DC-to-mm-Wave Absolute Potential Measurements Inside Digital Microwave ICs Using a Micromachined Photoconductive Sampling Probe

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Abstract

A micromachined photoconductive sampling probe is used to determine detailed wave forms at different circuit nodes and corresponding propagation delays from within an InP HBT frequency divider operating at 2.7 GHz. The results demonstrate for the first time the capability of photoconductive probes for absolute-voltage, DC-coupled potential measurements in integrated circuits.

Introduction

In recent years different approaches for in-circuit measurement techniques have been pursued. A number of promising techniques in terms of high spatial resolution and high bandwidth are based on optical measurement methods (e.g. electro-optic sampling as well as photoconductive sampling using freely positionable probes [1-3]). Electro-optic sampling is field sensitive, so that it is well suited for measurements of field distributions [4], while in contrast, the photoconductive sampling technique probes voltages and is thus useful for potential measurements [2]. The majority of the measurements obtained using these techniques yield relative values of the potential or electric field strength, so that calibration routines are necessary to determine the absolute actual value. Moreover, the measurements are typically performed with ac-coupling so that the dc components are not accessible. In this paper we demonstrate that our recently developed, micromachined photoconductive sampling probe [2] is capable of distinguishing absolute microwave signal amplitudes at circuit-internal nodes. Thus, the signal's measured value is equal in size to its actual value, both for the dc and the ac component. To highlight this capability a digital frequency divider circuit operating at 2.7 GHz has been investigated. Detailed wave forms that vary in shape and frequency at different nodes and the corresponding propagation delays inside the circuit are presented. The measured interconnecting lines have a width of 5 μm, revealing the high spatial resolution of the probe. The results of these time-domain measurements demonstrate the usefulness of the probe, ranging from digital circuit diagnostics and model validation, to characterization of in-circuit electrical transients such as those induced by cosmic particles in satellite microelectronics (so-called 'single event effects') [5,6].

Photoconductive Sampling Probe

The probe used consists of a micromachined epitaxial layer of low-temperature-grown GaAs (see Figure 1), attached to a single mode optical fiber that couples 100 fs laser pulses to a 30 x 30 μm^2 interdigitated photoconductive sampling gate. Integrated with a JFET source follower, the probe has high input impedance and a low capacitance, so that noninvasive measurements of ac electrical signals are possible. The probe has a sensitivity of 15 nV/(Hz)$^{1/2}$ when in conductive contact with the probed node [5]. Due to the high input resistance of the source follower the instantaneous DC voltage at the probe node is present at the source follower without significant degradation and can also be determined at the output of the source follower.

Because the optical input to the probe tip is via an optical fiber, it is easy to position the probe, and the compact cross section allows measurements even inside packaged circuits. The 7 μm width of the metal tip provides high spatial resolution, sufficient for today's interconnects in digital microwave circuits. It should be mentioned that the resolution

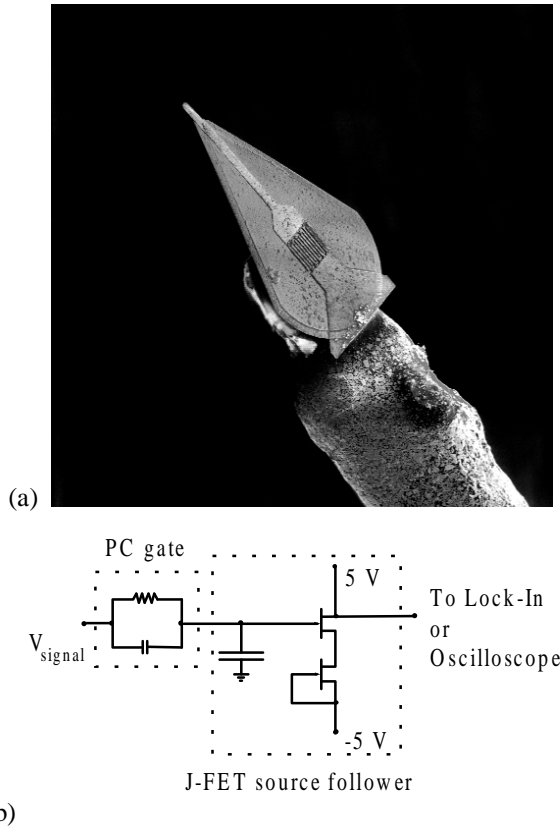can easily be increased to the sub-μm range using a conical tip [7] if necessary.

(a)

(b)

Fig. 1. Photoconductive sampling probe: (a) SEM image, (b) equivalent circuit; the probe is 130 μm x 230 μm (at its widest points) by 1 μm, The finger size of the interdigital MSM switch is 1.5 μm
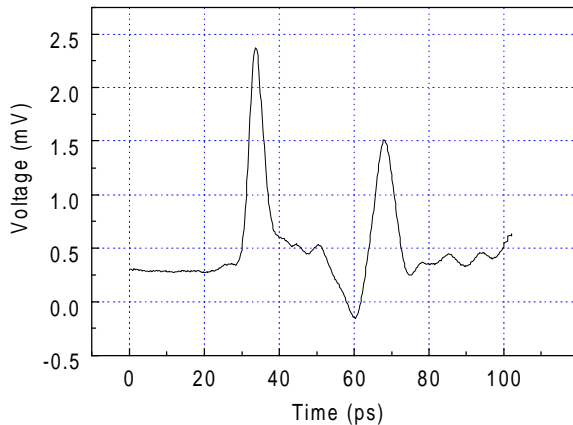

Fig. 2. Measured time response of the photoconductive probe (the second pulse at t= 70 ps represents the electrical pulse reflected from the input of the coplanar strip line)

The bandwidth of the probe is measured using a so-called pump-probe style of experiment. The Ti-sapphire laser generates electrical pulses with duration of ∼1 ps on a coplanar strip. Figure 2 shows the voltage wave form measured by the probe. The t_{FWHM} of 4.2 ps reveals a bandwidth up to 150 GHz for this sampling system.

Experimental Setup

The measurements inside the circuit are performed using the experimental setup shown in Figure 3. The basic principle used in this setup is equivalent-time sampling of the microwave signal, with the optically activated photoconductive switch acting as a sampling gate. The setup uses a phase referencing technique to synchronize the microwave signal source and the pulsed laser source in order to cancel out phase fluctuations. The reference signal is generated by a RF mixer with the LO provided by the output signal of a fast photodiode and a fraction of the microwave signal used as the RF. The IF signal triggers a digitizing oscilloscope that records the downconverted wave form of the sampled microwave signal at the probed node, including the DC offset.
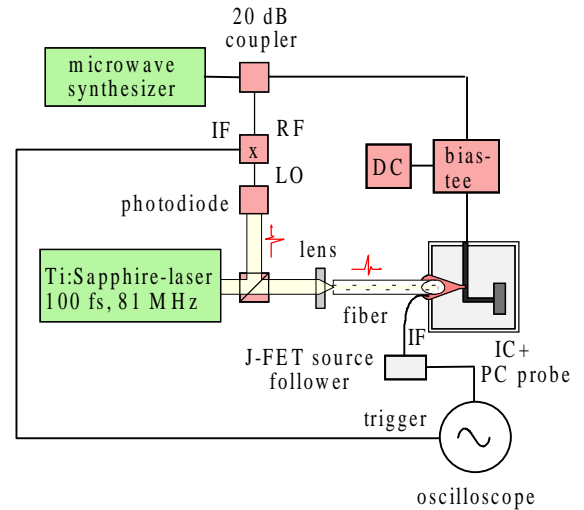

Fig. 3. Experimental setup for digital circuit measurements

Circuit Measurements

The examined circuit, shown in Figure 4's block diagram, is a high speed, InP heterojunction bipolar transistor (HBT) frequency divider [8]. The circuit provides a differential divide-by-four output based on a differential input clock, and is nominally
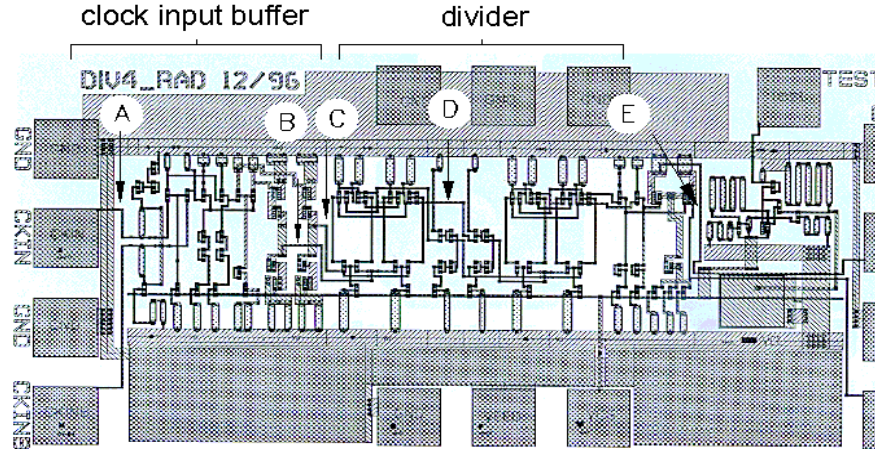
Fig. 5. Investigated InP frequency divider circuit

designed to operate at 3.5 GHz. The annotated layout in Figure 5 shows probing locations (A) - (E) for the entire circuit. The device operated single-endedly, with one side of the differential input floated to its threshold. The single-ended input was AC-coupled with DC biases set by internal circuit nodes.
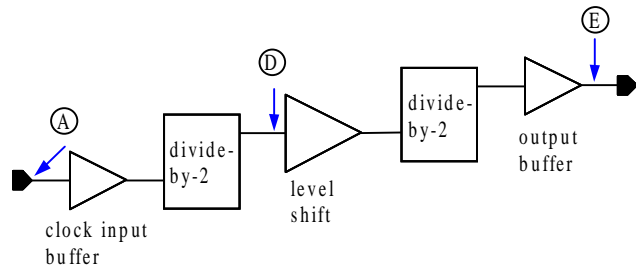

Fig. 4. Block diagram of InP divider circuit with probing locations (A), (D), and (E)

The single-ended input was probed at location (A) at the input to the clock buffer, which is the base electrode of the first HBT of the circuit. The result is shown in Figure 6. The 2.7 GHz sinusoidal input shows both the internal DC level of -2.1 V and the expected input swing of 630 mV peak (0 dBm) to peak. Comparison with the collector output of this HBT (not shown) reveal a gate delay of 7.1 ps.

The differential outputs of the input clock buffer were probed at locations (B) and (C) as shown in the layout. The results are shown in Figure 7 (a) and (b) where (B) is the "true" output and (C) is its complement. The output levels are roughly two diode drops below ground, as expected.

Two cascaded divide-by-two circuits create the divide-by-four function. Figure 8 shows the first stage divide-by-two output probed at position (D) on

the layout. Figure 9 shows the buffer output probed at position (E) with an output frequency of 675 MHz (2.7 GHz/4), as expected.
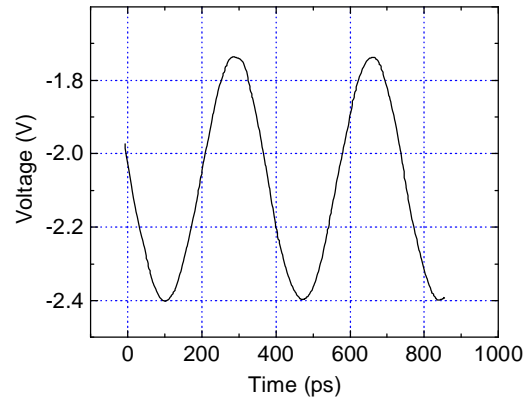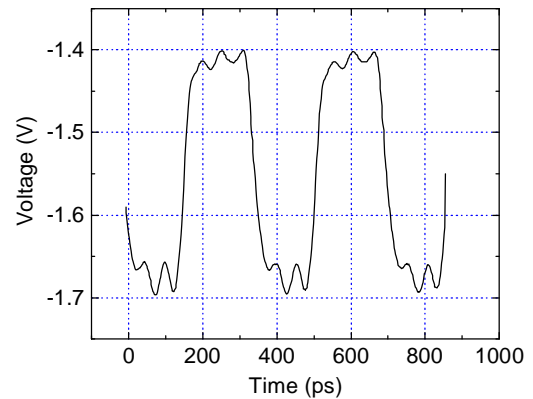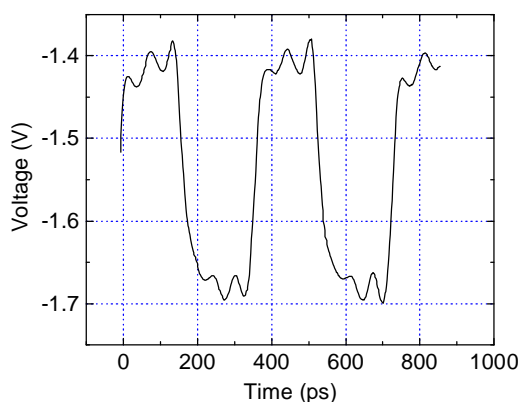

Fig. 6.   Sinusoidal microwave input of 2.7 GHz measured at pos. (A)

(a)

(b)

Fig. 7. (a) 'True' output signal of the clock-input buffer section (pos. B), (b) Complement output signal of the clock-input buffer at pos. C
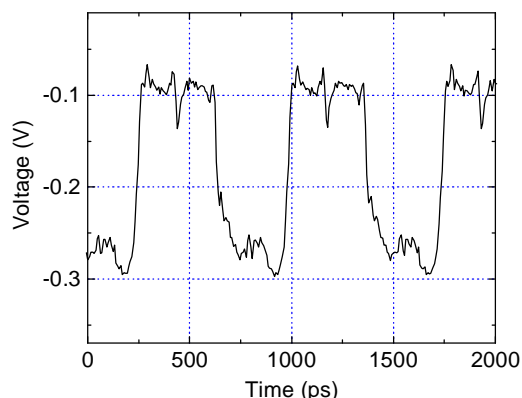

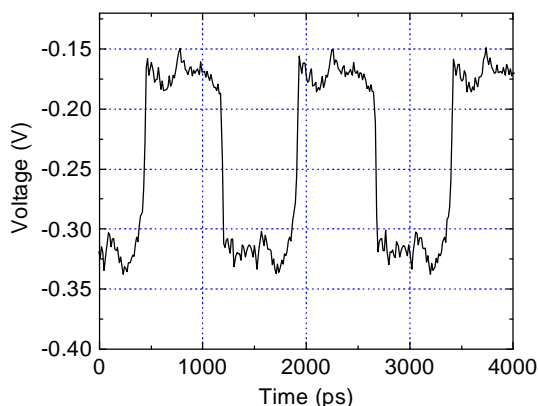Fig. 8. Output signal of the first divide-by-2 at pos. D

Fig.9.   Output signal of the output buffer at pos. E

Conclusions

The in-circuit measurement capabilities of a micro-machined photoconductive probe tip are presented, revealing that the probe has potential as a diagnostic tool for IC testing (*e.g.,* for gate delays, faults, *etc.*), with high spatial resolution, high time resolution, and low interference with the device under test. Special emphasis is placed on the fact that absolute voltages (both for dc and ac) are accessible with a bandwidth exceeding 100 GHz.

References

1. T. Pfeifer, H.-M. Heiliger, E. Stein von Kaminski, H.G. Roskos, and H. Kurz, "Fabrication and characterization of freely positionable silicon-on-saphirre photoconductive probes", J. Opt. Soc. Am. B 11, 2547 (1994)

2. R.K. Lai, J.-R. Hwang, J. Nees, T.B. Norris, and J.F. Whitaker, "A fiber-mounted, micromachined photo-conductive probe with 15 nV/Hz$^{1/2}$ sensitivity", *Appl. Phys. Lett.* **69**, 1843-1845 (1996)

3. K. Takeuchi, A. Mizuhara, "Potential image observation with ultra-high space-time resolution", OSA Spring Topical Meeting 'Ultrafast Electronics and Optoelectronics', Technical Digest p.151 (1997)

4. G. David, R. Tempel, I. Wolff, and D. Jäger (1996), "Analysis of microwave propagation effects using 2D electro-optic field mapping techniques", Optical and Quantum Electronics, vol. 28, 919-931 (1996)

5. Ledbetter, T. Weatherford, G. David, J. Hayden, R. Lai and J. Whitaker: "In-situ picosecond resolution measurements of SEU transients in GaAs Logic", accepted for IEEE Transactions of Nuclear Science

6. G. David, J. Whitaker, E. Ledbetter, T. Weatherford, D. Fouts, W. Goyette, K. Jobe, and K. Elliott, "A picosecond-response photoconductive-sampling probe for digital circuit testing", IEEE LEOS'97, San Francisco, USA

7. J. Nees, S. Wakana, and S. Hama, "Ultrafast-ultrafine probing of high-speed electrical waveforms using a scanning force microscope with photoconductive gating", Opt. Quantum Electron. 28, 843 (1996)

8. F. Jensen, W. E. Stanchina, R. A. Metzger, D. B. Rensch, R. F. Lohr, R. W. Quen, M. W. Pierce, Y. K. Allen, and P. F. Lou, "AlInAs/GaInAs HBT IC Technology," IEEE J. Solid-State Circuits, Vol. 26, p. 415 (1991)