Appl. Phys. B 69, 455–458 (1999) / Digital Object Identifier (DOI) 10.1007/s003409900078

Applied Physics B
Lasers
and Optics

Spatio-temporal imaging of voltage pulses with a laser-gated photoconductive sampling probe

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Received: 17 February 1999/Revised version: 22 April 1999/Published online: 29 July 1999

Abstract. We report on the fabrication process of a scanning force microscopy (SFM) cantilever probe suitable for the investigation of ultrafast transient signals in microwave integrated circuits. High temporal resolution is achieved by integrating a laser-gated photoconductive switch within a coplanar waveguide structure onto a low-temperature GaAs cantilever. This is demonstrated by temporal and spatio-temporal measurements performed on a coplanar strip line.

PACS: 07.79.-v; 07.79.Lh; 84.40; 42.65.Re

The reduction of device and line dimensions in integrated circuits and the increase in the electronic device speed requires analytical tools that offer high temporal and sub-micron spatial resolution. Different techniques to combine ultrafast time resolution with scanning tunneling microscopes (STM) have been proposed [1–4]. All these measurements were restricted to surfaces of metals or highly doped semiconductors. However, in most cases microwave circuits are fabricated on insulating semiconductor materials and are covered by a passivation layer. Therefore, scanning force microscopy (SFM) with picosecond time resolution is expected to be the adequate analytical tool as the feedback mechanism in SFM does not rely on a conducting surface.

In photoconductively gated ultrafast scanning probe microscopy (USPM) [1] an optical pulse train is converted into an electrical pulse train using a photoconductive switch. These pulses are fed to the device under test (DUT). Simultaneously, the same optical pulses are used to turn on and off a photoconductive switch integrated into a GaAs SFM cantilever to measure a high-speed electrical signal using photoconductive sampling technique. The time resolution is achieved by varying the time delay between pump and probe beam.

In this paper we introduce a cantilever probe with an integrated waveguide structure. In order to minimize frequency dispersion and attenuation of the propagating signals, a coplanar waveguide was designed and adapted to the cantilever geometry. Additionally, a photoconductive switch is arranged between the electrodes of the coplanar waveguide. In contrast to conventional in-line photoconductive switches this configuration does not represent an impedance discontinuity [4]. First measurements on transmission line samples were performed in both contact and non-contact mode. These results demonstrate the intriguing potential of this SFM-based method.

1 Experimental setup

In Fig. 1 a schematic of the experimental setup is shown. A mode-locked Ti:sapphire laser supplies an optical pulse train with a repetition frequency of 76 MHz, and pulse widths of about 100 fs. The wavelength of the laser is tuned to

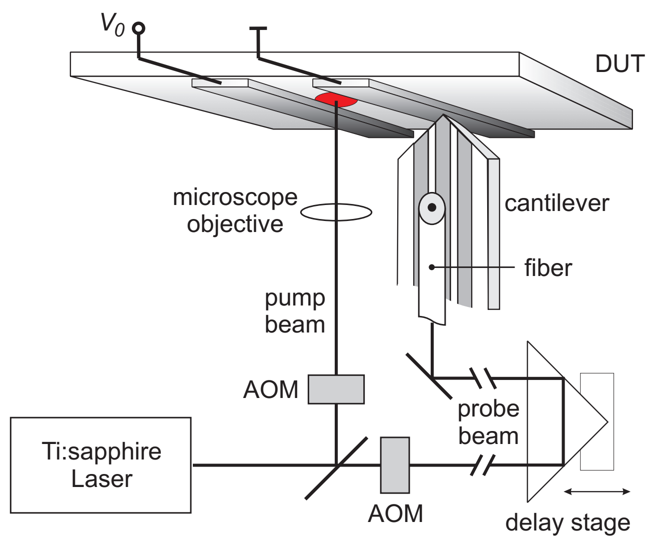

Fig. 1. Schematic setup of an ultrafast scanning probe microscope used to investigate the device under test (DUT)

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850 nm to achieve absorption in GaAs. The laser beam is split into a pump and probe beam. The probe-beam path contains a motorized stage to vary the delay time with a maximum delay of 2 ns. Pump and probe beam are modulated separately by acousto-optic modulators at frequencies of $f_{\text{Pump}} = 800\,\text{kHz}$ and $f_{\text{Probe}} = 804\,\text{kHz}$ to reduce thermal effects [5]. The probe beam is coupled into a single-mode fiber that is glued on top of the photoconductive switch on the cantilever. As shown in Fig. 1 the pump beam is focused with a microscope objective onto the gap between the transmission line electrodes on the sample surface. The photogenerated charge carriers locally increase the conductivity between the biased transmission line for a period of time corresponding to their carrier life time. In this way, short transient voltage pulses are launched and propagate along the transmission line. For the spatially resolved detection of these pulses, the cantilever tip is positioned at the desired location. A part of the pulse energy is coupled into the very end of the cantilever waveguide. To sample this transient signal with high temporal resolution, the photoconductive switch on the cantilever is illuminated with the probe-beam pulses. Finally, the pre-amplified signal is measured with a lock-in amplifier at the difference frequency $\Delta f = f_{\text{Probe}} - f_{\text{Pump}}$.

2 Manufacturing of GaAs cantilever

Low-temperature-grown (LT) GaAs is ideally suited for photoconductive switching purposes due to the short carrier lifetime (down to 150 fs has been reported [6]) combined with a carrier mobility of about 200 cm^2 /Vs which ensures a high responsivity. Thus a 1-μm-thick layer of LT GaAs is grown by MBE on top of a semi-insulating (SI) GaAs substrate. This wafer is processed from both sides. The main fabrication steps of the cantilever are summarized in Fig. 2. All etching processes are carried out by means of wet-chemical etching techniques as described in [7] using H_2O_2:H_2SO_4:H_2O as etchant. In step (a) a lift-off process is carried out in order to obtain the coplanar waveguide structure consisting of Au/Ge material. Au/Ge forms an Ohmic contact on GaAs. Typically, the thickness of the Au/Ge layer is in the range of 100–500 nm. The cantilever shape and its final thickness are defined in step (b). To process the bottom side of the wafer in step (c) the top side is protected with wax and glued on a glass plate. An infrared mask aligner is used to adjust both sides without additional marks. After cleaning the bottom side by organic solvents and O_2-plasma etching the next lithography and etch processes are performed. In step (d) the cantilever is removed from the stabilizing frame by a spray etching process as described earlier [8]. As mentioned above, the optical pulses are coupled onto the photoconductive switch via a single-mode fiber cleaved under an angle of 45°. In step (e) the fiber is positioned above the surface of the cantilever so that the laser beam illuminates the photoconductive area between two of the three Au/Ge electrodes of the integrated coplanar waveguide structure. Finally, the fiber is fixed using a UV-curing optical adhesive. A 600-μm-long and 190-μm-wide cantilever without an attached fiber is shown in Fig. 3. To adjust the spring constant of the cantilever, the thickness of these probes can be varied from 10 μm down to 1 μm. The coplanar waveguide with 8 μm contact spacing and 10 μm width is designed to achieve a waveguide impedance of 50 Ω. The waveguide structure of the cantilever was designed to reduce dispersion as well as attenuation of the propagating signals.

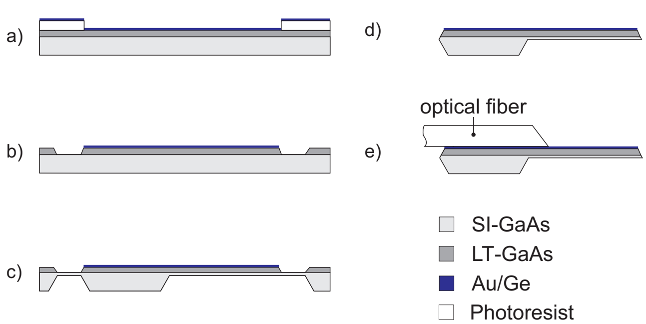

Fig. 2a–e. The main steps of cantilever fabrication. **a** A lift-off process is used to process the coplanar waveguide structure on the LT GaAs layer. **b** The cantilever geometry is defined by an optical lithography step and a subsequent wet-etching process. **c** The final cantilever thickness is determined by the spray etching process from the bottom side. **d** Freeing of cantilevers. **e** Mounting of a cleaved single-mode fiber on top of the waveguide

3 Characterization of probes

Illuminating the LT GaAs material between two electrodes of the cantilever with the laser beam reduces the electrical resistance of the LT GaAs layer from 150 MΩ down to 100 Ω. To determine the temporal resolution of the sensor, cross-correlation measurements on the cantilever were performed. For this purpose a bias of 5 V was applied between the center and the outer electrode of the cantilever (Fig. 4a). Electrical pulses are generated by illuminating the gap between these

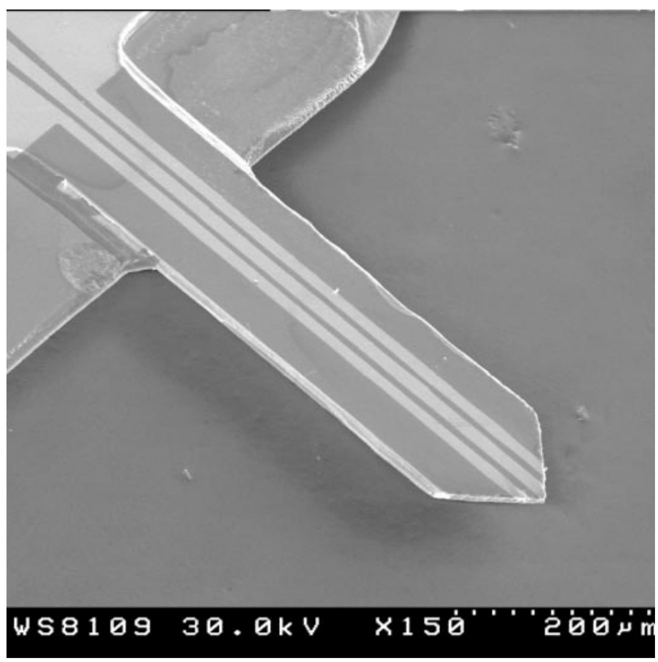

Fig. 3. Scanning electron microscopy image of a 600-μm-long, 190-μm-wide, and 6-μm-thick cantilever with an integrated coplanar waveguide. The spacing of electrodes is 10 μm and the Au/Ge layer thickness is about 200 nm

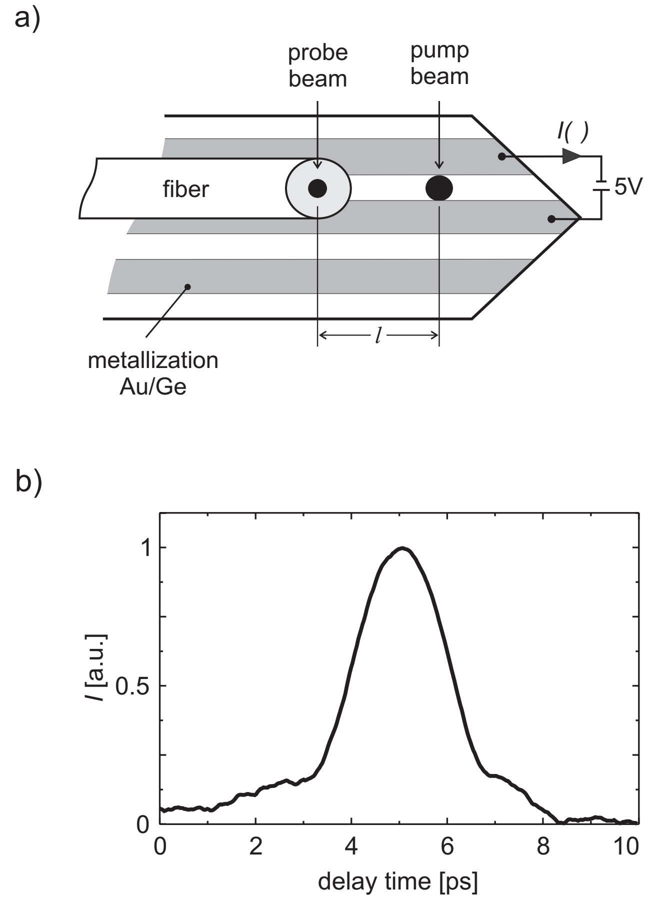

Fig. 4. **a** Top view of a cantilever with integrated coplanar waveguide. The focused pump beam and the probe beam transmitted through the slanted fiber are used to form two photoconductive switches separated by the distance l. **b** Photocurrent cross-correlation measurement versus the delay time τ

electrodes with both the pump and probe beam. The beams are separated by a distance l of approximately 150 μm. To obtain the cross-correlation function of these electrical pulses the current is measured as a function of the delay time τ (Fig. 4b). The full width at half maximum (FWHM) of the correlation function is a measure of the temporal response of the photoconductive switch. The measurement demonstrates the capability of achieving a time resolution of less than 2 ps.

4 Measurements

The schematic of our measurement setup is shown in Fig. 5. The DUT consists of a coplanar strip line with 10 μm electrode spacing and width. To generate the electrical pulses a switch voltage of $V_0 = 7$ V is applied between the two lines. The cantilever is positioned at a distance of 300 μm from the electrical-pulse-generating pump beam and aligned under an angle of about 50° with respect to the sample surface. A part of the wave propagating on the coplanar strip line is coupled into the cantilever electrode. This signal propagates along the cantilever waveguide and passes the photoconductive switch at the probe beam location. When the switch is made conductive, a current is initiated which is proportional to the field gradient between the center and the outer electrode. As indicated in Fig. 5 this current is measured in dependence on the delay time τ.

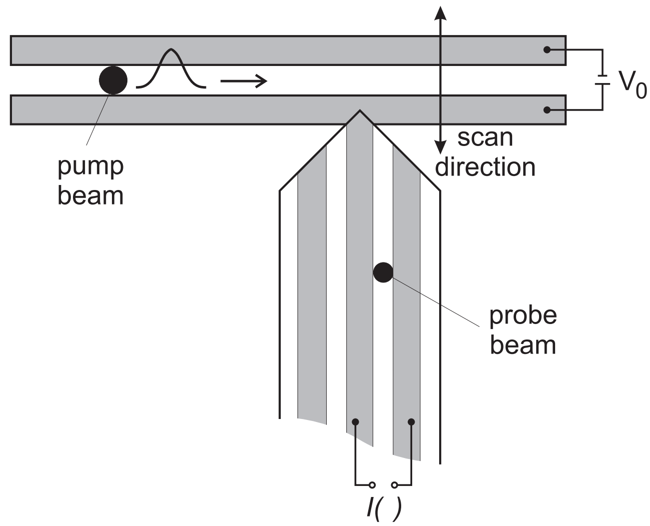

Fig. 5. Measurement geometry for the temporal and spatio-temporal investigation of the electrical field distribution of a strip line. For the sake of clarity the fiber for the illumination of the photoconductive switch on the cantilever was omitted. The current I between the center and right electrode of the cantilever is measured as a function of the delay time τ. The *arrow* indicates the scan direction for spatio-temporal measurements

Figure 6 shows the time-resolved signals picked up in contact (I_c) and approximately 100 nm above (I_{nc}) the grounded electrode of the transmission line. To facilitate the comparison of measurements, both graphs are normalized to the maximum signal of the contact measurement. In contact mode the arrangement can be described as a resistively coupled voltage probe; i.e. the measured signal is proportional to the original voltage pulse on the transmission line. In non-contact mode the signal is transmitted through capacitive coupling between tip and sample which leads to the differentiation of the transient signal. This can be seen comparing the numerical derivative $\partial I_{nc}/\partial t$ of the contact mode signal and the non-contact mode signal I_c as plotted in Fig. 6. The same effect was already observed with tunneling tip probes and is explained in [5]. The rise time (10%–90%) of the con-

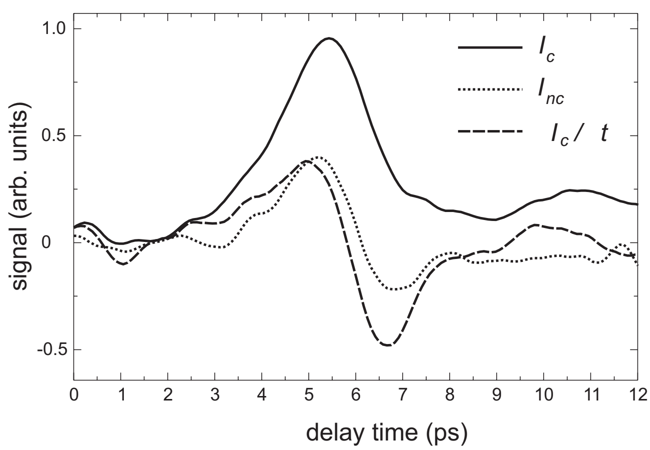

Fig. 6. Comparison of a time resolved measurement on the grounded electrode of the transmission line in contact mode I_c, in non-contact mode I_{nc}, and the numerically differentiated contact mode signal $\partial I_c/\partial t$

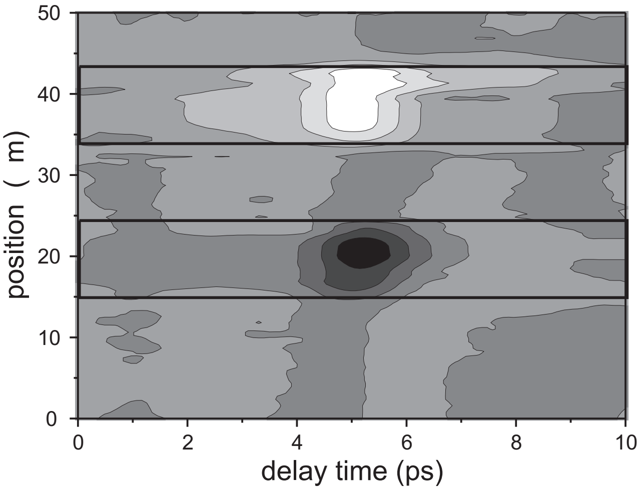

Fig. 7. Spatio-temporal image in contact mode of a voltage pulse generated by optical excitation between two contacts of a biased coplanar strip line. In the linear gray-scale, white represents the area with maximum positive values of the signal and black the maximum negative values. The *black lines* indicate the location of the transmission line electrodes. The scan range was 50 μm and the delay time was varied over 10 ps

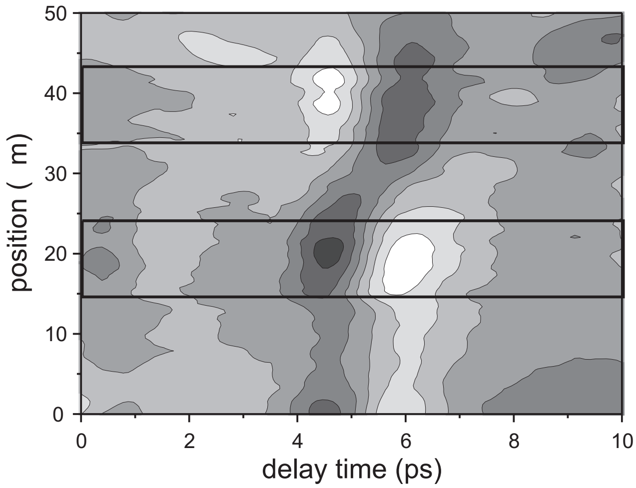

Fig. 8. Spatio-temporal measurements in the non-contact mode of a voltage pulse propagating along the transmission line at the same location as in Fig. 7. The distance between cantilever and sample was fixed to about 0.1 μm

tact (non-contact) signal is approximately 2.3 ps (1.4 ps) with a FWHM of 1.9 ps (1.5 ps). A significant difference to results obtained with tip-probes used in STM is, that the transient signal in non-contact (tunneling) mode is decreased by a factor of about 100 compared to the contact measurement [5, 9]. In the case of GaAs cantilever probes both signals are of the same magnitude. This is because the capacitance formed by the sensor and sample is larger for the cantilever than for the tunneling tip.

To generate a spatio-temporal image of the propagating voltage pulse, a line scan is carried out perpendicular to the transmission line as indicated in Fig. 5. At each position a scan in delay time is performed. The voltage distribution across the transmission line was measured in contact (Fig. 7) and non-contact (Fig. 8) mode. The transient signals at the different locations on the scan line are depicted in linear gray-scale contour plots where the white (black) areas correspond to the largest positive (smallest negative) values. Black lines are added to indicate the location of the transmission line electrodes. The original pulse shape is detected when the cantilever is in contact with the metal strip line whereas the differentiated signal is obtained on top of the semiconductor surface. Therefore, these signals have to be integrated to obtain the original mode profile of the propagating pulse. This was done with the measured data to obtain the processed image depicted in Fig. 7. In the non-contact mode the distance between sample and cantilever tip was fixed to about 100 nm. Due to the capacitive coupling as described above, the differentiated signal is obtained also on the metal electrodes (Fig. 8). Both measured spatio-temporal images can be explained in terms of an odd zero-order mode launched on the coplanar strip line.

In the contact mode the dominant contribution to the signal arises from the resistive coupling between sample and cantilever which is a local interaction. In non-contact mode the spatial resolution is degraded by capacitive coupling across the junction which presumably occurs over a more macroscopic region. Appropriate samples have to be designed and fabricated to study the spatial resolution in more detail. This will be investigated in more detail in a forthcoming paper.

5 Conclusion

For electrical testing of integrated microwave circuits a versatile SFM cantilever probe is presented. The SFM offers several advantages in contrast to conventional ultrafast scanning tunneling microscopy. It does not rely on conducting surfaces and additionally is capable of being operated in both contact and non-contact mode. For the sampling of ultrafast signals a coplanar waveguide providing a photoconductive switch was integrated onto a LT GaAs cantilever. Transient signals on a coplanar strip line were investigated. A temporal resolution of 1.9 ps (1.5 ps) was achieved in contact (non-contact) mode. The same transient signals were spatio-temporal imaged in both contact and non-contact mode, which underlines the versatility of the probe.

Acknowledgements. We would like to thank Claus Sørensen from the III-V Nanolab for the growth of the LT-GaAs samples.

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