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Absolute Potential Measurements Inside Microwave Digital IC's Using a Micromachined Photoconductive Sampling Probe

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***Abstract*— A measurement system for internal node testing of integrated circuits using a micromachined photoconductive sampling probe is described and characterized. Special emphasis is placed upon the system performance, demonstrating how absolute voltage measurements are achieved in a dc-to-mm-wave bandwidth. The feasibility of the setup is illustrated using an InP heterojunction bipolar transistor frequency divider. Detailed waveforms at different circuit nodes and the corresponding propagation delays from within this circuit at operating frequencies up to 10 GHz are presented. The results demonstrate for the first time the use of photoconductive probes for calibration-free, absolute-voltage, dc-coupled potential measurements in high-frequency and high-speed integrated circuits.**

***Index Terms*— Integrated-circuit testing, microwave measurements, nondestructive testing, photoconductive measurements, time-domain measurements, voltage measurement.**

I. Introduction

In RECENT years, different approaches for in-circuit measurement techniques for high-frequency and high-speed integrated circuits have been pursued. For example, electro-optic sampling [1]–[3] and electro-optic field mapping [4] have been successfully demonstrated. In addition, scanning probe microscopes [5], as well as electromagnetic probing techniques using dipole or monopole type probes [6], [7] have shown potential for making high-frequency in-circuit measurements. One aspect that all these measurement techniques have in common is that they only yield relative values of the potential or electric field strength, so that calibration routines are necessary to determine actual absolute signal values. Moreover, the measurements are typically performed with ac-coupling [5], so that the dc component is not accessible. In contrast, we demonstrate in this paper that our recently developed measurement setup based on photoconductive sampling is capable of absolute measurement of the microwave signal amplitude 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, and calibration routines are not necessary.

The photoconductive sampling technique has been used in the past for external port measurements of devices and circuits [8]–[10] with a bandwidth of several hundred gigahertz. This technique utilized picosecond electrical pulses generated by photoconductive switches and successfully measured the time domain characteristics of integrated devices under test (DUT's). Thus, it provided an alternative to the on-wafer network analyzer measurement technique but was exclusively limited to measurements of external ports. Miniaturized photoconductive probes (both micromachined and bulk) were then developed [11]–[16] to get access to arbitrary internal ports of integrated circuits. Bulk probes showed major limitations in ease-of-use and invasiveness, while micromachined probes revealed superior features because of the reduced parasitic capacitance and the flexible handling (e.g., fiber mounting of the probe is possible). The integration of a high impedance source follower as a readout circuit [14] has finally led to the probe embodiment used in this paper [15]. The readout circuit transforms the signal collection from a current measurement to a highly sensitive voltage measurement. This avoids leakage current to the probe and thus minimizes the circuit distortion. Absolute voltage levels are accessible because the parasitic capacitance of the sampling gate is significantly reduced. This also leads to an increased modulation bandwidth, providing higher signal-to-noise ratios, and sensing of electrical signals even through passivation layers [17] has been demonstrated.

The probes up to now have only been employed in pump-probe style experiments where an electrical signal is also generated by the same laser system used to provide the sampling triggers. This type of experiment is not appropriate under actual circuit driving conditions, where an independent electrical source must be employed. Thus, a heterodyne mixing

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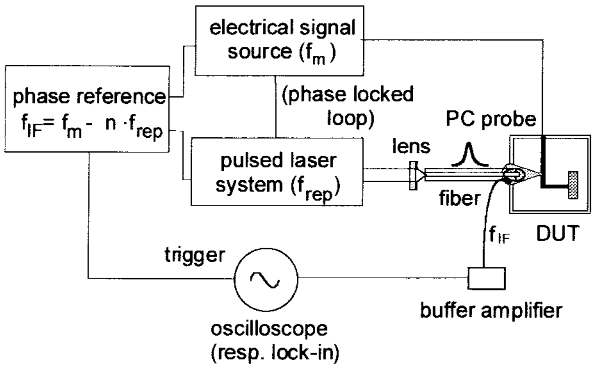


Fig. 1. Experimental setup for photoconductive in-circuit sampling measurements.

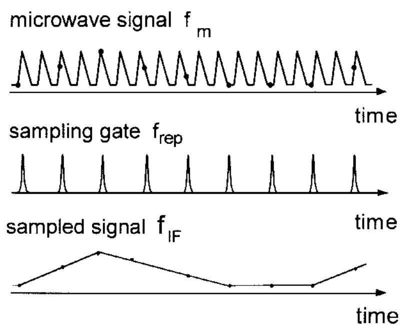
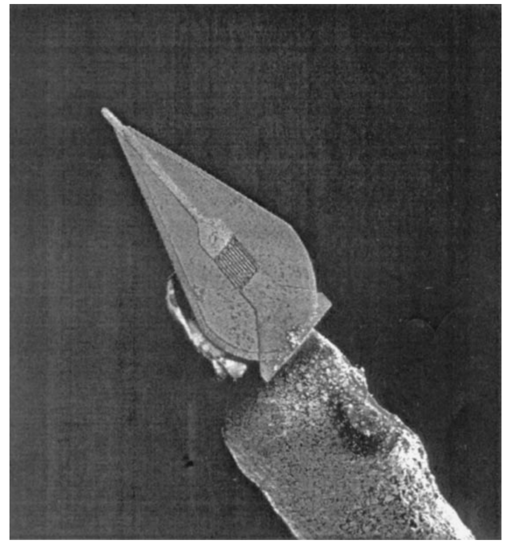
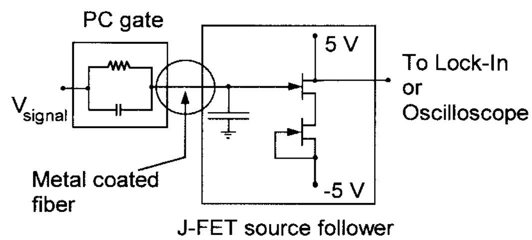


Fig. 2. Equivalent-time sampling scheme.



(a)



(b)

Fig. 3. Photoconductive sampling probe: (a) SEM image, (b) equivalent circuit; the probe is 130 μm × 230 μm (at its widest points) by 1 μm. The finger size of the interdigital MSM switch is 1.5 μm.

technique (for frequency-domain measurements) or an equivalent time sampling technique (for time-domain measurements) has to be used, requiring a synchronization between the gating laser pulse train and the independent, external electrical signal generator (i.e., a microwave synthesizer or an electrical pattern generator).

In this paper, the characteristics of the photoconductive probe along with those of the laser and the rest of the measurement system (e.g., bandwidth, sensitivity, spatial resolution, linearity for dc and ac operation) are discussed in relation to diagnostics of conventionally driven circuits. To highlight the capabilities, a digital frequency divider circuit operating between 90 MHz and 16 GHz has been investigated. Detailed waveforms that vary in shape and frequency at different nodes are presented, and propagation delays within the circuit are shown. The measured interconnect lines have widths down to 3 μm, revealing the high spatial resolution of the probe. The results of these equivalent time sampling measurements demonstrate the usefulness of the probe, ranging from digital circuit diagnostics, model validation, and fault isolation, to characterization of in-circuit electrical transients such as those induced by cosmic particles in satellite microelectronics (so-called "single event effects") [18], [19].

II. System Description

A. Measurement Principle

The principal experimental setup is sketched in Fig. 1. Heterodyne-mixing and equivalent-time sampling (Fig. 2) require that the unknown signal repeats periodically with a frequency f_m. If f_m is chosen to be

$$f_m = n \cdot f_{\mathrm{rep}} \pm f_{\mathrm{IF}}$$

where f_{IF} is an intermediate frequency (e.g., in the kilohertz-range, also called modulation frequency), n is an integer number, and f_{rep} is the repetition frequency of the sampling gates, then the signal will be sampled with the frequency f_{IF}, and a downconverted replica will appear at this frequency.

In the described measurement system, the sampling gates are provided by the photoconductive sampling probe. The probe is in conductive contact with a circuit internal node, where the unknown signal is to be measured. A train of femtosecond-duration laser pulses illuminates the probe, and its output voltage is recorded on a low-frequency electronic measurement instrument, such as an oscilloscope, making the temporal waveforms at the intermediate frequency accessible. A lock-in amplifier or a spectrum analyzer can also be used to display the amplitude and phase of f_{IF} and its harmonics, so that the unknown microwave signal can be determined in the frequency domain.

B. Photoconductive Sampling Probe

The sampling probe used in this work consists of a micromachined epitaxial layer of low-temperature-grown GaAs [see Fig. 3(a)] attached to a single mode optical fiber that couples the laser pulses to a 30 × 30 μm^2 interdigitated photoconductive sampling gate. The metal tip at the end of

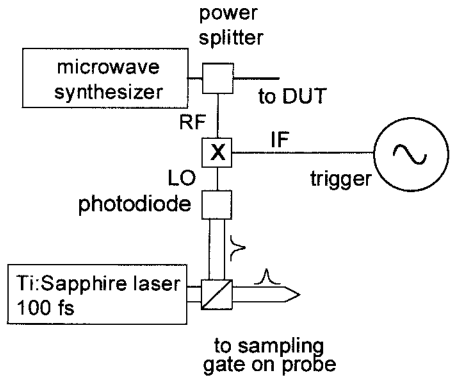


Fig. 4. Configuration for synchronization of a passively modelocked laser system and a microwave synthesizer.

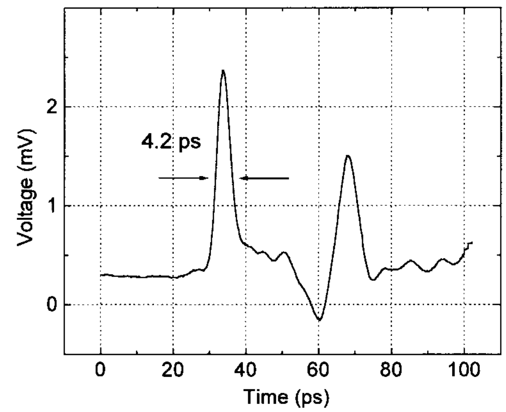


Fig. 5. Measured time response of the photoconductive probe (the negative transient and the subsequent positive pulse arise from reflections present on the coplanar strip photo switch).

the probe, which has a width of 7 μm, typically touches the circuit internal node to achieve a conducting contact.

The photoconductive gate has an off-state resistance of 100 MΩ, which is comparable to the input impedance of commonly used readout instruments (e.g., 10–100 MΩ for a lock-in amplifier). Since this embodiment would lead to a current flow and to charge draining from the test point, the probe is instead integrated with a JFET source follower [see Fig. 3(b)] having an input impedance of 1 TΩ and an input capacitance of 3 pF. This then acts as a readout circuit. The circuit avoids charge drainage from the DUT (currents are reduced to about 3 pA), so that measurement with minimal invasiveness is achieved. Moreover, the current measurement is converted to a voltage measurement. Due to the low amount of charge necessary to load the source follower input, the actual voltage level is built up in a short time, allowing a higher modulation bandwidth and the ability to measure absolute voltage levels [14].

Due to the high input resistance of the source follower, the instantaneous dc voltage at the probe node is also present at the source follower and can be determined at the output of the source follower without significant degradation.

Because the optical input to the probe tip is via a fiber optic cable, it is easy to position the probe, and the compact cross section of the sampling head allows measurements even inside packaged circuits.

C. Femtosecond Laser Systems

Two different pulsed laser systems have been used for the reported measurements. For both of them it is necessary to obtain synchronization between the laser pulse train and the external signal source (i.e., a microwave synthesizer). The laser systems used are as follows.

1) A passively modelocked Ti:Sapphire laser with a pulse duration of 100 fs and an average output power of 2 W. The synchronization of this free-running laser to the microwave synthesizer is obtained by the circuitry sketched in Fig. 4. The setup uses a phase referencing technique to synchronize the microwave signal source and the pulsed laser source in order to cancel out timing fluctuations. The reference signal is generated by an RF mixer with the local oscillator (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 waveform of the sampled microwave signal at the probed node, including the dc offset. This time synchronization is not perfect due to a timing jitter of about 3 ps caused by the laser. However, measurements of clock signals up to 20 GHz were still obtained from this system.

2) A more sophisticated model of the Ti:sapphire laser having 80-fs pulse duration and 1 W output power. This laser also has phase-locked loop feedback electronics controlling the laser cavity length so that a highly stable 80-MHz laser repetition rate and synchronization with an external oscillator are achieved. Phase-locking of the microwave synthesizer with this laser oscillator is possible via a 10-MHz reference signal. Due to the feedback, the timing jitter of the passively modelocked laser is reduced to less than 1 ps, and measurements with low phase noise can be obtained. Using this laser system, the mixer configuration in Fig. 4 can be replaced by an additional low-frequency synthesizer that is phase-locked with both the laser pulse train and the microwave synthesizer.

D. System Performance

1) Time Resolution and Bandwidth: The temporal resolution of the probe is measured using a pump-probe style of experiment. In this case, the Ti:sapphire laser system optoelectronically generates electrical pulses with durations of $\sim$1 ps on a coplanar strip line on a low-temperature grown GaAs substrate. Fig. 5 shows the voltage waveform measured by the probe. The excellent time response of $t_{\mathrm{FWHM}} = 4.2$ ps corresponds to a bandwidth of at least 150 GHz for this sampling system. That is, the probe should exhibit a frequency response well into the millimeter-wave regime.

2) Modulation Bandwidth: Without the source follower, the signal-to noise ratio for the photoconductive probe is optimized at an intermediate frequency f_I that is typically below 1 kHz. This limited bandwidth makes time-domain measurements at f_{IF} greater than $\sim$100 Hz impossible, and thus experiments have to be performed in the frequency range

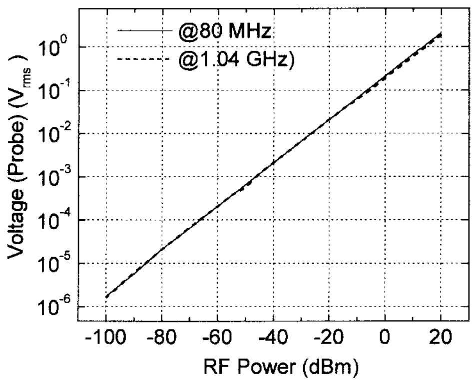


Fig. 6. Measured probe output voltage versus applied microwave power at two RF frequencies.

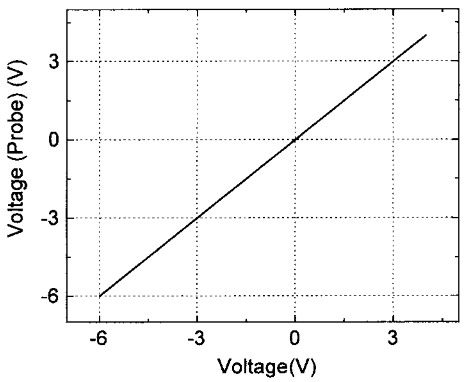


Fig. 7. Measured probe voltage versus applied input voltage.

where laser-induced noise, which has a $1/f$ spectrum, is at its maximum. In contrast, the reduced parasitic capacitance of the probe with the source follower leads to an increase of the modulation bandwidth of two orders of magnitude [17]. In this case, an average laser power of only a few milliwatts is necessary to obtain absolute measurement of voltage within the DUT.

3) Linearity: Fig. 6 shows the measured probe voltage dependence on input microwave power at two different frequencies, revealing an excellent linearity over 12 decades. It was, however, necessary to calibrate the readout circuit, since the source follower exhibited a deviation up to 10% from the actual value for input voltages exceeding ± 2.5 V. This deviation was measured to be constant between dc and a frequency of 100 kHz, and could therefore easily be compensated within the data acquisition software. In addition to the ac component, the dc component (Fig. 7) also showed outstanding linearity with applied voltage.

4) Sensitivity: The overall noise level of the system sets a limit on the sensitivity of the photoconductive probe measurements. The main noise source is the amplitude fluctuation of the gating laser pulses. In the case of optimum conditions (i.e., minimized laser power), a sensitivity of approximately 100 nV/(Hz)$^{1/2}$ is achieved.

5) Spatial Resolution: The positioning of the 7-μm width of the metal tip determines the spatial resolution of the probe used. This probe tip is sufficiently small that we may interrogate interconnects in many digital microwave circuits, even

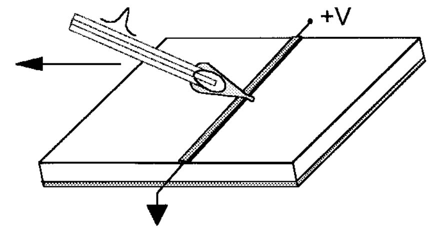


Fig. 8. Experimental setup for measurement of spatial resolution.

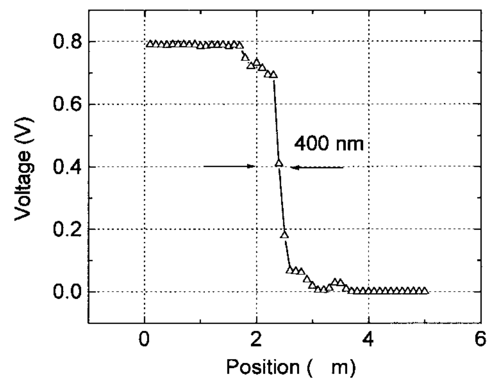


Fig. 9. Measured signal by translating the PC probe across the line.

with features much smaller than 1 μm. It should be mentioned that decreasing the probe tip width could easily increase the resolution further, or a fine conical tip can be employed to access the submicrometer regime [9]. To demonstrate the limit for the resolution of the current probe, a transmission line with a width of 5 μm was used as a DUT. The probe was translated transverse to the biased line using a high-precision translation stage (100 nm minimal incremental motion) while the probe output voltage was measured (see Fig. 8). Fig. 9 shows the experimental result with a high signal level corresponding to the amplitude of the applied 1-GHz signal. This decreases to the system noise level when the probe tip loses the conductive contact with the line. The minimal overlap between the metal line and the probe tip that is required to still measure the absolute voltage on the transmission line is determined to be about 400 nm. Thus, even circuit nodes with submillimeter structure size are accessible by the probe tip, if the traces in a circuit are not packed too densely that the probe would overlap multiple lines and short them.

III. Circuit Measurements

A. Device-Under-Test

The examined circuit is a high-speed, InP heterojunction bipolar transistor (HBT) frequency divider [20]. The circuit provides a differential divide-by-four output based on a differential input clock and is nominally designed to operate at 3.5 GHz. Internal dividers are based on latches constructed using differential pairs, where current is steered from one branch of the differential pair to the other to effect a change of logic state. The layout (Fig. 10) and the block diagram (Fig. 11) are annotated to show some of the probing locations. The device as configured was operated single-endedly, with one side of the differential input floated to its threshold. The single-ended

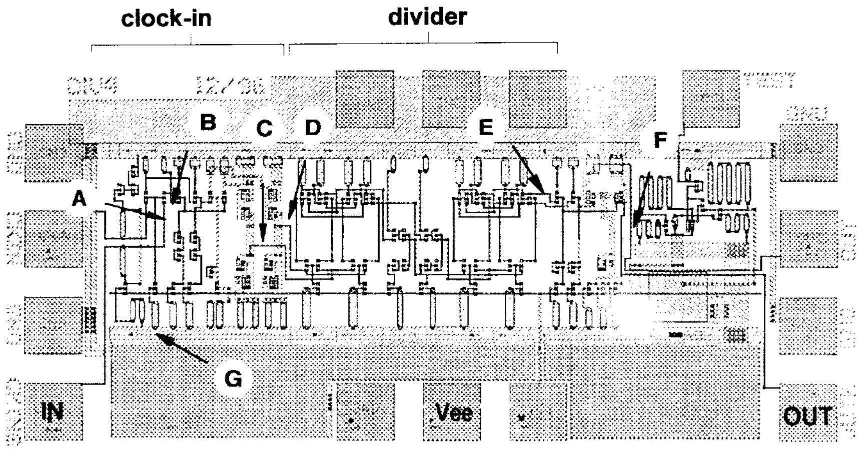


Fig. 10. Investigated InP frequency divider circuit with locations of probed nodes indicated.

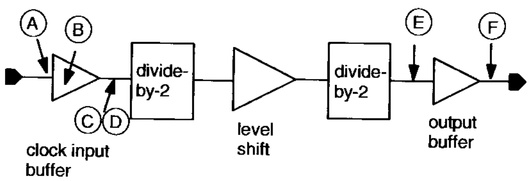


Fig. 11. Block diagram of InP divider circuit.

input was ac-coupled with dc biases set by internal circuit nodes.

B. Circuit Characterization

Internal node measurements of the circuit up to 16 GHz were performed. While in [21] results at 2.7 GHz were demonstrated, here we present measurements at a significantly higher frequency of 10.56 GHz.

The single-ended input was probed at location (A) in Figs. 10 and 11, with results shown in Fig. 12(a). The 10.56-GHz sinusoidal input shows both the internal dc level and an input swing of 700 mV peak to peak. This value is consistent with an attenuation of 7 dB due to the connecting microwave cable and dc blocking capacitor (applied output power of the synthesizer was 6 dBm). Position (B), as shown on the layout in Fig. 10 and schematically in Fig. 11, yields a waveform that illustrates how the collector of the differential amplifier circuit operates single-endedly, where one differential pair transistor acts as an emitter-follower and the other is cut off. This causes a distortion of the sinusoid at that location. The ac component is 350 mV and the dc level is -0.2 V. Note that a 7.1-ps propagation delay is measured between positions (A) and (B) corresponding to the expected transistor delay [after taking into account that the collector output (B) is inverted with respect to the emitter input (A)].

The differential output of the input clock buffer was probed at locations (C) and (D) as shown in the layout and block diagram. The results are shown in Fig. 13, where (C) is the true output and (D) is its complement. The phase inversion between the complementary outputs and the dc levels is as expected.

Two cascaded divide-by-two circuits create the divide-by-four function. Fig. 14 shows the second stage divide-by-two output probed at position (E) on the layout, revealing a frequency of 2.64 GHz (10.56 GHz/4). Fig. 15 shows the signal at the output buffer probed at position (F), with the same frequency of 2.64 GHz, as expected. The nonsinusoidal waveform indicates the presence of higher harmonics. When the circuit is operated at lower frequencies, for instance at its design frequency of 3.5 GHz, the higher harmonics completely transform the sinusoids to square waves [21]. Fig. 16 displays the characteristics of the noise on the power bus during the circuit operation. The bus has the expected -5.0 V dc bias for Vee, but with a 50 mV peak-to-peak ripple.

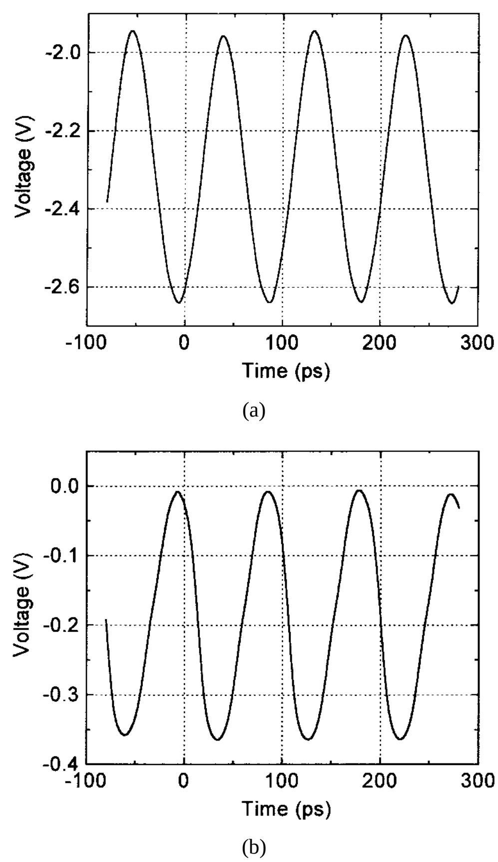
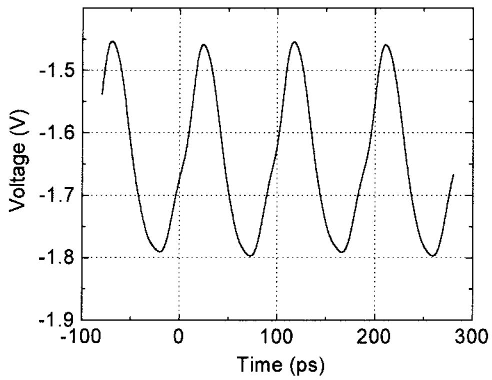
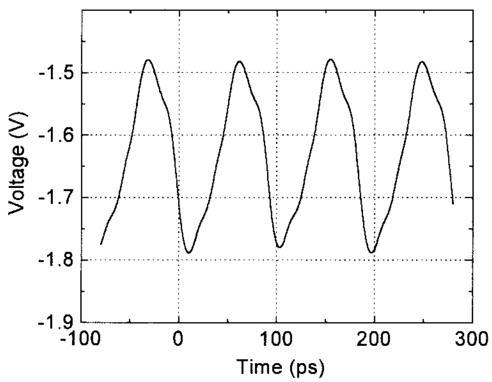


Fig. 12. Sinusoidal microwave input of 10.56 GHz, (a) measured at position (A), (b) measured waveform at position (B).



(a)



(b)

Fig. 13. (a) "True" output signal of the clock-input buffer section (position C), (b) complement output signal of the clock-input buffer at position D.

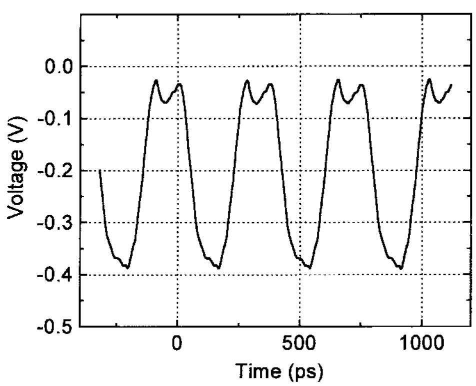


Fig. 14. Output signal of the second divide-by-two at position E (note the extended time axis).

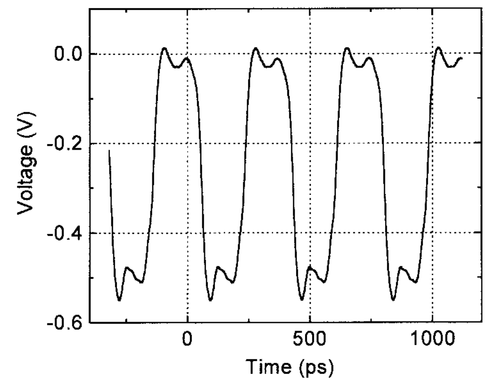


Fig. 15. Output signal of the output buffer at position F (note the extended time axis).

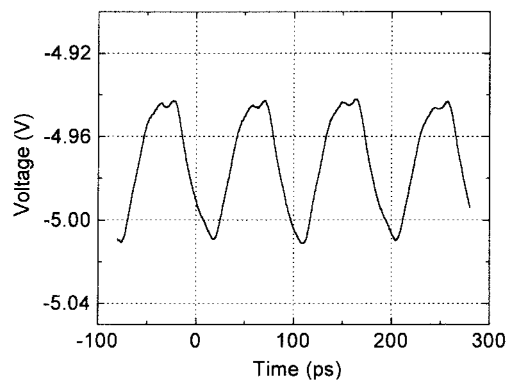


Fig. 16. Power bus noise at position G.

IV. Conclusions

The in-circuit diagnostic capabilities of a measurement system using a micromachined photoconductive probe tip are presented. A discussion of the system performance has revealed high spatial resolution, high time resolution, and low interference with a microwave digital DUT-circuit. Special emphasis is placed on the fact that absolute voltages (both for dc and ac) are accessible from a probe having a bandwidth that exceeds 100 GHz. Internal node waveforms inside a microwave frequency divider circuit at a frequency of 10.56 GHz show the characteristic operation of the circuit (e.g., gate delays, frequency division, and power bus noise). The results demonstrate that the probe has a broad potential as a diagnostic tool in IC testing, particularly for digital circuits as they push up toward millimeter-wave operating frequencies. Furthermore, the probe should also provide a novel capability for validation of circuit models as they become increasingly complex and cover higher frequencies of operation.

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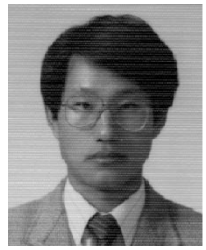
Gerhard David (M'97) received the Diplom-Physiker degree from the Georg-August University, Goettingen, Germany, in 1991 and graduated as a Doctor in Engineering (Dr.-Ing.) from the Gerhard-Mercator-University Duisburg (Institute of Optoelectronics), Germany, in 1996.

Since 1997 he has been a Research Fellow at the Center for Ultrafast Optical Science and the Radiation Laboratory (Department of Electrical Engineering and Computer Science), The University of Michigan, Ann Arbor. His research interests are in the development of ultrafast photoconductive and electro-optic measurement techniques for testing and characterization of high-frequency and high-speed integrated circuits, antennas, and optoelectronic devices. Currently he is working on optical-based techniques for simulation and characterization of space radiation effects in satellite-based digital electronics and imaging of near-field distributions of millimeter-wave antennas, antenna arrays, and quasi-optical power combiners. He has authored or co-authored more than 30 papers in the field of electro-optic sampling and microwave optoelectronics.

In 1993 Dr. David was awarded the EuMC Microwave Prize of the 23rd European Microwave Conference, and in 1997 he became a fellow of the Alexander von Humboldt-Foundation, Germany.



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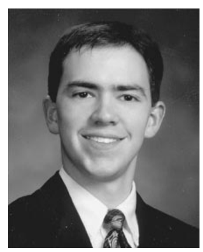

Matthew H. Crites was born near Chicago, IL, in 1974. He received the B.S. degree in electrical engineering from Boston University, Boston, MA, in 1996 and the M.S. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1998. He is currently working toward the Ph.D. degree at the Center for Ultrafast Optical Science at the University of Michigan.

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He has held positions at RCA Broadcast Systems in video camera design and RCA Advanced Technology Laboratories in CMOS/SOS and GaAs IC design. In 1984 he was a Research Assistant in the NCSU Solid State Laboratory studying single event upset effects in GaAs IC's. In 1990 he joined the Naval Research Laboratory's Radiation Effects Branch where he investigated MESFET and HBT charge collection effects and conducted accelerator and space-based experiments. In 1995 he joined the faculty as an Assistant Professor at the Naval Postgraduate School where is he presently developing radiation immune technologies in group IV and III/V semiconductors.

Dr. Weatherford has recently been awarded the NPS 1997 Research Achievement in the electrical and computer engineering department. He is a member of the IEEE Nuclear Science Society, Solid-State Circuits Society, and Electron Device Society and TMS. He has served on conference committees and reviewed for IEEE publications. He has authored and co-authored over 45 publications.

Kay Jobe received the B.S.E.E. degree from the University of Colorado in 1980.

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Since 1982, he has been with Hughes Space & Communications, El Segundo, CA, and is presently managing the development of very-high-speed ASIC's. His previous work has included the research and development of wideband Ku-band synthesizers, RF PWB's, direct digital synthesizers, and digital-to-analog convertors.

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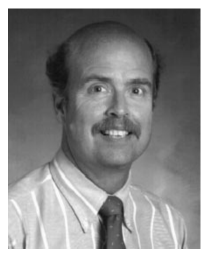
Stephen Thomas III received the B.S.E.(E.E.) degree in 1992, the M.S.E.(E.E.) degree in 1993, and the Ph.D. degree in 1997 all from the University of Michigan, Ann Arbor.

At the University of Michigan, he developed *in situ* diagnostics for real-time control of advanced dry etch processes. He also used e-beam lithography and dry etching to fabricate structures with high aspect ratio and nanometer scale linewidths. He joined HRL Laboratories in 1997, where he is currently a research scientist. His job assignments include work on process development for GaInAs/AlInAs-based HBT IC's and InP HEMT's.



Kenneth R. Elliott received the Ph.D. degree form the California Institute of Technology, Pasadena, in 1979.

He has pioneered the development of III-V semiconductor integrated circuit technology for the past 17 years. From 1980 to 1993, he was a Scientist at the Rockwell International Microelectronics Research Center. Since 1993, he has been a project manager at HRL Laboratories in Malibu, CA. Throughout his career, he has been pivotal in transferring III-V technology from laboratory environments to commercial prototype production. He provides technical expertise in diverse areas including device engineering, electronic materials for advanced devices, integrated circuit design, process development of advanced device structures, device modeling, radiation effects, and CAD. His current technical interests include the development of *in situ* monitoring and control techniques for the growth of device structures using MOVPE, the development of ultra-high-performance IC's using advanced devices, and the development of new approaches to multifunctional integrated circuits.

Dr. Elliott is a member of Phi Beta Kappa.