A fiber-mounted, micromachined photoconductive probe with 15 nV/Hz$^{1/2}$ sensitivity

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We report the performance of a micromachined, photoconductive-sampling probe that is fabricated on low-temperature-grown GaAs and mounted on a single-mode optical fiber. The epitaxial probe has a temporal resolution of 3.5 ps, a spatial resolution of 7 μm, and a sensitivity of 15 nV/(Hz)$^{1/2}$ when integrated with a high impedance, junction field-effect transistor source follower. The fiber, which couples short laser pulses to the interdigitated detector pattern on the probe, also provides flexible support and mobility. The probe's compact cross section makes it ideal for applications as an internal-node, picosecond-response, photoconductive sampling probe or wave form launcher for test and characterization of integrated circuits. © *1996 American Institute of Physics.* [S0003-6951(96)04739-0]

The use of photoconductive (PC) sampling technology having picosecond temporal resolution for the investigation of high-speed device and circuit performance is well established.[1–3] Most recently, applications using PC sampling gates integrated with a device under test (DUT) have been replaced by freely positionable probes based on silicon-on-sapphire (SOS) and low-temperature-grown GaAs (LT GaAs).[4–7] However, these probes, some of which have been designed for integrated circuit internal-node testing, are supported on bulk substrates and are, therefore, rigid. A DUT would have to be flat within several micrometers over a range of many millimeters in order to achieve parallel alignment and reliable probe tip contact. In addition, bulk LT GaAs probes are not transparent to the gating laser, making it difficult to both access the PC gate with laser illumination and contact the tip to the DUT. Probes fabricated from SOS, which at least is transparent, exhibit responsivity and resistivity that are inferior when compared to probes using LT GaAs.

The sensitivity limit for a PC sampling gate is a few μV/(Hz)$^{1/2}$, due mainly to the photovoltaic noise caused by the amplitude fluctuations of the gating laser pulses.[8] In a previous study, we have found that by reducing the parasitic capacitance and leakage current of the sampling circuit, through the use of a source follower produced from two junction field-effect transistors (JFET), the frequency of modulation used with phase-sensitive detection could be increased and the $1/f$ gate noise reduced.[9]

As a result of this work, a flexible, 1-μm-thick, micromachined PC probe that has an extremely low, 15 nV/(Hz)$^{1/2}$ sensitivity limit (due to the high impedance and low capacitance of an integrated JFET source follower) has now been fabricated and tested. The micromachined probe is mounted on a single-mode fiber that provides mechanical support and eliminates the need for laser alignment when the probe is repositioned. Furthermore, since the active layer of the probe is so thin, the gating laser pulses coupled to the PC gate by the fiber excite the LT GaAs from the side without the gate metallization with high efficiency. The probe itself also has a very small parasitic capacitance, which should result in a reduced invasiveness for applications to circuit testing.

The probe was fabricated using a layer of 1-μm-thick LT GaAs that was grown by molecular beam epitaxy at 220 °C and annealed at 600 °C for 10 min. It was necessary to remove the LT GaAs, measured via pump–probe transient absorption to have a 1.1. ps trapping time, from its semi-insulating substrate and a 0.5-μm $Al_{0.5}Ga_{0.5}As$ layer.[10] The tear-drop shape of the LT GaAs layer (Fig. 1) was defined by a phosphoric acid mesa wet etch through the LT GaAs layer. A chlorobenzene lift-off process was then used to define 500 Å/3000 Å of Ti/Au for the interdigital metal–semiconductor–metal (MSM) PC switch, electrode, and tip. The finger width and spacing for the MSM switch are 1.5 μm, and the total switch area is about 30×30 μm^2. The

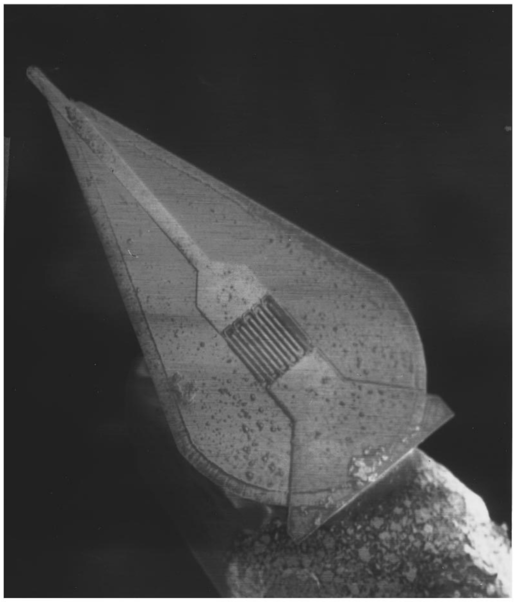

FIG. 1. Scanning electron microscope picture of the epitaxial lift-off probe. The probe is 130 by 230 μm (at its widest points) by 1 μm and consists of a Ti/Au interdigital MSM switch with fingersize and spacing of 1.5 μm.

[a)]Electronic mail: whitaker@caen.engin.umich.edu metal tip area is 7 μm wide and extends beyond the apex of the tear-drop-shaped epitaxial layer by about 5 μm. Lapping and wet etching were used to release the probe from the GaAs bulk substrate. Ammonium hydroxide and hydrofluoric acid were used to etch the GaAs substrate and $Al_{0.5}Ga_{0.5}As$ etch-stop layer, respectively, while the front side was protected by black wax. A 5×5 mm^2 die area produced 500 probes with a yield of 90%.

The probe is mounted using optical uv cement onto a single-mode fiber with a 45° polished bevel. This allows the guided laser pulses to internally reflect off the polished surface to the backside of the probe and into the switch area. The need for realignment of the PC gate illumination when the probe is repositioned is eliminated. In general, the entire probe is flexible, and the apex region of the probe bends smoothly when contacting a device. As a result, the fiber-coupled probe can touch a DUT at an arbitrary angle with reliable and repeatable electrical contact simply by observing the reflection from the bending probe tip.

We explored the capability of the probe by using it to measure picosecond pulses generated photoconductively using the gap separating the electrodes of a coplanar stripline on a LT GaAs substrate. A mode-locked Ti-sapphire laser operating at 810-nm wavelength with a repetition rate of 82 MHz produced 100-fs duration pulses that, for the sampling experiment, were split into two beams with one variably delayed with respect to the other. The first beam, modulated by an acousto-optic Bragg cell at frequencies that could be varied between 50 Hz and 110 kHz, was focused onto the gap between the coplanar transmission lines biased at 5 V. A $LiTaO_3$ electro-optic sampling probe was used to establish that a 1.5 ps signal was being generated by the photoconductive switch. The second beam, consisting of the gating laser pulses, was coupled into the single-mode fiber to activate the PC switch. Both beams could be adjusted from 20 mW down to 1 μW (240 pJ/pulse to 12 fJ/pulse) for obtaining a range of gating efficiencies and signal amplitudes from 20 mV to 1 μV.

The output of the MSM sampling gate was coupled to a source follower assembled using a pair of matched, *n*-depletion JFETs (model 2N5912).[11] The short-circuit, common-source input capacitance, C_{iss} of the JFET was 3 pF, and the gate input impedance was >1 TΩ. The equivalent input noise voltage of the JFET is about 10 nV/(Hz)$^{1/2}$ at 100 Hz and less than 5 nV/(Hz)$^{1/2}$ beyond 1 kHz. The output of the fiber-mounted probe was connected to this source follower by conductive silver paint, with a spacing of 1 cm between the PC probe and the amplifier. Thus, the MSM output must charge a capacitor of $\sim$3 pF. In contrast, without the source follower, the distributed capacitance encountered by the fiber-mount probe is estimated to be $\sim$220 pF for a 3-ft RG-58 coaxial cable and a lock-in amplifier.

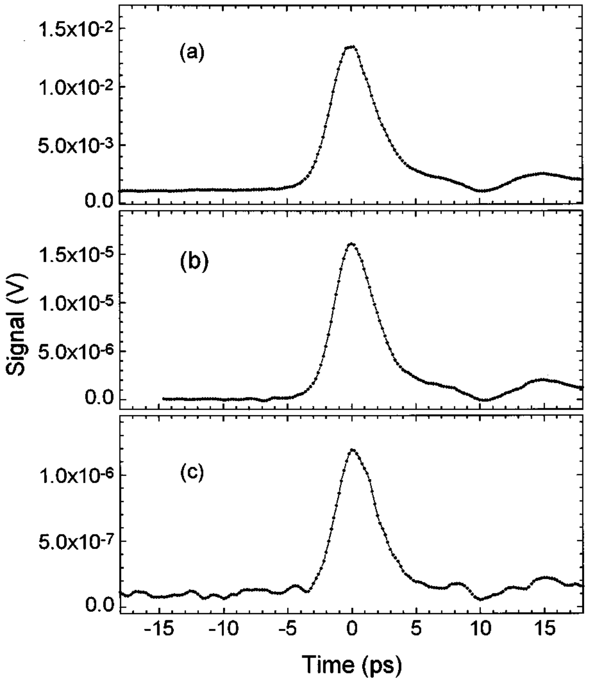

FIG. 2. Temporally resolved wave forms measured using the fiber-mounted epitaxial lift-off LT GaAs photoconductive probe with an integrated JFET source follower. The gating laser powers and modulation frequencies were (a) 2 mW and 1 kHz, (b) 200 μW and 10 kHz, and (c) 2 mW and 50 kHz.

Figure 2 shows three temporally resolved signals measured using the fiber-mounted probe with the integrated source follower. The probe made contact to the transmission line at a distance of 100 μm from the source. The signal level was varied from 13 mV to 1 μV by adding neutral density filters into the pump–beam path. Figure 2(a) is a trace of a single scan, while Figs. 2(b) and 2(c) are measured wave forms averaged over 10 scans. The PC gate noise amplitude is taken as the root-mean-square value calculated from the base lines for $t<0$ ps from Figs. 2(b) and 2(c). The signal amplitude was also measured as a function of the gating laser power from 10 mW down to 20 μW, and for lock-in modulation frequencies from 50 Hz to 110 kHz. Figure 2(a) is a measured wave form with a signal amplitude of 13.2 mV. In this case, the noise was dominated by pump laser fluctuations rather than PC gate laser fluctuations. The measured wave form in Fig. 2(c) has a signal amplitude of 1.1 μV and a 15 nV/(Hz)$^{1/2}$ noise level. Figure 2(b) shows that a high sensitivity [65 nV/(Hz)$^{1/2}$] can still be attained with a low probe intensity.

Figure 3 demonstrates the effect on the measured signals of varying the modulation frequency. The signal-under-test was fixed at 10 mV using a 1-mW pump power. The peak amplitudes of the sampled wave forms were then measured using the source follower [Figs. 3(a)–3(d)], and without the source follower [Figs. 3(e) and 3(f)]. The incorporation of the JFET source follower has enabled a substantial increase of the modulation frequency used with a PC probe.

In general, the choices of gating laser power and modulation frequency do not influence the time resolution of the probe at laser powers less than 20 mW. For instance, the full width at half-maximum (FWHM) of the sampled wave form is 3.8–4.0 ps for all measurements shown in Fig. 3; after deconvolution, the speed of this fiber-mounted LT GaAs probe is estimated to be about 3.5 ps. However, the gating laser power has been found to influence the noise of a PC gate.[9] That is, the noise is proportional to the square root of the gating laser power and has a $1/f$ frequency dependence. In addition, the modulation frequency affects the magnitude of the measured wave form since the actual voltage of the

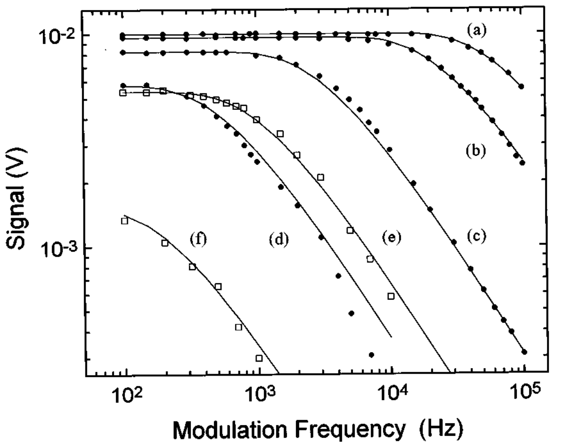

FIG. 3. Modulation bandwidth of the fiber-mounted probe with an integrated JFET source follower (•) using gating laser powers of (a) 10 mW, (b) 2 mW, (c) 200 μW, and (d) 20 μW. Also shown is the modulation bandwidth of the probe alone (□) using gating laser powers of (e) 10 mW and (f) 1 mW.

signal can be achieved only at a low modulation frequency. Since all the distributed capacitance except the 3-pF C_{iss} is eliminated in the new amplified probe, we can now use a 50-kHz lock-in amplifier modulation frequency without sacrificing significant signal amplitude (with a 2-mW gating laser power). At this modulation frequency, the photovoltaic noise was reduced to 15 nV/(Hz)$^{1/2}$, while the amplitude of the output wave form dropped by only about 50% [see Fig. 3(b)]. We conclude that the minimum detectable actual signal in this experiment is about 30 nV/(Hz)$^{1/2}$, corresponding to the result in Fig. 2(c) at a 50-kHz lock-in frequency. For comparison, the minimum detectable signal of the fiber-coupled probe without the source follower is found to be about 4 μV/(Hz)$^{1/2}$ (using 10-mW gating laser power and a 1.5-kHz lock-in frequency). The root-mean-square noise was found to be about 1.4 μV/(Hz)$^{1/2}$. However, the amplitude of the output wave form was only 32% of the actual signal [see Fig. 3(e)]. This result from the micromachined probe demonstrates that there is no degradation in performance compared with bulk LT GaAs probes.[4]

The fiber-coupled LT GaAs probe can also be used as an efficient picosecond wave form launcher. The correlation of the response of two probes with their tips placed 15 μm apart on a grounded metal line has a FWHM of 5 ps. The launcher was biased at 5 V while the sampling probe was connected to the JFET source follower and lock-in amplifier. Because of their small dimensions, two probes can be placed close to a DUT to make measurements without incurring errors due to dispersion in the transmission line. This launcher/sampling probe configuration opens the possibility of high bandwidth testing with on-wafer probes that eliminate the need for the signal to travel long distances before being measured.

In conclusion, we have used GaAs micromachining technology to develop an epitaxial-layer PC sampling probe with a 3.5 ps temporal response and a 15 nV/(Hz)$^{1/2}$ noise limit. This sensitivity is 100 times better than the previously believed 1-μV/(Hz)$^{1/2}$ noise limit.[4] The compact features, fiber-coupling capability, and straightforward alignment method make this sampling probe an excellent internal-node circuit testing tool. Incorporation of a submicron tip for measurements on very fine circuit or device structures will also increase the utility of the probe.

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