transmission lines and the DUT may be fabricated on a common substrate, eliminating the need for wirebond connections.

3. Photoconductive switching and electro-optic sampling allow generation and acquisition of fast rise-time waveforms. Experiments may thus be conducted with signal bandwidths exceeding 100 GHz. The traveling-wave characterization of linear circuits, known as the scattering parameter method, can also conceivably be obtained from waveforms acquired with the symmetrical pulse propagation technique.

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2.C A Substrate-Independent Noncontact Electro-Optic Probe Using Total Internal Reflection

The process of designing high-speed integrated circuits requires a knowledge of the appropriate device responses within their range of operational frequencies. To answer this need for design information, several approaches have been used to sample ultrafast electrical transients. Of these approaches, only one, electro-optic sampling, gives the flexibility of noncontact probing while maintaining a 1-THz bandwidth. Two classes of a noncontact electro-optic sampling have been demonstrated to date:[1] one using an electro-optic device substrate as a probing medium, and a more versatile class, using an external electro-optic superstrate to sample fringe electric fields. Here we describe an embodiment of the second class.

Superstrate sampling first appeared in a paper entitled "Two-Dimensional E-Field Mapping of Picosecond Optics and Optoelectronics."[2] In this embodiment of electro-optic sampling, a slab of electro-optic material is coated with a highly reflective dielectric stack and placed, reflective surface down, over an electronic circuit or device. A sampling beam then reflects off the coating, passing through electric fields fringing into the crystal above the device under test (DUT). Further improvement to this approach was made by trimming the electro-optic slab to a tip of 40- to 100-μm square to reduce dielectric loading.[3] This article presents a total-internal-reflection (TIR) electro-optic probe of small dimensions, which also eliminates the need for a high-reflectivity dielectric stack.

There are two main advantages attributed to the use of TIR in a probe tip. First, it eliminates the need for a dielectric stack, which must be at least 2-μm thick to prevent serious leakage of light through to the substrate. This improves the ultimate spatial resolution of the probe by allowing the tip to be brought within 1/5 λ of the surface being probed (λ is the probe beam wavelength) before TIR is frustrated and light is coupled into the DUT. Second, the probe is made more rugged by the removal of the dielectric stack.

A truncated pyramid, as illustrated in Fig. 32.12, is made to ~100-μm dimensions, with its walls at 22.5° to its axis. Light focused

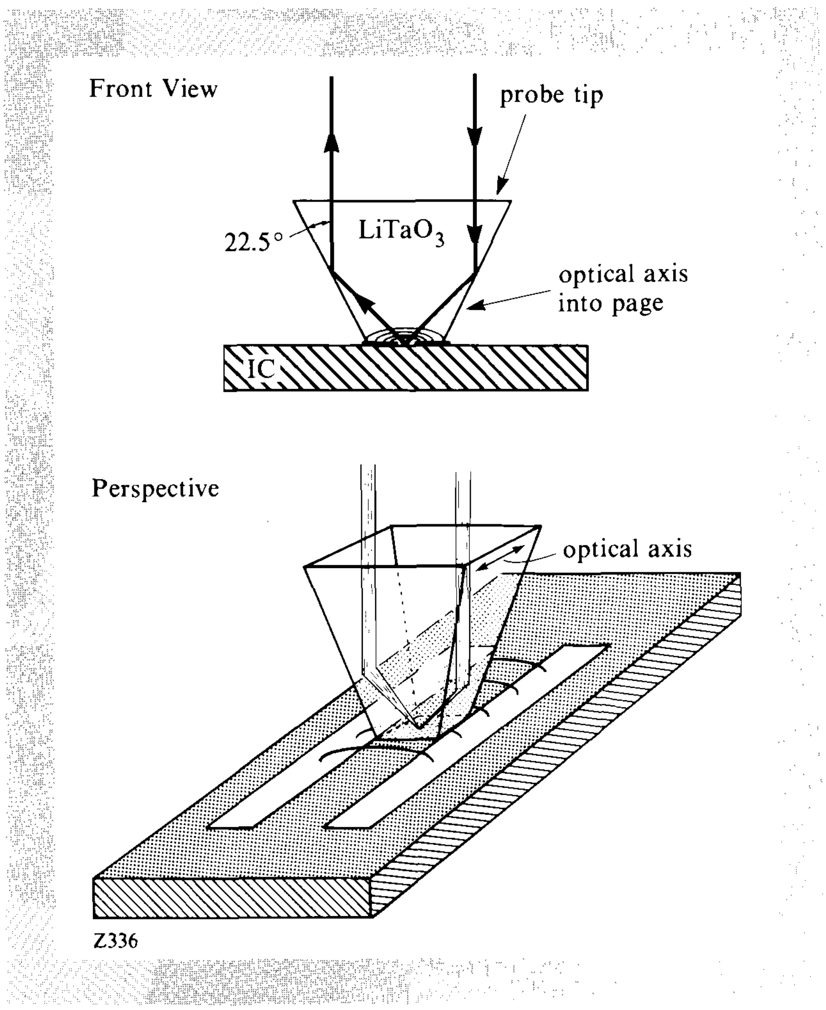

Fig. 32.12
Total internal reflection probe.

through the base of the probe may then reflect successively off a side wall, the probe tip, and the opposite wall, returning parallel to the input beam and displaced by twice the tip width. The alignment of the crystal's optical axis in this case would be normal to the plane of the beam; thus, it would sense components of electric field in that direction. A longitudinal "voltage" probe integrating $\mathbf{E}\cdot\mathbf{dz}$ along the optical axis could also be made using GaAs, KDP, or other crystals exhibiting a longitudinal Pockels effect. Once a TIR probe with a 100-μm square tip was fabricated, using standard polishing techniques, a system was configured as illustrated in Fig. 32.13 for testing a 1-μm-gate MESFET structure provided by Bell Northern Research. In this arrangement, a source laser having two beams of 70-fs pulses at a repetition rate of 100 MHz and an average power of about 2 mW is used both to trigger a test pulse and to sample electrical transients at appropriate points on the device. The trigger, or switching beam, passes through a variable optical delay line and is focused onto the gap between the device's gate and common source. This causes the gate to be momentarily switched to ground.

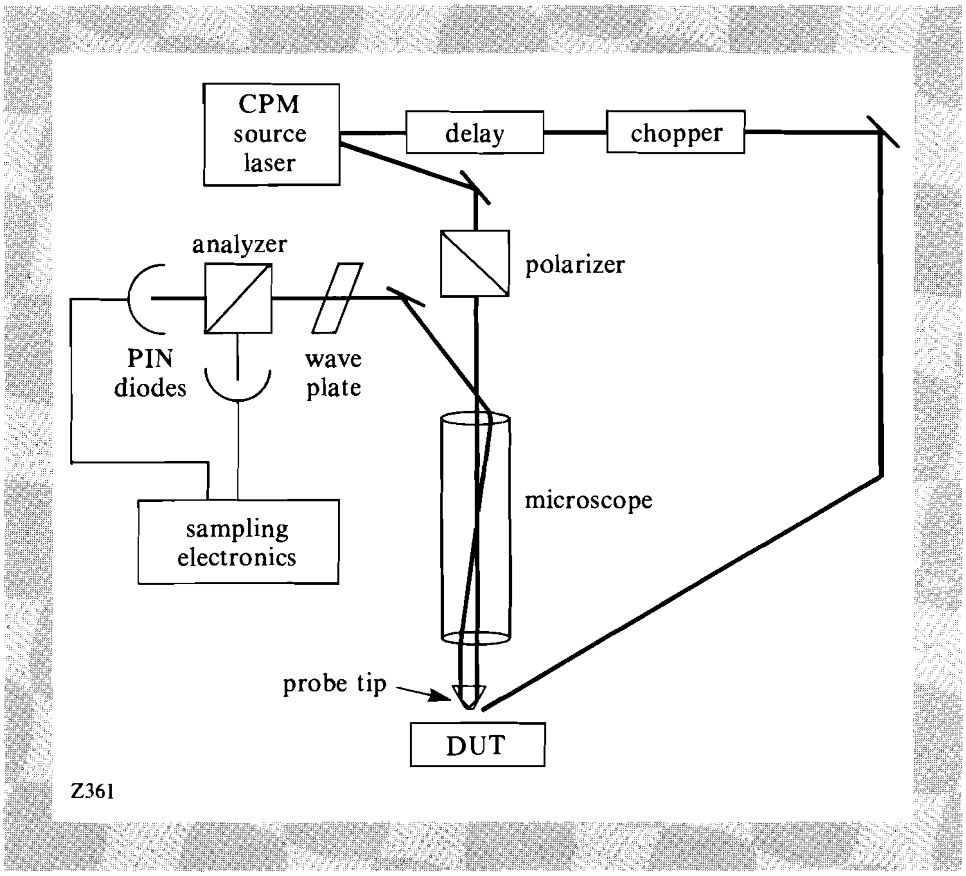

Fig. 32.13
Schematic of TIR probe in sampling system.

The second beam from the source laser, after passing through a polarizer oriented at 45° to the probe's optical axis, is focused onto the probe tip and then translated to the side, to retro-reflect through the probe as described previously. The probe beam then passes back through a compensator and analyzer and onto a pair of PIN photodiodes. A description of the sampling technique and signal processing used in this experiment can be found in Ref. 1.

Figure 32.14 shows the positions of the probe tip and excitation beam. The input signal was formed by optically exciting carriers in the 5-μm gap between the gate as source pads. With the TIR probe over the same gap, an input waveform was measured. Then, with the probe over the gap between source and drain pads, an output waveform was also measured. In either case, a known sinusoidal voltage was applied to the gaps to give a voltage calibration.

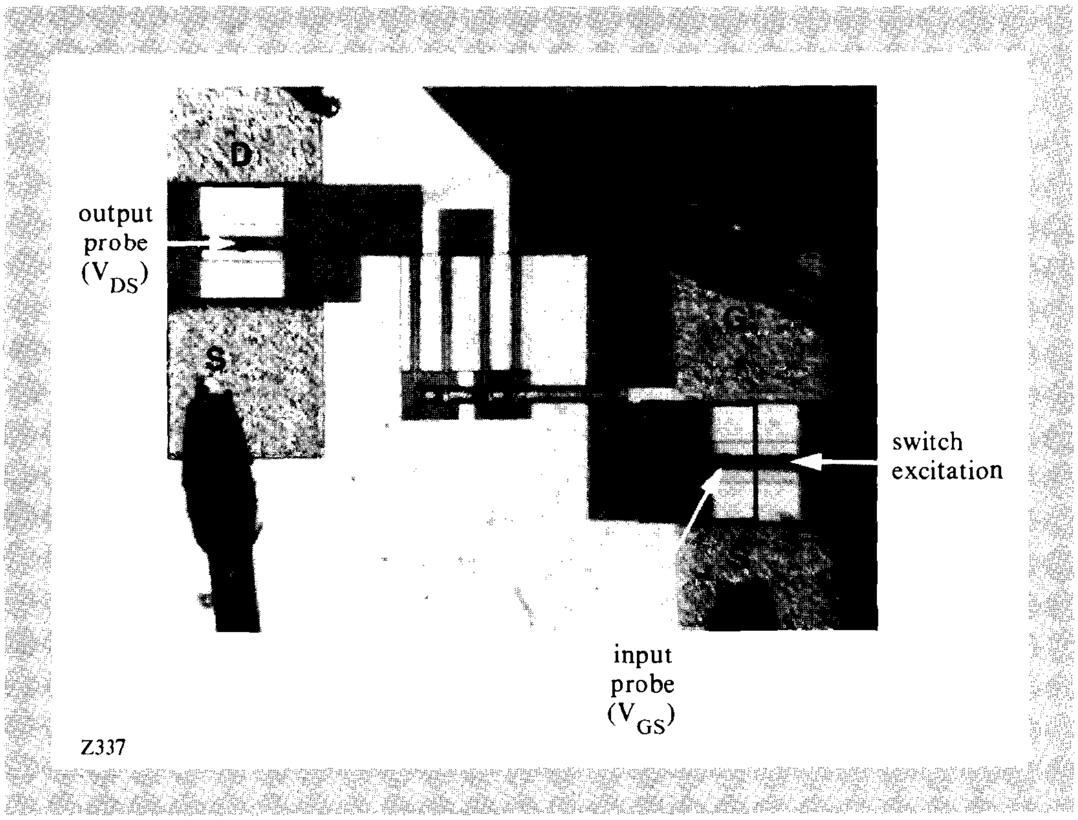

Fig. 32.14
1-μm gate MESFET tested using the TIR probe. The squares indicate probe positions; the circles indicate probe beam locations; and the fitted circle indicates the excitation beam position.

The 350-fs rise time of the input signal (Figs. 32.15 and 32.16) demonstrates the probe's ~1-THz bandwidth while the output (Fig. 32.17) indicates a 13-GHz device roll-off. The maximum device frequency corresponds to the value of f_{max} obtained using a standard network analyzer.

In conclusion, a rugged, noncontact, substrate-independent electro-optic probe with ~1-THz bandwidth has been demonstrated. Because this probe requires no dielectric coating, it provides the possibility of submicron spatial resolution. Work is currently in progress to use the bandwidth available with noncontact probes, to provide more standardized measurements for designers of ultrafast circuits.

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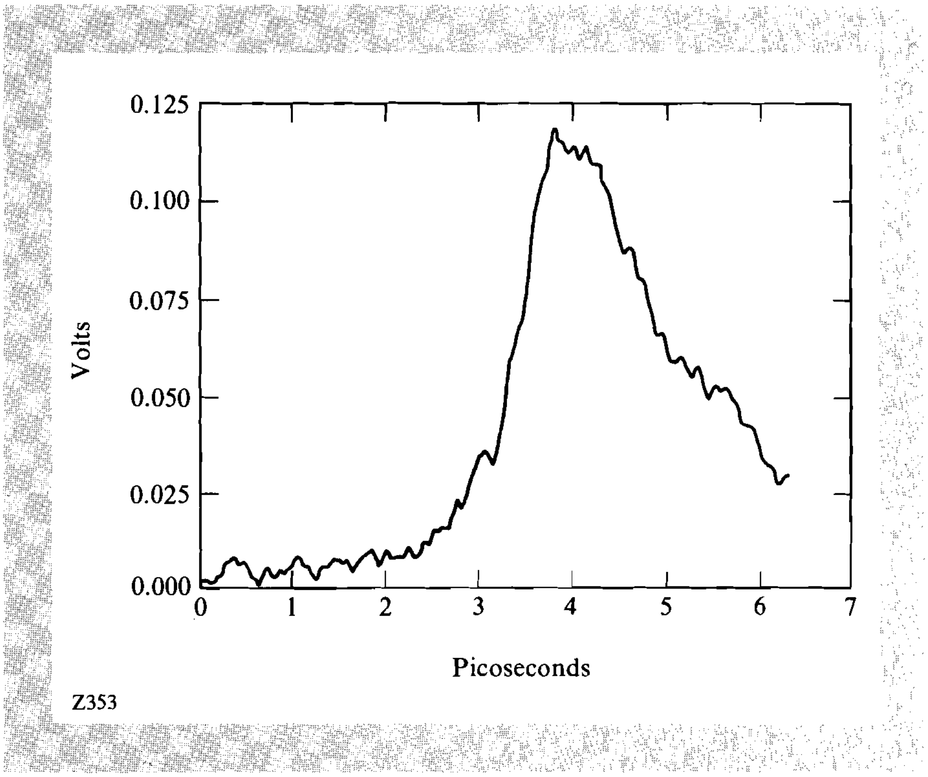

Fig. 32.15
Input electrical pulse showing the subpicosecond time response of the sampling system.

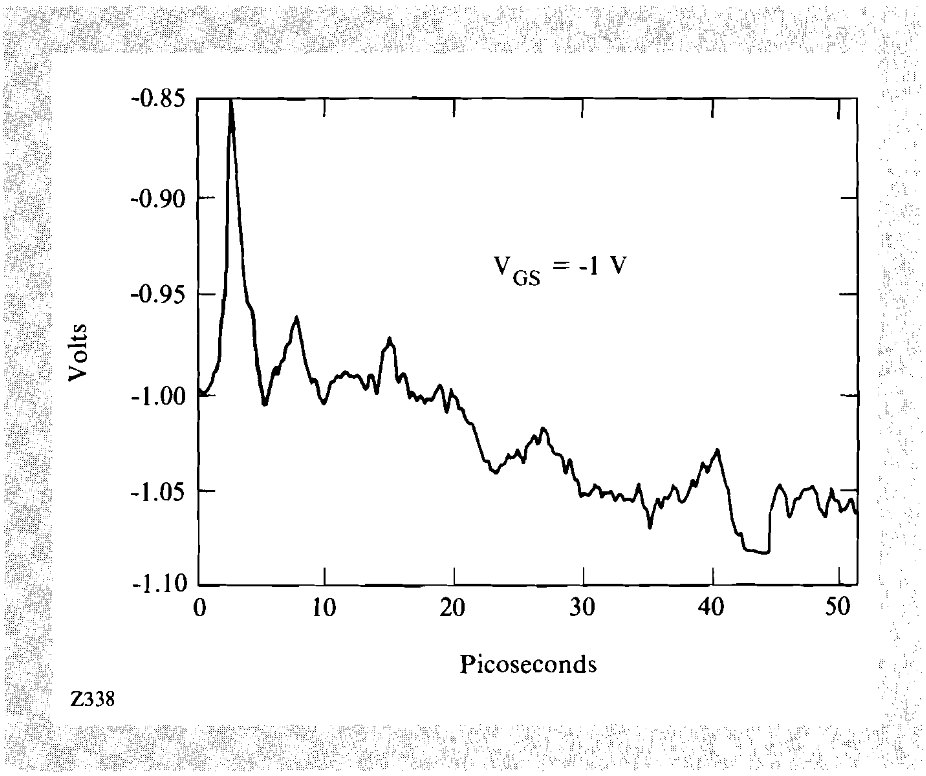

Fig. 32.16
Input waveform.

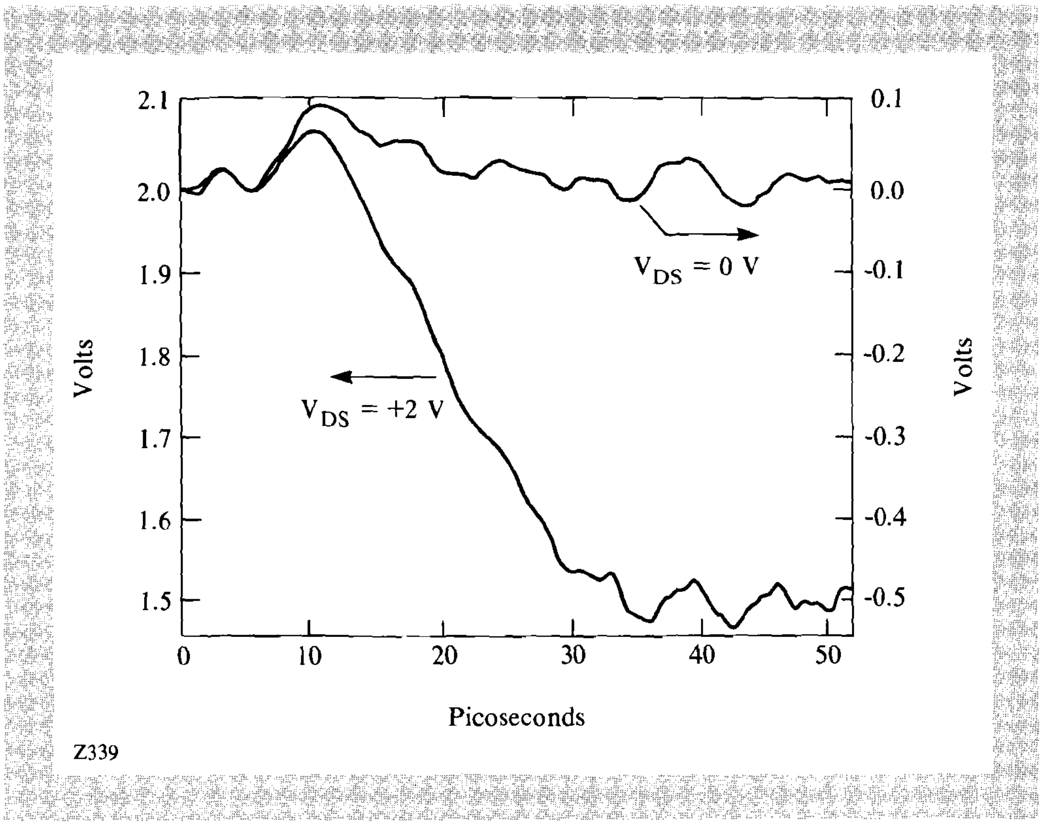

Fig. 32.17
Device output for biased and unbiased cases.

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