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Title: ULTRAFAST SCANNING TUNNELING MICROSCOPY USING A PHOTOEXCITED LOW-TEMPERATURE-GROWN GALLIUM ARSENIDE TIPS

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

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Abstract

We demonstrate 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 1.2 ps.

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The invention of the scanning tunneling microscope (STM) revolutionized the field of surface science, enabling the first images of surface structure on an atomic length scale. In the quest for both atomic spatial and temporal resolution several groups[1-4] have integrated an ultrafast optoelectronic switch which gates the current from the tip, achieving picosecond time resolution. In this paper, we describe a novel STM tip consisting of a cleaved GaAs substrate with a 1-μm thick epilayer of low-temperature-grown GaAs (LT-GaAs) deposited on the face. Since the LT-GaAs has a carrier lifetime of 1 ps, photoexcitation of the tip with an ultrafast, above-bandgap pulse both provides carriers for the tunneling current and photoconductively gates (with ps resolution) the current from the tip. We use this tip to detect picosecond transients on a coplanar stripline and demonstrate a temporal resolution of 1.2 ps in tunneling mode. While the properties of CW photoexcited GaAs STM tips have previously been studied;[5] the combination of an LT-GaAs tip with ultrafast optical excitation to yield ps temporal resolution has not previously been demonstrated.

A sketch of the LT-GaAs STM tip is shown in Figure 1. The tip consists of a (100) GaAs substrate cleaved to a size of 0.1 mm by 0.1 mm by 0.02-mm thick and covered with a 1-μm-thick epilayer of LT-GaAs. We emphasize the simplicity of these tips which makes their fabrication easy and cheap. The 100-fs, 800-nm output from a mode-locked Ti:sapphire laser is split into a pump beam and a time-delayed probe beam. The pump beam is mechanically chopped and used to generate 2.6-ps voltage transients which propagate on a coplanar stripline. The probe beam is delayed relative to the pump and is focused onto the LT-GaAs STM tip mounted above the stripline. The tip is mounted in a RHK STM-1000 piezo-controlled head which is stabilized with its own control electronics and provides a DC bias to the stripline of typically 1-7 V. The tunneling current from the tip is amplified and input into a lock-in amplifier. The lock-in output reveals the transient tunneling signal for each value of delay.

When the LT-GaAs tip is illuminated with up to 30 mW of optical power we are able to demonstrate spatial resolution of 1-10 nm using the DC tunneling current; at higher excitation fluences the spatial resolution degrades significantly. For incident powers up to 100 mW, the transient signal from the lock-in varies linearly with the DC tunnel current.

Figure 2 reveals the dependence of the transient signal on tip-sample separation for incident optical power up to 100 mW and a positive tip-sample bias of about 1 V. For low power excitation the signal strength decreases exponentially with distance, as expected of a tunneling signal, while at higher optical powers the signal remains constant up to an intensity dependent tip-sample separation. Such behavior has been observed in previously in cw-excited GaAs tips[5] where it was attributed to current limiting occuring when the tunneling conductance becomes large (i.e. at small tip-sample separations) via the pinning of the Schottky barrier conductance. We note that those optical powers where we observe significant saturation behavior exhibit degraded spatial resolution. The inset in Figure 2 reveals the temporal waveform in the tunneling regime. The waveform is extremely clean since detrimental propagation effects have been eliminated and it is identical to the waveform measured in contact mode, unlike results obtained with metal tips in series with a photoconductive switch. Its width is 2.9 ps yielding a 1.2 ps temporal resolution after deconvolving the measured 2.6 ps width of the voltage transient from the response.

In contrast to STM operation with conventional metal tips, a tunneling signal is observed with no applied tip-sample bias. In this case an effective surface photovoltage is generated on the tip when the photogenerated electron-hole pairs are separated by the internal electric field. The behavior of the transient signal with no bias voltage, shown in Figure 3, exhibits a more marked saturation behavior at high excitation fluences. However at low fluences, an exponential dependence of the transient signal strength with tip height is observed. A waveform obtained in this regime is shown in the inset and it exhibits the same clean behavior observed under biased conditions.

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Figure Captions

1. Schematic of the LT-GaAs STM tip. The tip consists of a (100) GaAs substrate cleaved to a size of 0.1 mm by 0.1 mm by 0.02-mm thick and covered with a 1-μm-thick epilayer of LT-GaAs. The LT-GaAs layer is grown at 300 C and subsequently annealed for thirty minutes at 550 C, yielding an approximate carrier lifetime of 1 ps. This GaAs tip is bonded to 0.01-inch-diameter tungsten wire using a gold contact pad (50 μm by 50 μm by 0.1-μm-thick). The dark resistance of the tip is typically 3-5 GΩ.

2. The dependence of the transient signal on tip-sample separation for incident optical power up to 100 mW and a positive tip-sample bias of about 1 V. The inset reveals a transient waveform obtained at the operating point specified by the arrow.

3. The dependence of the transient signal on tip-sample separation for incident optical power up to 110 mW and without a tip-sample bias. The inset reveals a transient waveform obtained at the operating point specified by the arrow.

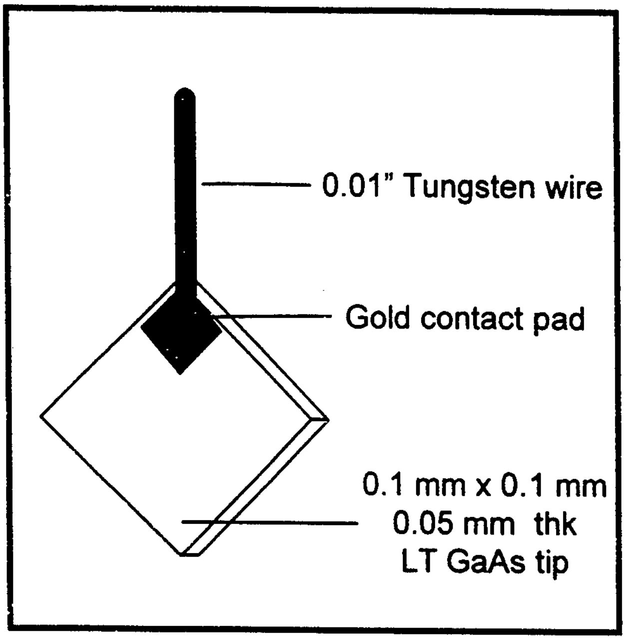
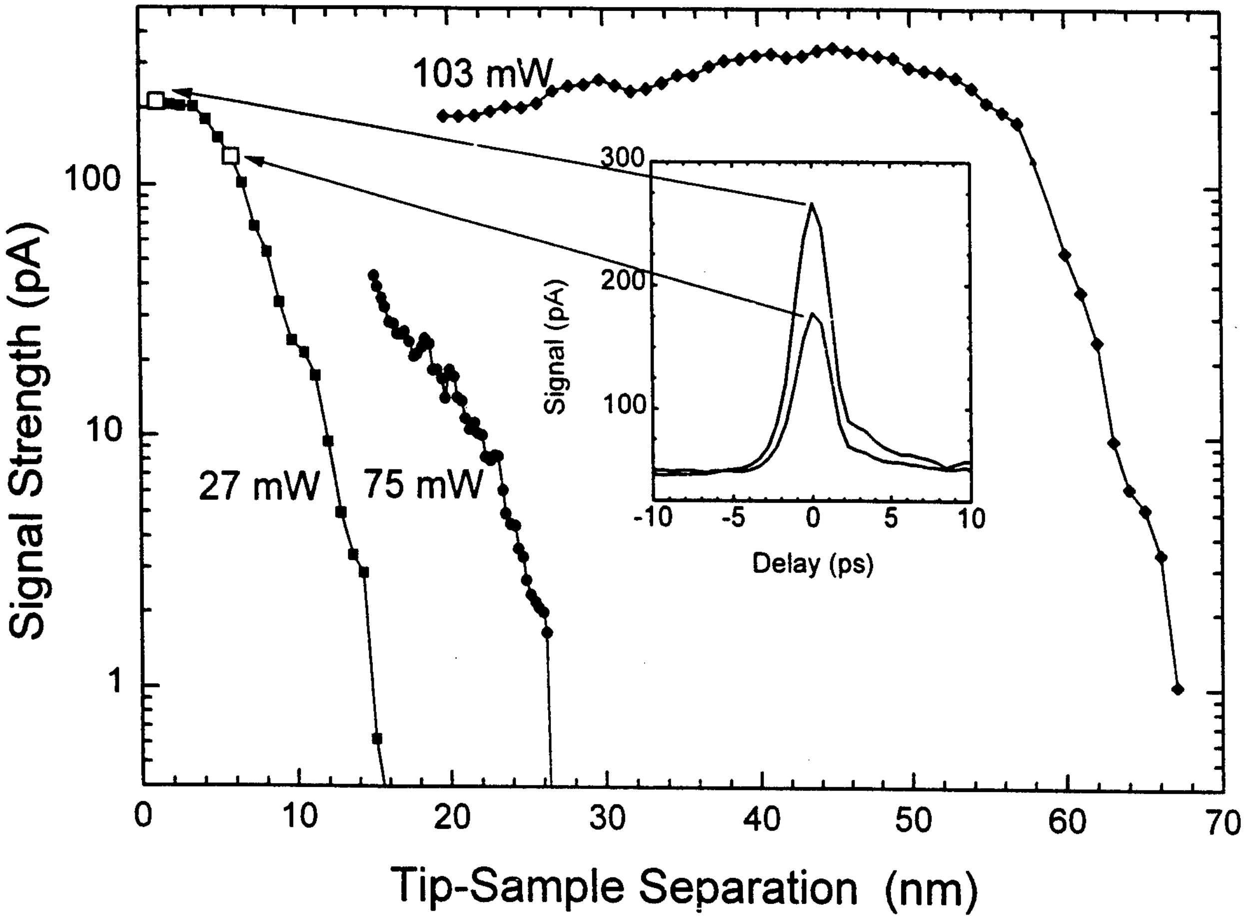

0.01" Tungsten wire
Gold contact pad
0.1 mm x 0.1 mm
0.05 mm thk
LT GaAs tip

Figure 1



103 mW
27 mW
75 mW
Signal Strength (pA)
100
10
1
0
10
20
30
40
50
60
70
Tip-Sample Separation (nm)
300
200
100
Signal (pA)
-10
-5
0
5
10
Delay (ps)

Figure 2

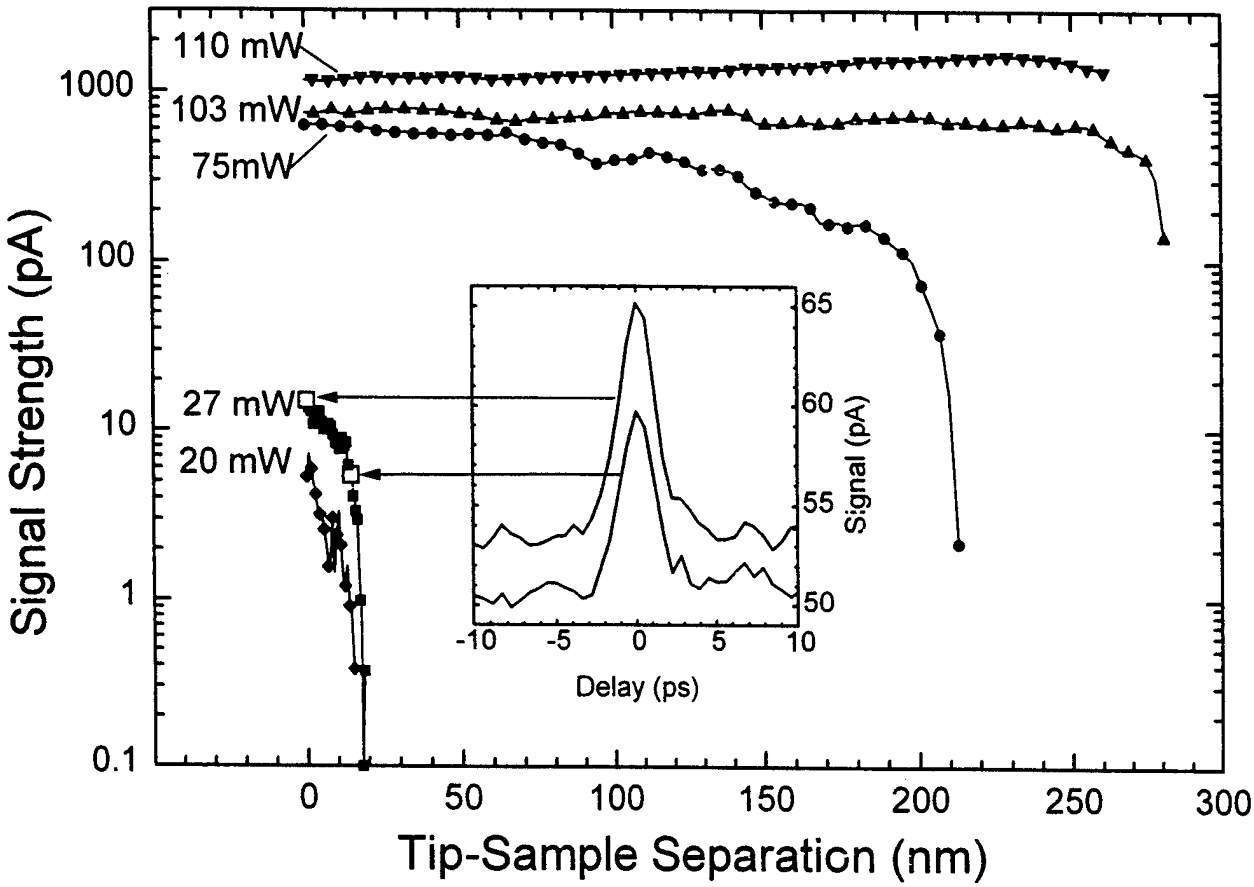

110 mW
103 mW
75mW
27 mW
20 mW
1000
100
10
1
0.1
0
50
100
150
200
250
300
Signal Strength (pA)
Tip-Sample Separation (nm)
65
60
55
50
Signal (pA)
-10
-5
0
5
10
Delay (ps)

Figure 3

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