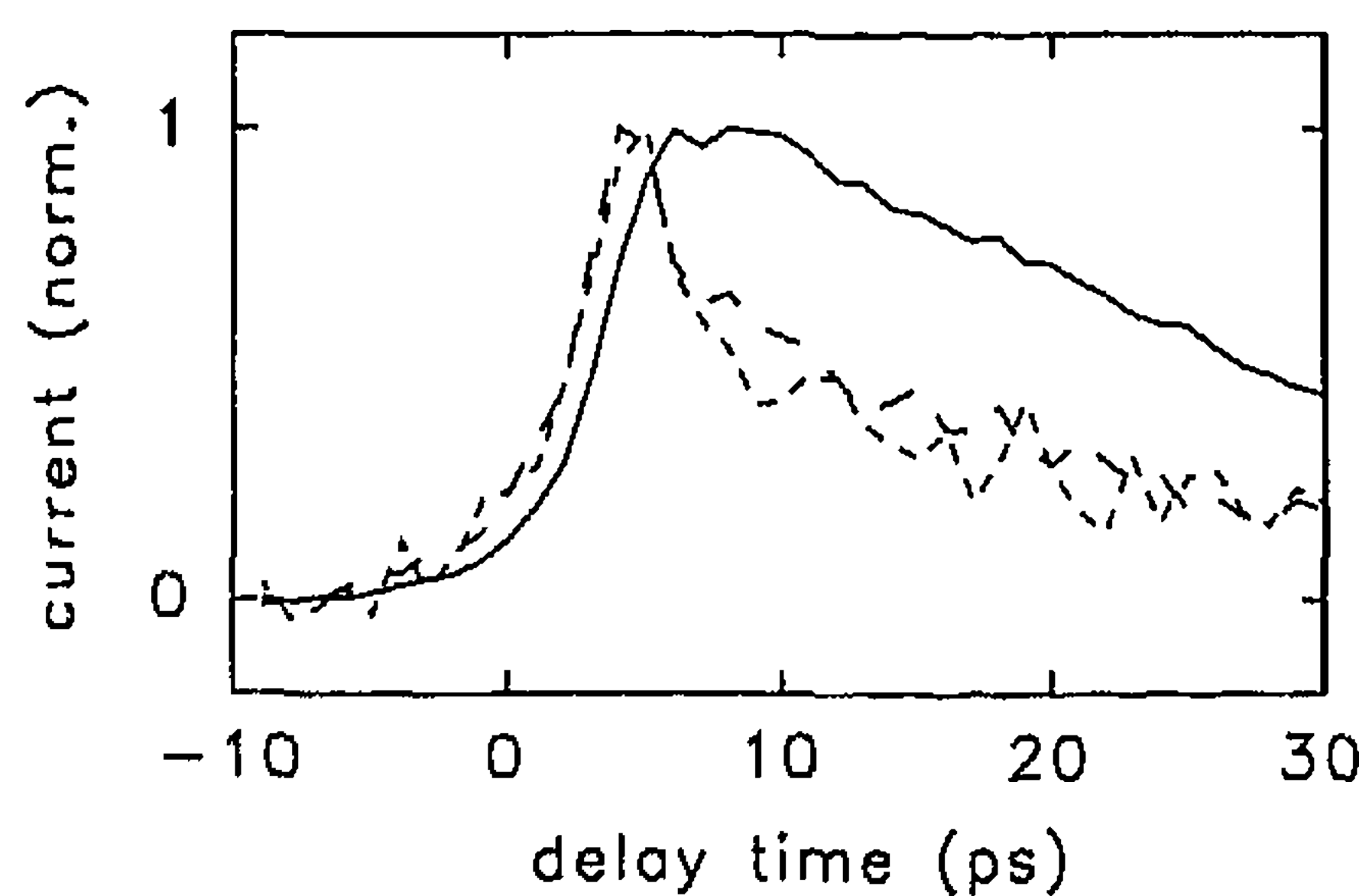


FIG. 4. Comparison between the detected picosecond signals when the ultrafast STM tip is in low-ohmic contact (solid), and when the tip is in the tunneling regime, with tunneling resistance of 70 M Ω (long-dashed line) and 470 M Ω (short-dashed line). Each curve has been independently scaled vertically.

Next, measurements of THz transients detected by the tip are presented for different contact resistances between tip and CPS. The transmission line is held at a small bias V_{TL} (-0.04 to -0.3 V) when the tip is brought into tunneling using the constant-current regulation system of the STM. Since the average dark resistance of the tip switch can exceed typical tunnel resistances of ~ 1 G Ω and so influence the constant-current feedback system, we have lowered the average dark resistance to ~ 1 M Ω by directing a continuous-wave (HeNe) laser beam onto the tip switch in addition to the pulsed beam. The averaged "on" resistance with only the gate beam present is ~ 1 M Ω .

We have varied the average series resistance of switch and tunnel junction between 23 M Ω and 1.2 G Ω . Figure 4 shows the shape of the detected signal when the tip is in contact and when the tip is in tunneling. The measurement in tunneling is the average of three scans, each taking approximately 1 min to record. In this regime, we find experimentally that the THz signal changes shape and arrives earlier than the signal as measured in contact. In the tunneling regime, we observe a 6 ps rise time (10%–90%) of the signal. This value lies close to the 3 ps risetime obtained by Weiss *et al.* In Fig. 5 the peak signal strength [$\max(I) - I(t < 0)$] versus average conductance has been plotted. The peak signal strength shows a linear relation and disappears when the tip is retracted. The

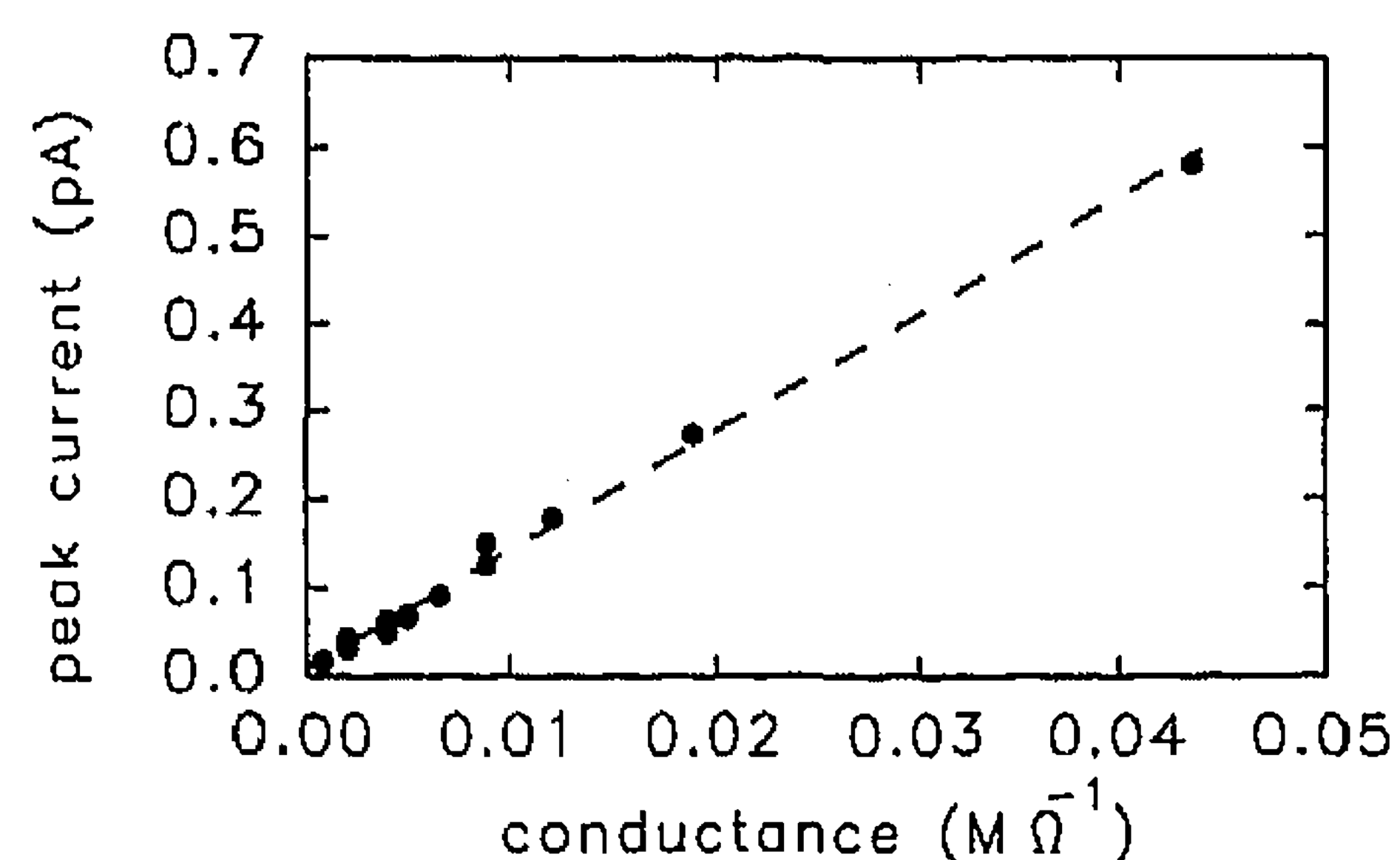


FIG. 5. Measured peak transient signal strength (dots) as a function of the average series conductance of switch and tunnel junction. The dashed line is a least squares fit.

signal strength measured at 1.2 G Ω is a factor of 10^3 weaker than the signal in contact. Similar results have been found by Weiss *et al.*^{6,7} The remarkable observation that the signal disappears upon retracting the tip suggests that capacitive coupling, if present, only takes place in the tunneling region, and that the geometrical capacitive coupling between the strip and CPS is absent. We did not find a systematic difference between the signals detected by 40–50 μm and by 175 μm strip-length tips. In both cases, the signal strength was equal within 30%, ruling out a possible dipolar antenna action of the strip.

IV. SUMMARY

We have introduced a new ultrafast tunneling tip design for picosecond scanning tunneling microscopy, fabricated by a single photolithographic step and accurate cleaving. With the tips, we are able to detect voltage transients on coplanar striplines with picosecond time resolution, both in contact as well as in the tunneling regime. We have investigated the transient signals detected by tips having two different strip lengths (i.e., distance between tip apex and optoelectronic switch). The signal edge detected by the short strip tips arrives 1 ps earlier than the edge detected by the long strip tips. Measuring in the tunneling regime ($R_t = 0.023$ –1.2 G Ω), we have observed a 6 ps rise time (10%–90%) of the signal. Here, the THz signal amplitude was found to depend linearly on the tunnel conductance, and disappeared when the tip was retracted. Systematic differences between signals detected by the long and short strip tips in the tunneling regime have not been found.

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