Detection of picosecond electrical transients in a scanning tunneling microscope

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Abstract

We have developed a scanning tunneling microscope using an optoelectronic switch which gates the tunneling tip current. The switch is fabricated within several tens of microns 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 recent years, great interest has arisen in the development of scanning probes with 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 submicron 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].

We have developed an ultrafast local probe based on an 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 paper, we introduce a novel tip design that is elegant in its simplicity and has picosecond temporal performance.

Our 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 travelling 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 μm, assuming a propagation velocity of $0.4c$. Our method enables us to fabricate the switch within several tens of microns from the tip. By molecular beam epitaxy a (1 0 0)-oriented GaAs wafer is covered with an epilayer of low-temperature grown GaAs (LT-GaAs) having subpicosecond carrier life time 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 photolithograpy (see Fig. 1). The repetitive pattern is aligned below 45° with the easy-cleavage (1 1 0 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. This large mesh of
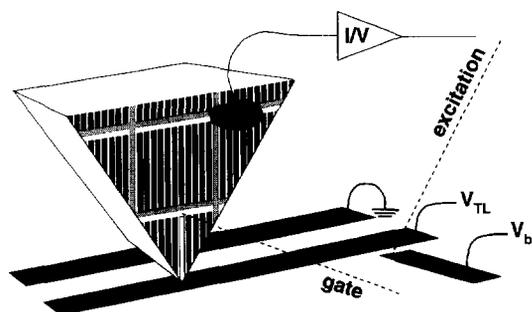
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Fig. 1. Ultrafast gated tunneling tip design with integrated opto-electronic switch, above a coplanar stripline on which picosecond electrical transients are generated by the "excitation" optical pulse. The single metallization layer has been depicted 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 grey mesh connects the switch to the outside. The black strips are unused.
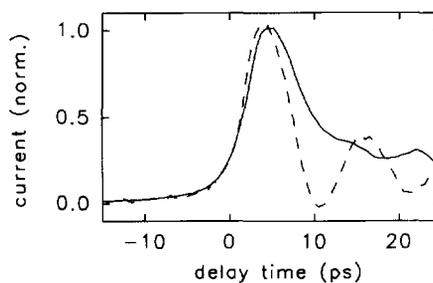

Fig. 2. Comparison between the measured transient signal as detected by an optoelectronic switch on the coplanar stripline (dashed curve) and as detected by the ultrafast STM tip in contact with the stripline (solid). The transient has been generated by a second biased optoelectronic switch on the coplanar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

metallization can easily be wired to an amplifier. The 9-μm 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 μm have been fabricated from the same mask pattern. The strip width is 15 μm. 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 where 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 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 a 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 modelocked laser is split into two, providing 70 fs pulses at a 95 MHz repetition rate. 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 "gate" beam passes a mechanical stage, through which the time delay τ between excitation and gate pulses can be varied, before it is focussed onto the tip switch. The average current measured by I/V converter and LIA is recorded for different time delays.

First, we 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. 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. In the present case the pulse duration is not so short, that the reduced strip length of our tip design is of critical importance. Further improvements of the CPS and tip will be made to shorten the pulses. It was found that the tip may be placed several times in contact with the substrate before significant tip damage occurs.

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 GΩ and so influence the constant-current feedback system, we lowered the average dark resistance to ~ 1 MΩ by directing a continous-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 MΩ.

We have varied the average series resistance of switch and tunnel junction between 23 MΩ and 1.2 GΩ. Fig. 3 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 about one minute 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 Fig. 4 the peak signal strength [max(I) − $I(t < 0)$] versus average conductance has been plotted, showing a linear relation which disappears when the tip is retracted. The signal strength measured at 1.2 GΩ is a factor 10^3 weaker than the signal in contact.
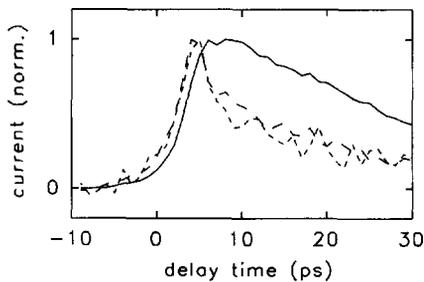
Fig. 3. Comparison between the detected picosecond signals when the ultrafast STM tip is in low-ohmic contact (solid), and when the tip is in tunneling regime, with tunnel resistance of 70 MΩ (long dashes) and 470 MΩ (short dashes). Each curve has been independently scaled vertically.
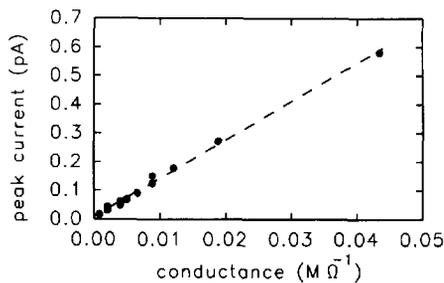

Fig. 4. Measured peak transient signal strength (dots) as a function of the average series conductance of switch and tunnel junction. The dashed line is a least squares fit.

Similar results have been found by Weiss et al. [6, 7]. The remarkable observation of the disappearing signal upon retracting the tip suggests that capacitive coupling, if present, only takes place in the tunneling region, and that the geometrical capacitance of the strip with respect to the CPS is absent.

In conclusion, we introduced a new ultrafast tunneling tip design for picosecond scanning tunneling microscopy, fabricated by a single photolithography step and accurate cleaving. With the tips we are able to detect picosecond voltage transients on coplanar striplines.

Acknowledgements

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