Photoconductive sampling probe with 2.3-ps temporal resolution and 4-μV sensitivity

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We report on a novel probe technology which is applied to the measurement of high-speed guided electrical signals. The probe consists of a high-impedance gate fabricated using an interdigitated electrode structure on semi-insulating, low-temperature-grown GaAs, and its operation is based on the optoelectronic technique of photoconductive sampling. The probe has a dynamic range of $>10^6$, permitting the linear measurement of short-duration signals with amplitudes ranging from microvolts up to several volts. Its resistance is 100 MΩ, and its capacitance is less than 0.1 fF, making this probe attractive for noninvasive, external circuit testing of ultrahigh-speed devices and circuits.

Novel semiconductor-material growth and processing technologies, as well as the development of high-spatial-resolution fabrication techniques, continue to push the response of electronic and optoelectronic devices to ever shorter times. Devices and circuits are now operating with bandwidths greater than 100 GHz—corresponding to rise and fall times of a few picoseconds—and with critical dimensions less than 1 μm. Conventional instrumentation is only able to perform direct measurements over such bandwidths, if at all, with great difficulty. In addition, commercially available probe technology, while increasing in measurement frequency past 100 GHz for network-analysis applications, consists mainly of the use of low impedance, and thus highly invasive, metallic contacts. It could thus be stated that currently available measurement techniques are limited in their ability to meet the combined requirements of high temporal and spatial resolution, internal node access, absolute voltage measurement, high sensitivity, noninvasiveness, and simplicity.

As a result of the deficiencies existing in the conventional technology, the development of new electrical signal measurement systems, such as photoconductive sampling,[1] electro-optic sampling,[2,3] and pulsed electron beam probing,[4] have been stimulated. However, each of these techniques, while demonstrating outstanding performance in one or more of the critical measurement criteria, has limitations in others. We now report the first demonstration of a contacting, noninvasive, free-standing, photoconductive-sampling probe that simultaneously meets all the provisions for the optimum probe outlined above. Ultrashort-pulse lasers and a new class of high-sensitivity, subpicosecond photoconductive switches are key elements of this probe, which is fabricated from low-temperature-grown GaAs (LT GaAs) of molecular beam epitaxy (MBE) and utilizes a metal-semiconductor-metal (MSM) interdigitated electrode structure as its photoconductive switch. By femtosecond time-resolved-reflectance techniques, we have measured the carrier lifetime of this LT GaAs layer to be 1.0 ps.[5] Its ultrafast lifetime, high mobility (>200 cm^2/V s), and high off-state resistance make this LT GaAs material ideal for the photoconductive gate of the sampling probe. To date, the first generation of this probe to be fabricated, has demonstrated a temporal resolution of 2.3 ps, corresponding to a bandwidth of 120 GHz, and a sensitivity of 4 μV/(Hz)$^{1/2}$.

Figure 1 is a scanning electron microscope (SEM) picture of the photoconductive sampling probe. It consists of a 2-μm interdigital photoconductive switch and a titanium tip of 8-μm-diam base, 5-μm-diam table, and 3-μm height. The titanium tip, fabricated by a similar fabrication process as that used to produce field emission cathodes,[6] makes contact with the transmission line guiding the electrical signal to be measured. A clorobenzene lift-off process was used with a 2.3-μm-thick photoresist and a 3-μm-thick titanium metal film was deposited using *e*-beam evaporation. During the titanium deposition, the opening in the photoresist allows the tip to be formed on the substrate, but the size of the opening decreases due to the condensation of titanium on its periphery. As the size of the aper-

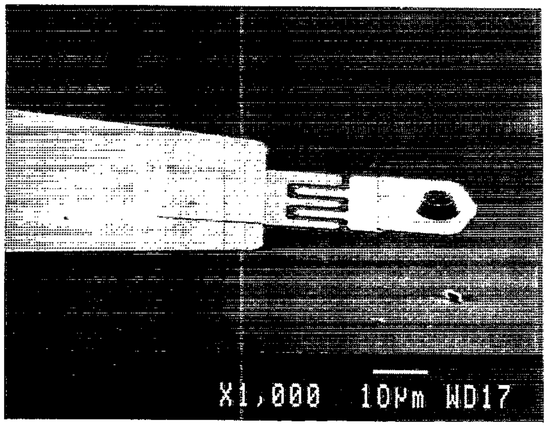

FIG. 1. SEM picture of photoconductive sampling probe. The probe consists of a titanium contact tip with 8-μm diam and 3-μm height, and an interdigital photoconductive switch with 2-μm finger width and spacing. The titanium contact tip and photoconductive switch were deposited on a MBE-grown LT GaAs layer.

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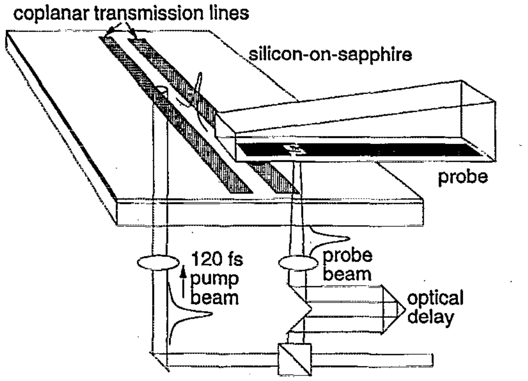

FIG. 2. Schematic diagram of experimental setup. The pump beam generates photovoltaic pulse of Ti/Si Schottky junction, and the probe beam switches the photoconductive gate of the probe. The sapphire crystal of the SOS is transparent to the laser beam.

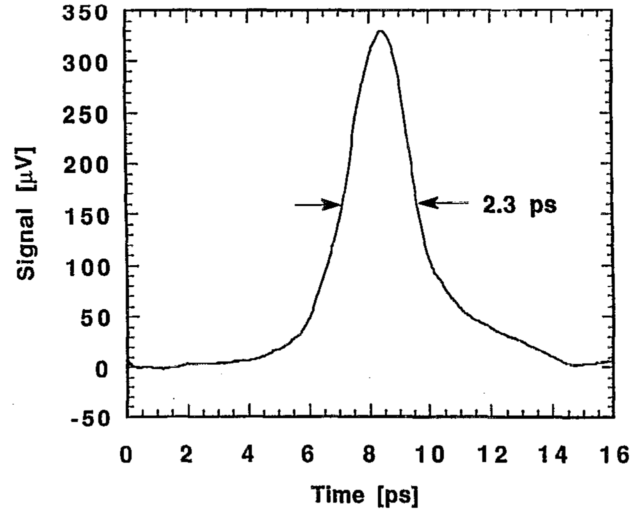

FIG. 3. Measured photovoltaic electrical pulse. The peak amplitude is 330 μV and the FWHM is 2.3 ps. The signal scan noise level is 1 μV with a lock-in time constant of 1 s.

ture decreases, a cone grows inside the cavity. For the probe described in this letter, we have used an 8-μm-diam circular photoresist pattern for the initial hole diameter.

The photoconductive switch on the probe is a MSM structure with electrodes fabricated from 500-Å/2500-Å Ti/Au, with both a 2-μm finger width and spacing. The contact tip and photoconductive switch metal were deposited on a LT GaAs layer by e-beam evaporation. The LT GaAs layer was grown at 200 °C and annealed at 600 °C for 10 min in an arsenic overpressure. Epitaxial GaAs layers grown by MBE at low temperature exhibit a significant reduction in carrier lifetime over GaAs layers grown at a conventional temperature.[5] After the metallization and the lift-off processes, the boundary of the probe was cut by a diamond saw.

We characterized the photoconductive sampling probe by measuring the propagation of an ultrashort electrical pulse along a coplanar transmission line on a silicon-on-sapphire (SOS) substrate. The optical source used in the generation of the short electrical pulses and the gating of the photoconductive switch on the probe was a self-mode-locked Ti-sapphire laser operating at a 100-MHz repetition rate.[7] The Ti-sapphire laser crystal has a broad gain bandwidth and is well suited to optical ultra-short-pulse generation and amplification. Also the Ti-sapphire laser has low noise characteristics compared to other femtosecond lasers such as the colliding pulse mode-locked dye laser.[8] We have used intracavity dispersion compensation in the mode-locked Ti-sapphire laser to produce pulses with duration as short as 120 fs. The laser pulse train was divided by a beamsplitter into two components: a pump beam to generate photovoltaic pulse at the Ti/Si Schottky junction on SOS, and a probe beam to open the LT GaAs photoconductive gate. A schematic diagram of the probe, the transmission line to be tested, and the laser-pulse beam path is given in Fig. 2. The sapphire crystal supporting the SOS circuit under test is transparent to the wavelength of the Ti-sapphire laser, so that we can focus the probe beam through the bottom of the SOS substrate onto the optoelectronic gate. Part of the probe beam is harmlessly absorbed by the Si layer of the SOS while the remaining pulse energy gates the photoconductive switch of the probe.

The photovoltaic effect of the Schottky junction between the Si of the SOS and the Ti of the transmission line electrode was used to create the short-duration electrical signal to be measured. The 1-μm Si layer had been previously ion bombarded with oxygen so that its carrier lifetime would be decreased to 2 ps. The contact of the probe tip was controlled by measuring the resistance between the tip and the transmission-line metallization and by monitoring optical interference. The photoconductive gate on the probe was opened by the probe-beam pulses for 1 ps, corresponding to the carrier lifetime of the LT GaAs. This permitted measurements of the signals at specific intervals in the time domain. The whole pulse wave form was measured by changing the relative time delay between the pump and probe beams and looking at the amplitude of the transient in each new sampling window.

The signal response measured using the photoconductive sampling probe is shown in Fig. 3. The FWHM of the pulse is 2.3 ps, and the peak amplitude is 330 μV. The signal scan noise level is 1 μV with a lock-in time constant of 1 s. To confirm absolute voltage measurement, we applied a calibrated electrical signal at the lock-in frequency to one of the transmission lines and measured the same value as the calibrated voltage on the lock in. Figure 4 shows that the probe response was linear from 40 μV to 100 mV. Thus, the photoconductive sampling probe technique requires no sensitivity calibration process.

The off-state series resistance of the photoconductive gate on the probe and probe contact was greater than 100 MΩ. The capacitance of the switching gap is low, <0.1 fF, and the inductance of the probe contact tip is less than 15 pH. For a 1-ps electrical pulse, corresponding to a 350-GHz bandwidth, the capacitive coupling of the photoconductive switching gap and the inductive coupling of the probe tip to the circuit under test are negligible.

In conclusion, we have demonstrated a newly devel-

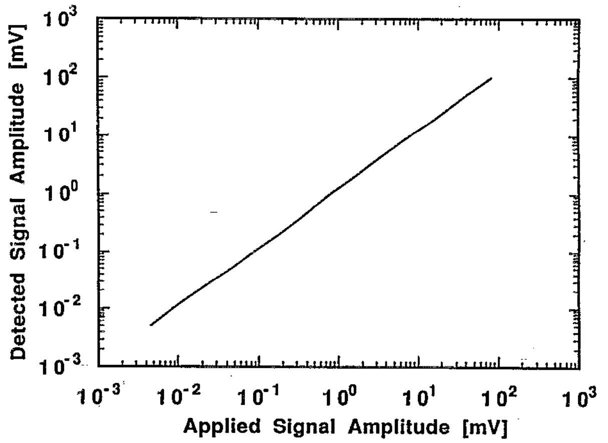

FIG. 4. The linearity of photoconductive sampling probe response to electrical signal on the transmission line from 40 μV to 100 mV.

oped photoconductive sampling probe technology. It has 2.3-ps temporal resolution and 8-μm spatial resolution with 4-$\mu V/(Hz)^{1/2}$ sensitivity. In addition, it showed a linear response to an electrical signal from 40 μV to 100 mV, and it measured the absolute voltage of the signal. We are further developing this new photoconductive sampling probe so that it is not necessary to test circuits having substrates transparent to the optical probe beam. This probe will be capable of noninvasive, highly sensitive characterization of high-speed digital circuits, and it will also be useful as a probe in an optically based millimeter-wave vector network analyzer.

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