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Ultrafast scanning tunneling microscopy using a photoexcited low-temperature-grown GaAs tip.

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Abstract We report ultrafast scanning tunneling microscopy using a low-temperature-grown GaAs tip photoexcited by 100-fs, 800-nm pulses. We use this tip to detect picosecond transients on a coplanar stripline and demonstrate a temporal resolution of 1.7 ps. A dependence of the transient signal upon spatial position of the tip is revealed, indicating that the signal arises from areas on the sample smaller than ~20nm

1. Introduction

In the quest for atomic spatial and picosecond temporal resolutions, several groups [1-5] have integrated an STM tip with an ultrafast optoelectronic switch that gates the tunneling current from the tip. We report a novel ultrafast STM tip consisting of a cleaved GaAs substrate with a 1- μ m thick epilayer of low-temperature grown GaAs (LT-GaAs) deposited on the face. Since LT-GaAs has a carrier lifetime of 1 ps, photo-excitation of the tip with an ultrafast above-bandgap pulse provides carriers for the tunneling current and photoconductively gates the current from the tip with picoseconds time resolution. We report a characterization of the tip under ultrafast photoexcitation and use this tip to detect picosecond voltage transients on a coplanar stripline.

2. Experimental Setup

A mode-locked Ti:sapphire laser provides 100-fs, 800-nm optical pulses at a repetition rate of 82 MHz. The output of the laser is split into a pump beam and a time delayed probe beam. The probe beam is focused on the LT-GaAs tip tunneling above a stripline. The pump beam is mechanically chopped and generates the voltage transients by optically switching the LT-GaAs epilayer between the stripline. The transient tunneling current is then revealed via lock-in detection for each value of delay τ .

The stripline consists of 50 μ m wide, 7 mm long platinum lines sputtered 10 μ m apart on a 1 μ m LT-GaAs epilayer and is held at a voltage difference of 15 V. The tip consists of a LT-GaAs square of 0.04 mm² 100 μ m thick bonded to a tungsten wire using a back gold contact and conducting epoxy. The dark resistance of the tip is typically of 3 G Ω .

3. Results and Discussion

Figure 1a shows the IV characteristic for an LT-GaAs tip under different laser fluence at constant tip-sample separation. Since the tip energy bands are bent upwards the surface field separates the photo-generated carriers and a non zero current flows at zero bias due to electrons tunneling into surface photo-holes. When the ultrafast pulse passes under the tip the sample Fermi level shifts changing the number of electrons involved in the photo-enhanced tunneling.

Fig. 1 DC-Current versus voltage (a) and versus tip/sample separation (b) for the LT-GaAs with 38 mW power on the tip at zero STM bias and in dark at 3V. The dependence of the transient strength on the separation is also shown.

Figure 1b shows the tunneling current as a function of tip-sample separation ($d-d_0$) with and without photoexcitation. For a clean tip and sample the expected work function would be ~ 5 eV. Although the difference in the apparent barrier with the tip in dark (0.84 eV) can be explained by native oxide contamination and the amorphous metal sample, the small value for the photoexcited tip (0.02 eV) is unclear but may be caused by photo-activation of surface states. The peak transient current also exhibits an exponential decay on separation with a decay constant close to that measured for the photoexcited DC tunneling current.

Fig 2a shows the transient current as a function of the delay. The first waveform is the correlation of the signal on the stripline. Deconvolving the 4.0 ps pulse yields a duration of 2.8 ps. The second pulse at 27 ps is a reflection off the end of the stripline. Unlike previous results [1-5], the waveforms from the tip in contact and in tunneling mode have the same shape and are free from other spurious signals. The width of the first pulse in tunneling regime is 3.3 ps indicating a temporal resolution of 1.7 ps after deconvolution.

Fig. 2b is a spatio-temporal scan of the transient current spanning 200 nm over the stripline and 45 ps in the delay. Features of 20 nm size due to differences in the sample conductivity are observed and indicate that the transient current arises from areas on the sample smaller than these dimensions.

The tunneling current can be described by a function $I=I(x,t,s,V)$ where x is the position, t the delay, s the tip sample separation and V the voltage which includes the dependence of the voltage transient. Since the transient signal in Fig. 2b is the amplitude of the modulated tunnel current induced by the modulating voltage at

the chopping frequency of the pump beam, it equals $\delta I = \partial I / \partial V \delta V(t)$ where $\delta V(t)$ is the transient voltage amplitude. Since the total derivative of the current along the delay is zero being the STM operated in constant current mode, also the conductivity $\partial I / \partial V$ is a constant of the delay. The scan in Fig. 2b can then be modeled knowing the voltage pulse waveform and the conductivity along the distance with the assumption that the voltage pulse does not depend upon the position. The fit obtained from this model is in agreement with the measured signal of Fig 2b.

Fig. 2 (a) Transient signal as a function of the delay as detected from device characterization, with the tip in contact and with the tip in tunneling regime. (b) Spatio-temporal scan of the transient signal on the stripline acquired in constant current mode.

4. Conclusions

We have shown the performances of a novel LT-GaAs tip under photoexcitation and used it to detect picosecond electrical transients on a coplanar stripline. The time dependent tunneling current has shown a temporal resolution of 1.7 ps and is free from other spurious signal. A spatio-temporal scan of the time dependent signal was presented and has revealed that the transient tunneling current arises from areas on the sample smaller than 20 nm.

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