Picosecond temporal resolution photoemissive sampling

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Sampling measurements of electrical transients generated photoconductively on a 5-μm gold coplanar transmission line on GaAs were performed via multiphoton photoemission. A temporal resolution of 5 ps was achieved, with a voltage sensitivity of 10 mV/$\sqrt{\text{Hz}}$. These results confirm that the temporal resolution attainable by this technique is enhanced when the dimensions of the structure under examination are reduced.

Photoemissive sampling was recently introduced as a new, contactless method for probing high-speed electrical waveforms on circuits and devices on any semiconductor.[1-3] As described in the previous literature, voltage measurements are performed by energy analysis of the photoelectrons emitted when signal-bearing metal lines on the surface of the device under test are illuminated by ultrashort light pulses. In previous experiments, in which photoemissive sampling was utilized to measure waveforms on microstrip transmission lines, the best temporal resolution obtained was limited to 40 ps. In this letter we describe photoemissive sampling experiments, performed on electrical transients generated photoconductively on a 5-μm coplanar stripline on GaAs, which demonstrate a temporal resolution of 5 ps. This improved temporal performance may be attributed directly to the reduced dimensions of the structure under examination. Our results constitute the first experimental confirmation that photoemissive sampling, and by implication, electron beam[4] and photoelectron-electron beam[5] sampling, can achieve temporal resolution below 10 ps.

The experimental setup is shown in Fig. 1. Our experiments utilize a dispersion-compensated, colliding-pulse-mode-locked (CPM) ring dye laser,[6] which provides fs pulses with a typical duration of 80 fs, at a 1.98-eV photon energy and a 117-MHz repetition rate. Photoelectrons are generated via a three-photon photoelectric effect. The test sample, a gold coplanar stripline on polished GaAs, is supported by an *xyz* translation stage within a vacuum chamber held at approximately 10^{-7} Torr. Two separate optical beams are admitted into the vacuum chamber and focused onto the test sample using a single 40× microscope objective lens with a 10.1-mm working distance. One beam, which illuminates the gap between the center conductor and ground plane of the transmission line, is used for photoconductive generation of a fast electrical signal which we use to test the temporal resolution of our technique. The second beam, which is focused onto the center conductor some distance down the line, is the probe beam.

The sample geometry is shown schematically in Fig. 2. The center conductor is 6.25 μm wide, separated by 5 μm from ground planes on either side, with a design impedance of 50 Ω. A 100-mV electrical step is generated photoconductively using the "sliding contact" geometry,[7] in which the optical excitation beam is focused between the positively biased center line and one of the ground planes. The probe beam is focused onto the center line at a spot 40 μm distant from the excitation location. The photoelectron current due to the probe beam exceeds the background photoelectron current generated unintentionally by the excitation beam by more than three orders of magnitude; we therefore conclude that the spatial resolution of our setup is more than adequate for probing structures of 5-μm dimension.

The photoelectron energy analysis is accomplished using a compact analyzer device compatible with the close spacing of the microscope objective lens to the sample. A 500-mesh (per inch) wire grid, biased at a positive potential as high as 3 kV and held approximately 320 μm above the test sample, is used to extract photoelectrons from the sample. A 100-μm square hole is opened in the mesh to permit passage of the optical beams. Two deflection electrodes are utilized to deflect electrons away from the objective lens and sideways towards the analyzer electrodes and a microchannel plate (MCP) for electron multiplication and detection. One deflection electrode is mounted on the side opposite the MCP and biased negative at several hundred volts; the second, which includes a transparent conducting tin/indium oxide film on a glass substrate, is mounted directly below the objective and biased several hundred volts positive.

The sample potential is derived in either of two ways. First, as in previous experiments,[1-3] a retarding field energy analysis may be performed by using the grids mounted directly in front of the MCP. Alternatively, one may utilize an electrostatic deflection filter[8] to perform the photoelectron energy analysis. Because the deflector voltages required to deflect photoelectrons towards the MCP depend on the sam-

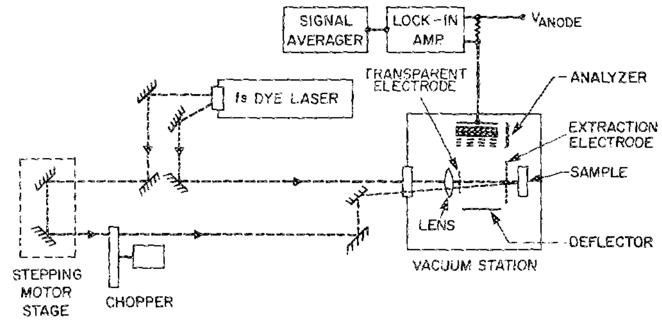

FIG. 1. Experimental apparatus for time-resolved voltage measurements by photoemissive sampling.

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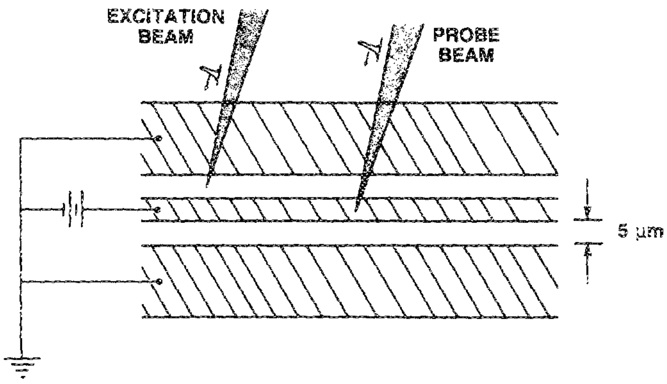

FIG. 2. Excitation and probe geometry for the 50-Ω, gold coplanar stripline on polished GaAs. The center line is 6.25 μm wide, separated by 5 μm on either side from much wider ground planes. The excitation and probe locations are separated by 40 μm.

ple potential, such an electrostatic deflection filter is inherent in our analyzer. The analyzer characteristics are shown in Fig. 3, for various transparent deflector electrode voltages. With the current setup, in which no special attempt was made at optimization, the filter is bandpass with a full width of 5 V.

For time-resolved measurements, the analyzer was adjusted so that the transmitted photoelectron current varied linearly with the sample potential. The excitation beam used to generate the photoconductive signal was chopped at a rate of 12 kHz; the resultant modulation of the probe photoelectron current was detected after the MCP using a 30-kΩ sampling resistor and a lock-in amplifier. The complete electrical waveform was acquired by varying the time delay of the excitation beam. The magnitude of the photoconductive signal was calibrated by connecting an audio frequency square wave generator to the signal line, with the excitation beam blocked. The time-resolved data shown below were obtained using analysis by electrostatic deflection, although similar results were obtained using a retarding field analysis. Our present detection scheme retains linearity for signal voltage swings of several volts, well in excess of the 100-mV signal amplitudes used in the time-resolved measurements.

The temporal resolution of photoemissive sampling is governed by the photoelectron transit time through the region of space in which the electric field depends significantly on the sample potential.[1,2,9] The "effective transit time" T is given by

$$T = (\sqrt{2m}/eE)\,(\sqrt{eES + U_0} - \sqrt{U_0})\,,$$

where E is the extraction field, m and e are the electron mass and charge, S is the spatial extent of the time-varying electric field, and U_0 is the initial kinetic energy of the photoelectrons in the direction of the extraction field. The transit time may be reduced by using a high extraction field E, as done in previous experiments,[1,2] and by minimizing the distance S. In a real circuit, the spatial extent of the local electric fields depends on the widths and spacings of the metal lines being probed; the characteristic distance S may be much smaller than the distance to the extraction electrode.[9,10] Thus, the transit time will be reduced and the temporal resolution improved when examining structures with signal lines spaced closely to ground planes. For the previous measurements performed on microstrip transmission lines,[1,2] we take $S = 500\ \mu$m; for a 50-kV/cm extraction field, we calculate $T = 34$ ps, in good agreement with experimental results.[2] For the current measurements performed on coplanar lines, we conservatively take $S = 10\ \mu$m; with $E = 50$ kV/cm and $U_0 = 0$, the transit time is reduced to 4.8 ps.

In Fig. 4 we show the time-resolved measurement of an electrical transient generated photoconductively on the 5-μm coplanar stripline, for an extraction field of 85 kV/cm. The maximum permissible value for the extraction field is set by tolerance to capacitive loading, device sensitivity to an imposed field, and electrical breakdown between the test line and the extraction grid, and is generally less than 100 kV/cm. In our experiments at 85 kV/cm, the leakage current measured at the extraction electrode remained below 1 nA. The 10–90% rise time is 5.3 ps. These data exhibit a slight tail at the base of the rising edge; the steepest slope present on the rising edge would correspond to an even faster rise time of 4.2 ps. The observed rise time is in reasonable agreement with the calculated transit time T, using S in the range 10–15 μm. When weaker extraction fields were applied, slower rise times were observed (e.g., with $E = 30$ kV/cm, the rise time was 7.5 ps). These data provide the first clear experimental verification that the transit time scales

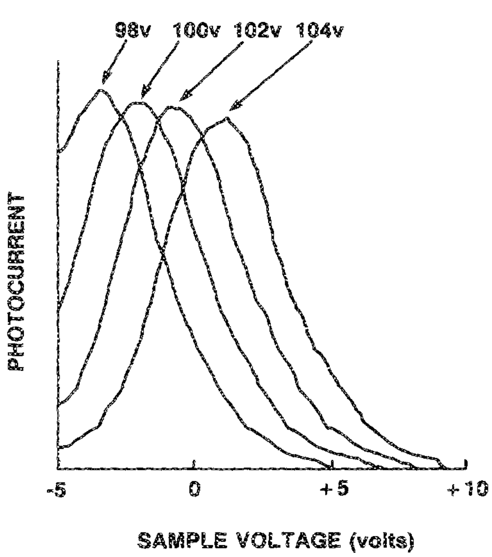

FIG. 3. Dependence of collected photocurrent on sample potential, for various transparent deflector voltages.

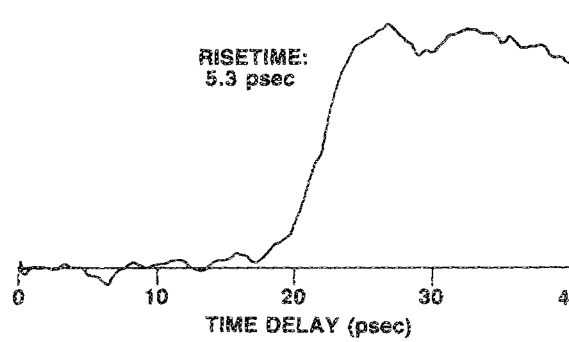

FIG. 4. Time-resolved measurement of a 100-mV electrical step, with an extraction field of 85 kV/cm.

down with the dimensions of the electrode structure under test.

The signal to noise ratio of 30 evident in Fig. 4 corresponds to a voltage sensitivity of approximately 10 $mV/\sqrt{Hz}$, in good agreement with the shot noise limit for an estimated photoelectron current of 0.1 pA. An improved sensitivity below 2 $mV/\sqrt{Hz}$ should be possible by optimizing the analyzer for a filter bandwidth of 1 V or below. A photocurrent of 10 pA, as obtained in previous experiments utilizing the increased intensity available from a cavity-dumped CPM laser,[10] would then yield a shot noise limited sensitivity in the range of several hundred $\mu V/\sqrt{Hz}$.

In summary, we have utilized the photoemissive sampling technique to probe electrical steps generated photoconductively on a 5-μm coplanar stripline on GaAs. Due to the small, 5-μm dimension of the structure examined, these experiments reveal a temporal resolution of 5.3 ps, an improvement by nearly one order of magnitude compared to previous results. A similar enhancement in temporal resolution should also be observed in experiments using the electron beam or photoelectron-electron beam measurement techniques. Further significant increases in temporal resolution are anticipated for circuit geometries with 2- or 1-μm design rules. Our results demonstrate voltage sensitivity and high-speed capability sufficient for probing ultrafast electrical signals in circuits and devices in any semiconductor.

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