High-speed electrical sampling by fs photoemission

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We propose and demonstrate a new method for contactless sampling of high-speed electrical signals, by spectral analysis of photoelectrons emitted when a signal-carrying conductor is illuminated by ultrashort light pulses. We present time-resolved measurements of sub-ns electrical signals on a gold transmission line on GaAs using three-photon photoemission induced by 80 fs visible laser pulses, and we discuss the temporal resolution of these measurements. This method is applicable to devices and circuits on any semiconductor.

The continued success in the achievement of higher speed (ps) electrical devices and circuits and in the shrinkage of device dimensions has created a keen need for contactless diagnostic techniques with high temporal resolution. Optoelectronic sampling techniques, utilizing the electro-optic effect[1,2] or photoconductive switching,[3] and electron beam probing techniques[4–6] have been developed to meet these needs. This letter describes a new method for contactless probing of high-speed electrical waveforms, by spectral analysis of the photoelectrons emitted when a signal-carrying metal conductor is illuminated by ultrashort light pulses. The work functions of metallizations used on silicon and GaAs-based devices ($\sim$4 and $\sim$5 eV, respectively, for aluminum and gold) are sufficiently high that UV light is required for single-photon photoemission. In this experiment we utilize three-photon photoelectron emission,[7–9] stimulated by a fs visible (2 eV) laser, to perform time-resolved measurements of sub-ns electrical pulses on a 50-Ω gold transmission line on GaAs. This technique may be applied to circuits and devices on any semiconductor. The temporal resolution is ultimately limited by the analyzer geometry; a resolution approaching a few picoseconds is anticipated.

The experimental arrangement, sketched in Fig. 1, shows a colliding-pulse mode-locked ring dye laser[10] serving as a source of fs pulses. The pulse duration is typically 80 fs with a wavelength of 625 nm (1.98 eV) and a repetition rate of 117 MHz. The test sample is a 50-Ω gold microstrip transmission line on a GaAs substrate. The microstrip line is placed within a vacuum chamber held at approximately 10^{-6} Torr and is connected by semirigid cable to a type N coaxial feedthrough. One optical beam is admitted through a window into the vacuum chamber and focused using a 40$\times$, 0.5 NA microscope objective to a spot size as small as 2 μm on the gold line. The objective is mounted inside the vacuum and has a 10.1-mm working distance.

In these initial experiments a planar copper anode mounted 6 mm above the sample surface functioned as electron spectrometer and detector, and a wire screen 3.5 mm below the anode was used to establish an extraction field. The anode contains a 3/8-in.-diam hole, covered with a transparent conductor (a film of SnO on glass) for optical access. The sample is mounted on an XYZ stage for focusing and translation. In time-resolved experiments ps electrical pulses are generated by focusing the second beam from the laser onto a high-speed photodetector outside the vacuum chamber. The light incident on the photodetector is chopped; the anode current is determined by using a lock-in amplifier to measure the differential voltage drop across a 1-MΩ resistor in series with the anode and a dc supply. The relative delay is controlled with a stepper motor-driven translation stage. Time-resolved measurements are acquired by repetitively scanning the translation stage and storing the lock-in output in a signal averager synchronized to the stage.

Measurements of three-photon photoemission from gold, using pulses from a Q-switched ruby laser,[7] show that $J = cI^3$, where J is the photoelectron current density in A/cm^2, I is the intensity in MW/cm^2, and $c = 1.02\times10^{-7}$ (A/MW)/(MW/cm^2)^2. Based on this formula, we would anticipate (for our experiment with 2.5 mW average laser power) an average current of several nanoamperes.

However, our measured photoemission signal from a smooth gold surface proved to be below the experimental sensitivity of a few tenths of a picoampere (for both TE and TM polarization and for angles of incidence from 0° to 60°). We have, however, observed a three-photon photoemission current of several nanoamperes from roughened gold. Three types of roughened surfaces were used: one where 300 nm gold was deposited on a lithographically defined, two-dimensional array (period = 300 nm) of features on a silicon substrate,[11] the second where 500 nm gold was deposited on unpolished GaAs with sharp features as small as 10 nm radius, and the third where 500 nm gold on polished GaAs was electrochemically roughened to produce features with dimensions of 50–100 nm.

The third order dependence of photocurrent on optical intensity, shown in Fig. 2 for the lithographically patterned sample, is indicative of a three-photon photoemission pro-

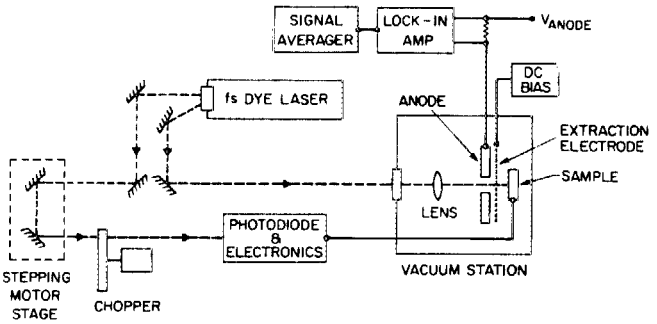

FIG. 1. Experimental arrangement for time-resolved measurements. The fs dye laser generates two beams: one beam is focused onto the photodiode to generate the electrical signal to be measured, and the other is the probe beam. The time delay is controlled by the stepping motor stage.

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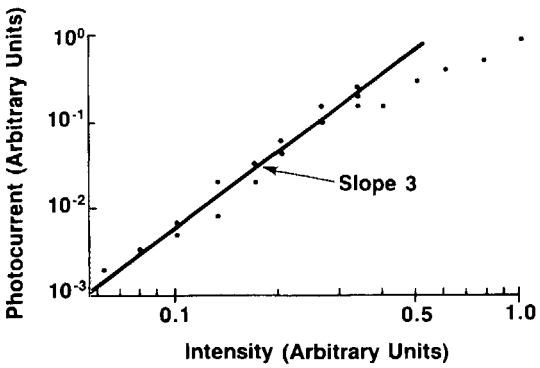

FIG. 2. Photocurrent vs optical intensity. The slope of the curve (slope = 3) indicates a three-photon photoemission process.

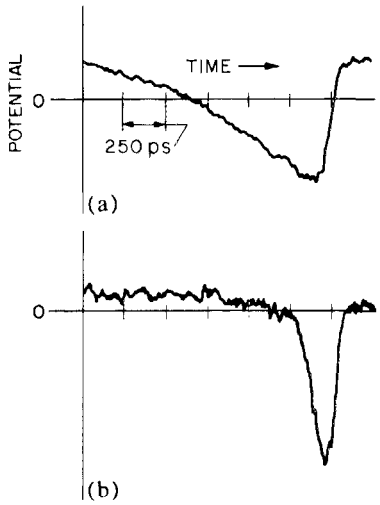

FIG. 3. Time-resolved photoemission trace of a 90 ps electrical pulse with an extraction field of (a) 40 V/cm and (b) 8000 V/cm.

cess. The saturation behavior evident at the higher intensities is attributed to space-charge effects.[12] The highest average power plotted in Fig. 2 is ~4 mW; for the measurements discussed later in this letter, the power is attenuated to 1–2 mW. For the lithographic sample, the magnitude of the photocurrent remained constant as the laser spot was scanned over the sample and is not strongly dependent on angle of incidence and polarization. The photoelectron yield is enhanced by at least four orders of magnitude compared to smooth gold surfaces, and a similar enhancement was found with the other two types of roughed surfaces. To our knowledge, this constitutes the first report of a surface-enhanced multiphoton photoelectric effect. The enhancement of other nonlinear optical phenomena on roughened metallic surfaces has been studied extensively. Such enhanced phenomena include Raman scattering[11,13] and second harmonic generation[14,15] from adsorbed molecules and from the metal microstructures themselves. An enhanced single photon photoelectric yield from submicron silver particles has been observed previously.[16]

For a fixed anode potential, the photoelectron current measured at the anode increases with increasing negative bias of the emitting surface; measurements are sensitive to sample voltage differences of a few tens of millivolts (with 1 s averaging time). Time-resolved measurements were performed using 90 ps, − 850 mV pulses coupled onto a 50 Ω microstrip transmission line on unpolished GaAs. The electrical pulses were generated by a comb generator, which was driven with the amplified fourth harmonic (468 MHz) of the photodiode output. The comb generator produced 90 ps, − 15 V pulses separated by 2.13 ns which were then attenuated to − 850 mV. Time-resolved photoemission traces are shown in Figs. 3(a) and 3(b) for extraction fields of 40 V/cm and 8000 V/cm, respectively, and an anode bias of − 1.5 V. The long leading edge of the waveform shown in Fig. 3(a) (1.08 ns rise time from 10% to 90%) is due to the limitation on temporal resolution to be discussed below. The waveform shown in Fig. 3(b) is more symmetrical, with a rise time of 136 ps (10%–90%) and a FWHM of 151 ps. The fall times of the two traces are nearly the same at 99 ps and are comparable to the fall time measured with a sampling oscilloscope.

The temporal resolution of this measurement is limited by the effect of a changing sample potential on the electric field between the sample and anode during the time of transit of photoelectrons to the anode. This field is primarily established by the extraction electrode; the region in which the field is sensitive to the sample potential has an extent comparable to the spacing between the signal line and the nearest ground plane, a spacing generally much less than the distance to the anode. We define an "effective" transit time as the time required for electrons to traverse the region of space in which the field is sensitive to the sample potential. In the case of a signal pulse which is short compared to the effective transit time, electrons leaving the sample in advance of the signal by one effective transit time or less are affected by the signal pulse while those leaving after the pulse has occurred are unaffected; this produces an asymmetry in the recorded waveform, with a long leading edge, but an undistorted trailing edge. The effective transit time T is given by

$$T = (\sqrt{2m}/eE)(\sqrt{seE + U_0} - \sqrt{U_0}), \quad (1)$$

where E is the extraction field, m and e are the electron mass and charge, s is the characteristic distance over which the field due to the sample extends, and U_0 is the initial electron kinetic energy in the direction of the extraction field. With $U_0 = 1$ eV and $s = 600\,\mu$m (the spacing between the signal line and ground plane in our experiment is 300 μm), the calculated effective transit times are 712 and 88 ps, for extraction fields of 40 and 8000 V/cm, respectively. These numbers are in general agreement with the data shown in Fig. 3. These data demonstrate that the effective transit time may be reduced through the use of high extraction fields.

Improved temporal resolution may be obtained by further reducing the effective transit time. This may be achieved through the use of an even higher extraction field, a short sample-anode separation, and (for reasons discussed above) a small spacing between signal line and ground plane. For example, in the case of a 5-μm coplanar transmission line,[17] the effective transit time for an electron accelerated by a field of 10 kV/cm is 8 ps; if a 1-μm coplanar transmission line is used and the field is increased to 10^2 kV/cm (such as 100 V across a 10 μm spacing), the effective transit time is reduced to 1 ps.

In summary, we have described a new, contactless method for sampling high-speed electrical signals, by analy-

sis of photoemission from signal-bearing metal conductors. Experiments aimed at modifying the analyzer geometry to reduce transit time to several picoseconds are currently in progress.

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