Photoconductive sampling with an integrated source follower/amplifier

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(Received 7 September 1995; accepted for publication 8 January 1996)

A hybrid, optoelectronic sampling circuit based on a photoconductive switch and a junction-field-effect-transistor (JFET) source follower/amplifier has been demonstrated to have picosecond response, high-sensitivity, absolute-voltage capability, and a very high impedance. The distributed capacitance of the electrical measurement system is reduced to the gate input capacitance of the JFET, and the conventional photoconductive current measurement is transferred into an absolute voltage measurement. Gating measurements with an improvement of 150 times in output voltage over unamplified photoconductive gates have been made using only 10 μW of average optical power. The effective on-state resistance of the photogate has also been increased by more than 150 times, indicating that a photoconductive probe with very low invasiveness may be produced. [S0003-6951(96)02211-5]

Progress in ultrafast photoconductive (PC) sampling technology has led to the demonstration of electrical wave form measurements with picosecond resolution and high voltage sensitivity. For instance, an optical-wave form analyzer based on an interdigitated, metal-semiconductor-metal (MSM) detector has been monolithically integrated with a sampling photogate on low-temperature-grown GaAs (LT-GaAs) and demonstrated by Chen *et al.*[1] to have 1.2-ps resolution and 500-pW noise equivalent power (NEP). Furthermore, free-standing PC-sampling probes using fast response photogates have been developed for integrated circuit testing.[2,3] Combined with a scanning force microscope (SFM) or scanning tunneling microscope (STM),[4] submicrometer spatial resolution and picosecond temporal resolution for device or circuit measurements are also soon to be realized. One problem, however, is that optically triggered sampling photogates extract significant charge in their low-resistance "on-state" and are invasive to the circuit they are probing, even though their average gate resistance is high. The removal of this current may also deplete the charge from a submicrometer device or a sensitive circuit, changing its state or operation. In addition, the voltage output of a typical PC photogate is much less than the actual signal voltage being measured, preventing absolute voltage measurements and limiting sensitivity.

In this work, we demonstrate a new picosecond-response, high-impedance PC photogate with a high sensitivity and the capability to measure absolute voltage with very low light levels. To accomplish this, the PC photogate has been integrated in a hybrid configuration with a pair of matched junction-field-effect-transistors (JFET), which act as a source follower/amplifier (SF/A). With this circuit, the photogate has been converted from a current monitor to a voltage monitor with the ultrahigh input impedance of the JFET. A measurement system using the sampling photogate with the SF/A would thus offer a lower invasiveness with improved sensitivity and accuracy as compared with unamplified probes. In addition, probes using the SF/A could be readily positioned to measure absolute voltages within circuits and also use the lower power outputs of currently available compact laser sources.

A schematic diagram of the PC-gating experiment using a SF/A is shown in Fig. 1. Both the detector and photogate are PC switches with similar interdigitated MSM structures. The detector is a Picometrix PX-D14 device with a temporal response of ~9 ps FWHM, while the photogate has a capacitance of 4 pF and a temporal response of 4 ps. They are each packed in separate modules with coaxial connectors for bias (detector only) and input or output of electronic signals. When connected, the short-duration wave forms travel less than 1 cm between the detector and the sampling photogate. A mode-locked Ti:sapphire laser operating at 780-nm wavelength with a repetition rate of 76 MHz produced 100-fs duration pulses to drive these PC elements. The laser beam was split into two beams, with one delayed with respect to the other by use of a moving mirror. The first beam is used to pump the detector module and generate ~9 ps duration elec-

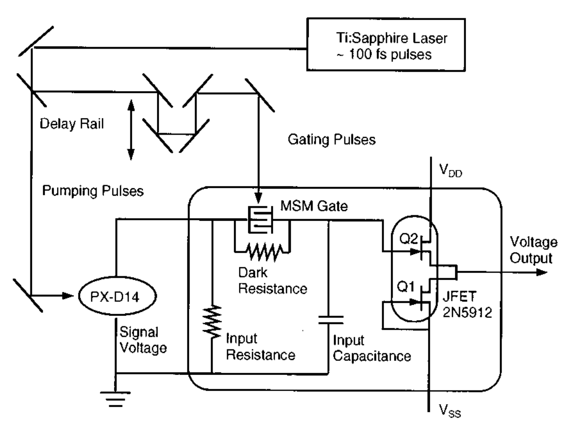

FIG. 1. Schematic diagram of the photoconductive sampling gate with a source-follower/amplifier.

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 0003-6951/96/68(11)/1464/3/$10.00

trical pulses to be used as the signals to be measured. The second beam, supplying the optical gating pulses, is varied so that it supplies an average power between 1.5 mW and 5 nW (20 pJ/pulse to 66 aJ/pulse). These pulses activate the photogate and open a sampling window at many delay times during the duration of the unknown wave form. The variable delay between the two beams has a scan rate that can be varied from 0.1 to 1 Hz. These rates correspond to integration time constants from 10 to 1 ms. A packet of charge, proportional to the convolution of the electrical pulse to be measured and the optical gating pulse at a certain pump-probe delay, is injected into the gate of the source follower at the repetition rate of the laser. The output voltage of the SF/A can be measured using a lock-in amplifier or a digital averaging oscilloscope. For comparison, we also measure the signal directly from the photogate module without the SF/A.

The SF/A is produced using a pair of matched, *n*-depletion JFETs, model 2N5912. The first transistor, Q1 (Fig. 1), serves as a constant current source with the source and gate pins tied together, while the second transistor Q2 works as a source follower. As a matched pair of transistors, the source voltage of JFET Q2 follows the gate voltage.[5] The bias values for the source follower are ±5 V dc and both JFETs are then operated in their saturation region. The short-circuit, common-source input capacitance, $C_{\rm iss}$ of a 2N5912 is 3 pF, and the gate operating current I_G, is typically 1 pA. The equivalent input noise voltage e_n, versus frequency is about 20 nV/Hz$^{1/2}$ at 10 Hz and less than 4 nV/Hz$^{1/2}$ beyond 1 kHz. The gate-source pinch-off voltage is about 2 V and the differential gate-source voltage is 15 mV at maximum. The offset voltage observed in the experiment is about 10 mV due to this mismatch. By directly wiring the output of the photogate to the gate pin of Q2 within a distance of 5 mm, we avoid the distributed cable capacitance (20–30 pF/ft) that is typically encountered in the PC-sampling technique. The total gate capacitance for the SF/A is about 7 pF due to both the photogate and $C_{\rm iss}$. Since the gate bias current of Q2 is negligible, the transferred PC charge is stored on the gate of this JFET. The only way for the stored charge to dissipate is along the dark resistance of the photogate itself. Since the voltage is the charge divided by the input capacitance, by using a smaller capacitance, the voltage level will build up more quickly. An equilibrium voltage will be induced when the charge injection rate to this buffer capacitance balances the leakage current through the dark resistance. The input voltage will then be present at the SF/A output.

Figure 2 shows the temporally resolved output signals from the photogate with the SF/A for average optical powers on the detector of 5 μW and 1.5 mW and with 10 μW of average optical gating power. The traces were acquired at a 1-Hz scanning rate without averaging, corresponding to a dwell time constant of 1 ms at each delay step. The FWHM of the pulses is 9.4 ps. There was no degradation in the temporal response of the photogate with the SF/A. Without the SF/A, the signal voltage was found to be over 100 times smaller with the same 10 μW optical gating power.

Figure 3 shows the peak amplitude of the measured temporal wave forms versus optical gating power for two detector signals excited using average optical pumping powers of

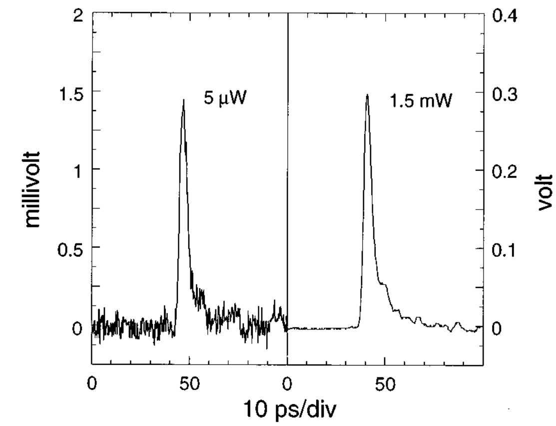

FIG. 2. The temporally resolved output signal for average optical pumping powers of 5 μW and 1.5 mW on the PX-D14 detector. Both wave forms were acquired in 1 s using 10 μW of average optical gating power with the source follower/amplifier.

300 and 30 μW. The optical gating power is varied from 5 nW to 1.5 mW. Measurements conducted using a photogate without the SF/A are also shown. For gating powers less than 3 μW, the output voltage of the SF/A is linearly proportional to the gating power. These outputs are 150 times higher than those without the SF/A. This is because the signal charge can dissipate only through the 150 MΩ dark resistance of the photogate rather than the 1 MΩ input impedance of the oscilloscope. In this case, the noise level is 3.2 μV/Hz$^{1/2}$, limited by the resolution of the digital oscilloscope. The results in Figs. 2 and 3 demonstrate the 150 times signal-to-noise improvement realized, especially at low gating power, when the SF/A is used.

For optical gating power above 10 μW, the output signals become saturated. This saturation is due to the decreasing charge injection rate as the voltage of the input capaci-

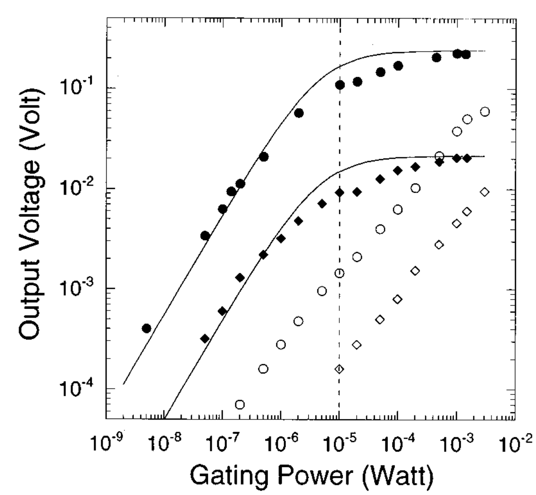

FIG. 3. The peak amplitude vs average optical gating power for the photogate either with (filled symbols) or without (open symbols) an integrated source follower/amplifier. Two peak output signals from the detector, 22 mV (♦) and 230 mV (●), are generated using 30 and 300 μW of average optical pumping powers. The solid lines are calculated from a dc approximation and the dashed line is the saturation optical gating power of 10 μW.

tance approaches that of the signal under test. Although the real peak signal can only be resolved by deconvolution, this saturation shows that the voltage of the SF/A input capacitance indeed has the same magnitude as the signal under test. The two solid lines in Fig. 3 are computed from a quasi-dc approximation, $V_{\mathrm{output}} = \eta PRV_{\mathrm{signal}}/(1+\eta PR)$, where η is the photogate responsivity per voltage applied, P is the optical gating power, and R is the dark resistance of the photogate. For our photogates, $\eta = (0.008\ \mathrm{A/W})/(5\ \mathrm{V})$ and $R = 150$ MΩ from dc measurements. A saturation optical gating power can be defined as $P_{\mathrm{sat}} = 1/\eta R$, or a computed value of 4.2 μW for this photogate. The experimental value of P_{sat} is 10 μW as the dashed line shows in Fig. 3. We note the differences between the quasi-dc guide lines and output signals above the gating power saturation corner around P_{sat}. While the reason for this is not clear, the trends for both sets are similar. They might result from the convolution between the photogate response and signal under test, which is sensitive to the temporal characteristics of both. In general, this saturation of the output voltage is an advantage for a photogate applied to device testing, since it will be less vulnerable to the gating-laser noise. More important, this saturation voltage is the absolute voltage of the signal under test, so a PC probe with the SF/A will not be restricted to relative amplitude measurements.

In terms of invasiveness, the average photogate conductance for 10 μW average optical gating power increases about 16 nS over the dark conductance. The on-state resistance is then estimated to be about 19 kΩ from the duty cycle of 3290 (4 ps on-state/13.16 ns off-state). However, the output voltage is already 50% of the signal under test or 230 mV for the experiment using 300 μW average optical pumping power. Without the SF/A, at least 10 mW of optical gating power is necessary to obtain the same signal level. Here, the on-state resistance is 30 Ω and the invasiveness will be increased by about 630 times. Thus, when the SF/A is used, we have a picosecond temporal response photogate for absolute voltage measurement with a high on-state resistance for low invasiveness and a low gating-power requirement.

The noise sources of the PC-sampling gate with the SF/A have also been investigated in an experiment where the pumping laser beam is modulated with an acoustic-optic modulator, and the output signal of the SF/A is averaged by a lock-in amplifier. The dominant noise source is the gating laser noise, which is proportional to the square root of the gating laser power. At a 100 Hz lock-in frequency, the noise is about 1.8 and 0.17 μV/Hz$^{1/2}$ for 1.4 mW and 10 μW gating laser powers, respectively. However, the laser noise drops at higher lock-in frequencies. For 1.4 mW gating laser power, the noise is 25 nV/Hz$^{1/2}$ at 10 kHz and 5 nV/Hz$^{1/2}$ at 60 kHz. At this point, the noise is limited by the SF/A at about 4 nV/Hz$^{1/2}$ for a lock-in frequency above 1 kHz. Without the SF/A, the lock-in frequency is limited by the large parasitic capacitance. The amplitude of the output signal drops faster than the noise decreases for a lock-in frequency beyond 200 Hz. The sensitivity of PC sampling without the SF/A is about 2 μV/Hz$^{1/2}$, limited by the $1/f$ noise of the gating laser power around a 100 Hz lock-in frequency.

In conclusion, we have demonstrated that the integration of a source follower/amplifier can improve the performance of a PC-sampling photogate over 100 times in regard to invasiveness and gating efficiency, while maintaining a 1-ps temporal response and enhancing the signal-to-noise performance. Laser powers as low as 10 μW have been proven to be sufficient for driving the photogate, and the requirement that an external current preamplifier or a lock-in amplifier be used to achieve acceptable signal-to-noise ratio has been eliminated. The integration of the photogate with the SF/A will help speed the development of compact, economical photoconductive sampling probes and measurement systems.

This research was sponsored by the Air Force Office of Scientific Research, Air Force Material Command, USAF, under Grant No. DOD-G-F49620-95-1-0227. Support was also provided by the National Science Foundation through the Center for Ultrafast Optical Science under STC PHY 8920108. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied of the Air Force Office of Scientific Research or the U.S. Government.

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