High-speed circuit measurements using photoemission sampling

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High-speed sampling of the voltage waveform on a microstrip transmission line is performed by exploiting the multiphoton photoelectric effect induced by a visible cw mode-locked laser source. Energy analysis of the electrons emitted from the surface of the strip line is used to infer the emission point potential at the arrival time of the laser pulse. The technique may be applied to measure voltage waveforms on metallization lines of any integrated circuit or electronic device and is capable of picosecond time resolution and millivolt sensitivity.

Progress in ultrahigh-speed electronic and optoelectronic device technology has reached the stage that the capabilities of existing measurement instrumentation are being exceeded. In response to this need, one of the first approaches to the picosecond time-resolved characterization of fast devices and integrated circuits involved the technique of photoconductive sampling.[1] Recently, the technique of electro-optic sampling has received much attention.[2,3] Subpicosecond temporal resolution and submillivolt sensitivity may be achieved with this technique. However, the most general embodiment of the method requires that the signal to be measured must be propagated from the device under test to a special electro-optic modulator.[2] For the special case of GaAs devices and integrated circuits, the electro-optic properties of the GaAs substrate itself have been exploited to perform *in situ* high-speed measurements.[3] This technique is attractive because it allows signal waveforms to be measured at nearly any point inside a complex circuit. However, its applicability is restricted to circuits fabricated on substrates that are electro-optic. The most widely used electronic material, silicon, does not exhibit an electro-optic effect and so the method is not applicable.

Electron beam probing is another technique used to measure signal waveforms on integrated circuits.[4] It is generally applicable to any type of device or integrated circuit, and systems capable of waveform sampling with 200 ps time resolution are commercially available.[5] Improved time resolution has been achieved in experimental systems using specially modified electron accelerators.[6] However, these systems required rather elaborate microwave bunchers and beam blanking systems operating at *X*-band frequencies and have only been successfully applied to the characterization of discrete Gunn diode oscillators.

We report the development of a new technique for measurement of high-speed signals in electronic devices. The method is really a hybrid between optoelectronic sampling and electron-beam (*e*-beam) probing in that the signal waveform is measured by energy analyzing electrons ejected from the surface of a metallization line on the device into vacuum using a picosecond laser pulse to stimulate the electron emission. By exploiting the multiphoton photoelectric effect,[7] it is possible to use a visible wavelength laser to eject the electrons. Since the method involves the direct measurement of voltage on a metal line, it can be used on any type of electronic device, regardless of the electronic material being used to fabricate the device. The temporal resolution obtained in our preliminary experiments and reported here is better than 40 ps, and ultimate resolution of better than 10 ps should be achievable.

We now describe the basic principle of the technique in more detail. A short, visible laser pulse is focused onto the surface of a metal electrode on top of the circuit under test. In our experiments, we use a frequency doubled and fiber-grating pulse compressed cw mode-locked Nd:YAG laser.[8] This laser system produces pulses of duration less than 500 fs at a wavelength of 532 nm, a repetition rate of 100 MHz, and an average power of 200 mW. Under typical conditions, 30 mW is focused onto the sample surface using $f/20$ optics. This leads to peak pulse power on the surface of several hundred MW/cm^2 which is sufficiently high to produce easily detected multiphoton photoemission.[7] These electrons are accelerated by the electric field set up between the sample and an extraction grid. As the sample potential varies, so will the acceleration field between the sample and the extraction grid. This leads to a shift in the energy distribution of the electrons as they pass through the extraction grid. The magnitude of this shift is equal to the magnitude of the voltage change on the sample. By measuring the change in electron current which subsequently passes through a suitably biased retarding grid, the shift may be inferred and the sample voltage thereby measured. This method of voltage measurement by electron energy analysis is similar to that used in electron beam probing. The difference is that in electron beam probing, it is the secondary electrons ejected by a pulsed electron beam in a scanning electron microscope which are analyzed.

For sufficiently short pulses, the time resolution of this technique is limited by the transit time of the electrons from the sample surface to the extraction grid. This is because the net acceleration is proportional to the time integral of the electric field over the duration of transit. (We note that this limitation applies equally to both photoemission sampling and electron beam probing.) For this reason, it is desirable to bring the extraction grid as close to the sample surface as possible and to use as high an extraction field as possible. The electron transit time t may be calculated as

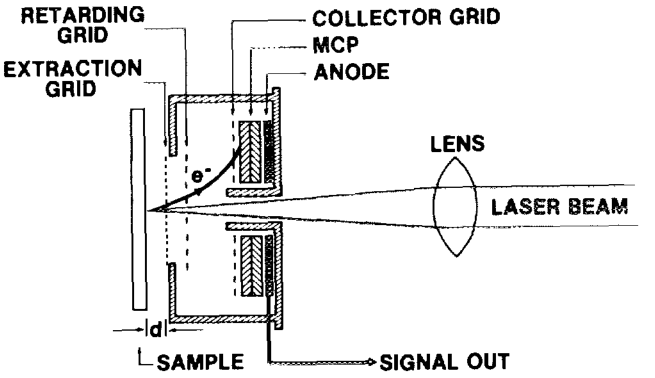

FIG. 1. Schematic diagram of the three-grid retarding field electron energy analyzer.

$$t = 3.37\times 10^{-9}\ (d/E)^{1/2}, \tag{1}$$

where d is the distance from the sample to the extraction grid in mm, E is the extraction field in V/mm, and t is in s.

A very simple and compact parallel grid retarding field electron analyzer was used for the present experiments. A schematic diagram of the analyzer is shown in Fig. 1. The laser beam was focused through the back side of the analyzer as shown. A microchannel plate (MCP) detector with a 6-mm-diam center hole was used for this purpose. The collector grid also had a concentric 6-mm hole, but no special holes were needed in the extraction and retarding grids. The retarding grid mesh size was 50 wires/in. and the extraction grid size was 100 wires/in., corresponding to 450-μm and 200-μm grid spaces, respectively. The analyzer structure was placed within close proximity to the sample ($d \approx 750$ μm) and we found that we could easily align the focused laser beam directly through the grid spaces in the retarding and extraction grids. The entire structure was held in a vacuum chamber at 10^{-6} Torr pressure.

We have tested the system on a simple microstrip sample consisting of a gold stripline on a high resistivity GaAs substrate. The work function for gold[9] is approximately 4.9 eV, hence three photons at 2.3 eV (532 nm) are required to overcome the work function and ejected electron kinetic energies of up to 2 eV are expected. The performance of the electron energy analyzer was tested by measuring the electron current detected by the microchannel plate as a function of sample voltage for various retarding grid bias voltages. A sample of such "S-curve" data is shown in Fig. 2. These data were taken with 1333 V/mm extraction field, and 30 mW of laser power. The peak count rate from the channel plate under these conditions was typically $\sim 3\times 10^5$ counts/s. This corresponds to a photocurrent from the sample in the range of a picoampere. The retarding grid voltage necessary to extinguish the transmitted electron signal would ideally be equal to the sample voltage plus the approximately 2 V width of the initial energy distribution. Note that there is actually a significant offset. The offset increases with increasing extraction voltage and is due to a slight penetration of the extraction field through the retarding grid. This occurs because the spacing between the extraction grid and retarding grid (1.25 mm) is only 2.78 times larger than the size of the spaces in the retarding grid (0.45 mm). After subtraction of the offset, we have demonstrated that there remains a linear relation between sample voltage and required retarding grid voltage. The offset could be reduced or eliminated by increasing the ratio of intergrid spacing to grid space dimension.

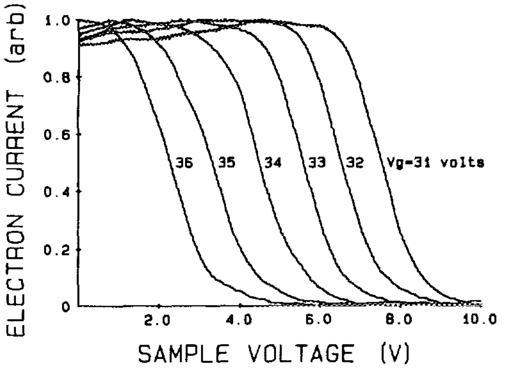

FIG. 2. "S-curve" characteristics of the electron energy analyzer. Each curve shows the microchannel plate signal as a function of sample potential for various settings of the retarding grid potential. The extraction field in all cases was 1333 V/mm.

In order to utilize the characteristics of this detector to achieve a linear voltage measurement with wide dynamic range a feedback circuit similar to that used in e-beam probing systems is used.[10] This circuit varies the retarding grid voltage as the sample voltage varies in order to maintain the signal at the inflection point of the "S curve." In order to reduce the sensitivity to laser power fluctuations (up to 8% peak), a 30-kHz modulation voltage is added to the retarding grid and the signal is demodulated at twice this frequency in a lock-in amplifier. The feedback circuit acts to maintain the lock-in output at null.

Results obtained using the system to sample high-speed pulse waveforms are now presented. A portion of the laser beam was split off and passed through a variable optical delay line to illuminate a high-speed radiation-damaged InP photoconductor[11] with a previously measured impulse response of 20 ps. The voltage pulse from this detector was then launched down the gold stripline through 18 GHz subminiature series A connectors and sampled by the photoemission sampler. Figures 3(a)–3(c) show the sampled waveforms for various extraction fields at a d spacing of $\sim 750\,\mu$m. For comparison, Fig. 3(d) shows the waveform as measured by photoconductive sampling.[12] For this measurement, the voltage pulse was propagated off the 2-in.-long gold stripline through SMA connectors to a CdTe photoconductive sampler with a previously measured resolution of 10 ps.[13] From Fig. 3(d) and the known properties of the InP pulse generator and the CdTe photoconductive sampler, we estimate that the actual pulse width at the position of the photoemission sampler is 60 ps. By deconvolution, we may then estimate the time resolution in Figs. 3(a)–3(c) to be 121, 54, and 39 ps, respectively. Based on Eq. (1), using a d spacing of $750\,\mu$m, we would expect the corresponding values of 131, 65, and 46 ps. One possible reason that the measured resolutions are better than those calculated is that the

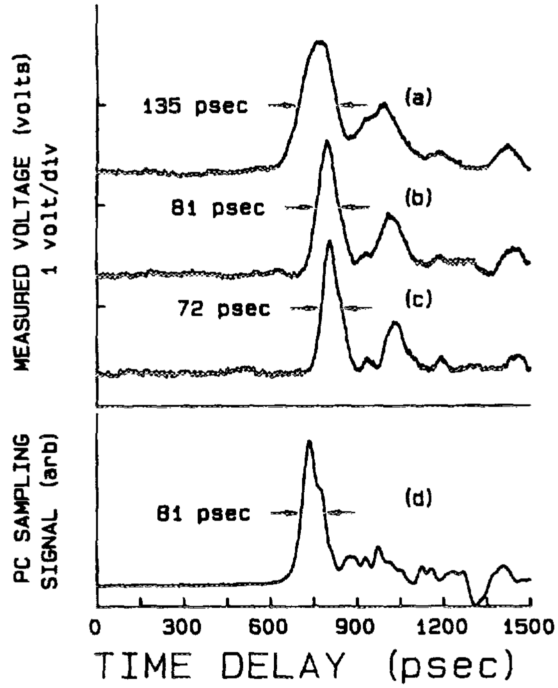

FIG. 3. (a)–(c) Voltage waveforms produced by an InP photoconducting detector as measured by photoemission sampling on a gold stripline. Each curve was measured using a different extraction field: (a) 666 V/mm; (b) 2666 V/mm; (c) 5333 V/mm. The waveform in (d) was measured using conventional photoconductive sampling with a CdTe sampler.

extraction grid is somewhat flexible and may have been attracted to the sample by the large applied field, thus giving an actual *d* spacing that is smaller than what was measured in zero field.

Experimentally, we found that the maximum extraction field was limited to ~5500 V/mm. Above this value, corona discharge and electrical breakdown were observed. Improvement in time resolution is still possible by further reducing the *d* spacing at constant extraction field. From a practical point of view, the minimum *d* spacing is probably $\sim 50\,\mu$m. This would give a time resolution, according to Eq. (1), of 10 ps.

The photoemission sampled waveforms in Fig. 3 were taken with a 1 s averaging time constant, and each waveform was averaged over five sweeps. From the noise level on the traces, we can estimate the present voltage sensitivity as approximately 40 $\mathrm{mV/(Hz)^{1/2}}$. As in the case of optoelectronic sampling, the principal source of noise arises from fluctuation noise in the laser output. Although the photoemission process proceeds via three photons and thus the yield is expected to follow a cubic dependence on laser power, we observe only a weak dependence of the position of the *S* curve on laser power. Since the feedback loop locks to the inflection point of the curve, laser power fluctuations are somewhat suppressed. Further improvement in voltage sensitivity may be expected by improving the laser amplitude stability and/or increasing the modulation frequency to the 5 MHz range as is done in electro-optic sampling.

In summary, we have demonstrated a new technique for sampling high-speed waveforms in electronic devices. Voltage waveforms are measured from metallization lines on the top of the device, thus the technique may be applied to electronic devices fabricated from any electronic material. The demonstrated time resolution is 39 ps and voltage sensitivity is 40 $\mathrm{mV/(Hz)^{1/2}}$. Improvement of the performance to better than 10 ps time resolution and 1 mV sensitivity is expected.

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