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High-Frequency On-Wafer Testing with Freely Positionable Silicon-on-Sapphire Photoconductive Probes

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Abstract

We describe the characterization of external photoconductive probes as both generators and detectors of picosecond electric transients. The probes are manufactured on transparent silicon–on–sapphire substrates and are suited for on–wafer testing in integrated circuits. We characterize the freely positionable probes concerning linearity, sensitivity, time resolution and invasiveness.

Introduction

Electronic and optoelectronic devices have become available with cut–off frequencies up to several hundreds of GHz. This technological push necessitates the development of new measurement techniques, because standard electronic measurement equipment such as network analyzers or sampling oscilloscopes are limited in bandwidth to 100 GHz.

Among optical measurement techniques, the recent advance in photoconductive (PC) sampling with freely positionable probes significantly extends the potential of on–chip characterization of ultrahigh–frequency devices.[1,2] A sensitivity of 1 μV has been reported for freely positionable PC probes based on LT–GaAs employing a low–noise laser source.[1] As an alternative, PC probes based on silicon–on–sapphire (SOS) technology are cheap, easy to manufacture, optically transparent and can be positioned to nearly any point of interest even in complex circuits. In this contribution, we present a detailed characterization of freely positionable PC–SOS switches both as detectors and generators for ultrafast electric signals.

Fabrication of flexible PC-probes and experimental set–up

Our PC probes utilize a metal–semiconductor–metal interdigitated electrode structure as PC switch (Fig. 1). To facilitate contacting to a device under test (DUT), a 5–μm–high titanium tip is located at the end of the short electrode. Fabrication of the finger structure is based on a standard lift–off process for patterning of the Cr/Au metallization on the SOS substrate. The silicon is implanted with Si^+ and Ne^+ ions to reduce the carrier lifetime.[3] For fabrication of the Ti tip, a special lift–off process with a several μm thick photoresist layer was developed.[2]

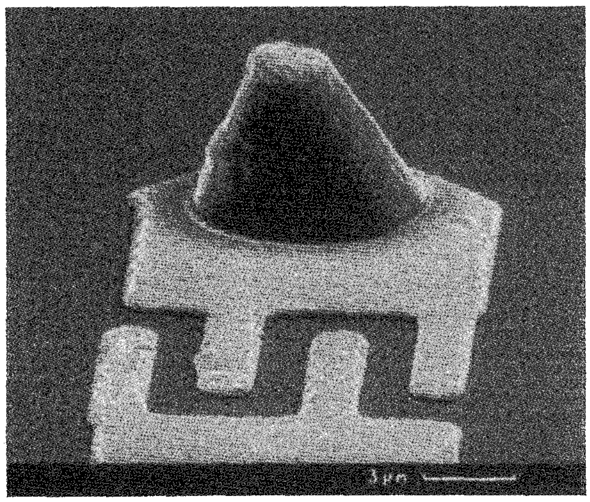

Fig. 1: SEM micrograph of a four–finger MSM–photoconductive sampling probe.

Time–resolved characterization is performed with a 100–fs ring dye laser in a pump–probe setup. We utilize THz–dipole antennas[4] and coplanar waveguides (CPW) with integrated PC switches as DUTs. The antenna is fabricated on ion–implanted SOS substrate (see Fig. 2a). It consists of a Hertzian dipole, realized as a 50–μm–long and 10–μm–wide Au strip with a 5–μm slot in the center. The two arms are connected to a coplanar transmission line (CTL) with 5–μm linewidth and 10–μm spacing. After a distance of 3.15 mm the CTL is expanded (25–μm width, 50–μm spacing). The Si is removed except for a mesa with the Hertzian dipole on top of it. The gap in the dipole together with the Si underneath forms the switch for electric pulse generation. The electric pulses launched on the antenna are sampled with the PC probe in full contact with one of the arms of the Hertzian dipole (see Fig. 2b).

The PC probe is conductive only within a time window set by the charge–carrier lifetime of the semiconducting material, which is 600 fs in appropriately ion–implanted Si.[3] The current through the PC probe is a measure for the electric field launched by the pump pulse on the DUT, which is traced as a function of optical delay between the pump and probe pulse.

Alternatively, a second PC probe is used as a generator of ps–electric transients on a CPW. In this case, the electric signals are sampled via external electro–optic (EO) detection technique employing a $LiTaO_3$–EO crystal.[5]

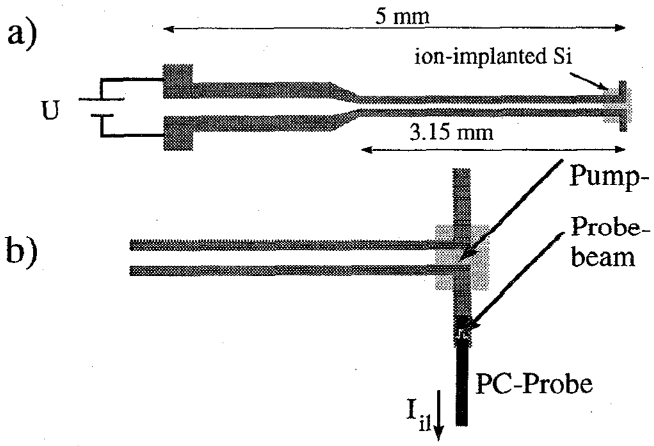

Fig. 2: (a) Schematic of the THz–dipole antenna. (b) Position of the PC probe on the antenna dipole.

Good contact between the PC probe and the DUT is ensured by measurement of the photocurrent (I_{il}) and the dark current (I_d) when a dc voltage of 1.5 V is applied between the PC probe and the DUT.

Experimental results and discussion

In a first experiment we investigate the temporal response of flexible PC probes on electric pulses of 40 mV peak amplitude and 1.3 ps duration (FWHM). In these measurements, the optical laser fluence on the switch of the flexible PC probe is varied, while the illumination strength of the pump beam on the PC region of the antenna is kept constant (compare Fig. 3). As a quantity for the probe laser fluence we measure the photocurrent I_{il} through the PC switch which is biased at 1.5 V before performing the time–resolved measurement. The peak amplitude of the detected signal rises linearly with the illumination strength on the PC probe (see inset of Fig. 3). No distortion in signal shape is observed when the probe fluence is increased. A PC signal duration of 2.7 ps (FWHM) is obtained, which is larger than the electric pulse width of 1.3 ps measured via EO sampling technique.[5]

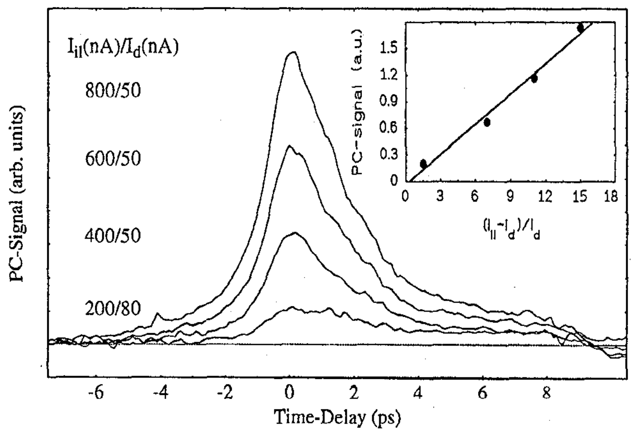

Fig. 3: Time–resolved PC signals of electric pulses of constant amlitude for various illumination strengths on the PC probe. The response of the PC probe to electric pulses of constant amplitude (40 mV) scales linearly with the probe photocurrent (I_{il}/nA) induced by the optical probe pulse (inset).

We have followed Auston's theory for a correlation of a pair of closely spaced photoconductors.[6] The observed linear dependence of the PC signals on the optical laser fluence of the probe beam gives clear evidence that the sensitivity of a PC detector is determined by its photoconductance, given by the product of the mobility and density of photoexcited carriers. The rise time of the correlation function is mainly determined by the photoconductance of the detector PC switch (flexible PC probe).[2] The decay depends on the photoconductance and capacitances of the generator (THz–antenna) and the detector switch as well as the impedance of the interconnecting transmission line.[2] We fit our measured PC data with Austons's formula assuming a bi–exponential time dependence of the photoconductance of the generating and detecting gap (see Fig. 4). The capacitance of the sampling gap and the transmission line impedance are calculated to be 1.7 fF and 120 Ω, respectively. Best fit to the measured data has been obtained with a generator capacitance of 5 fF.

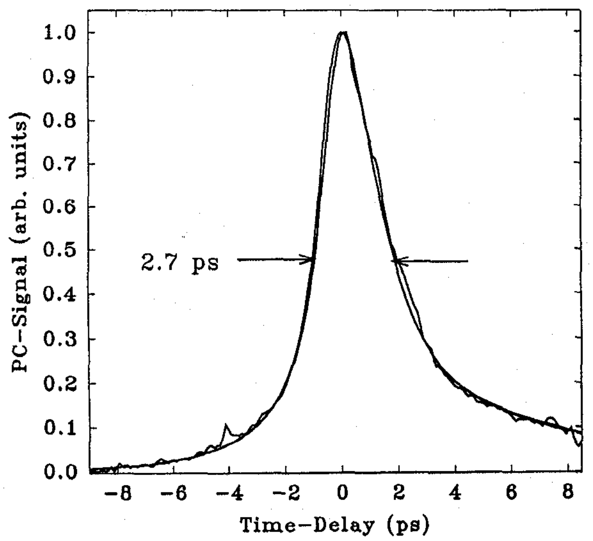

Fig. 4: Time–resolved PC signal from Fig. 3 for $I_{il} = 800$ *nA. The smooth curve is a fit to the measured data and is calculated by Austons's theory for a correlation of a pair of closely spaced photoconductors.*

Both the antenna as well as the PC probe exhibit a short carrier lifetime of 600 fs and a slow photoconductance decay with time constants of 6 ps and 2.2 ps for the generator and the detector, respectively. The relative contributions of the slow photoconductance decay to the total initial photoconductance amplitude are 8.5% for the antenna and 14% for the flexible PC probe. The time–resolution of the PC probe is mainly limited by carrier life–times of 2.2 ps in the Si–layer. With further reduction of the carrier life–time by optimized ion–implantation, a time resolution of approx. 1.5 ps will be achievable.[2]

The PC probes reveal linear response to electric signals of different strength as measured by variation of the power of the pump beam over two orders of magnitude.[2] The noise floor can be estimated from the data depicted in Fig. 3 to be approx. 400 μV for a single scan with 1 s lock–in time constant. To increase the sensitivity of SOS PC probes down to μV electric signals, higher excitation levels of the probe and laser sources with low noise characteristics instead of dye lasers are necessary.

To investigate the invasiveness of our PC probes, we detect propagating electric pulses on a CPW behind a point where a PC probe is in full contact with the signal conductor. The CPW (conductor width 60 μm, spacing 30 μm) is fabricated on SOS substrate with an integrated PC switch for electric pulse generation.

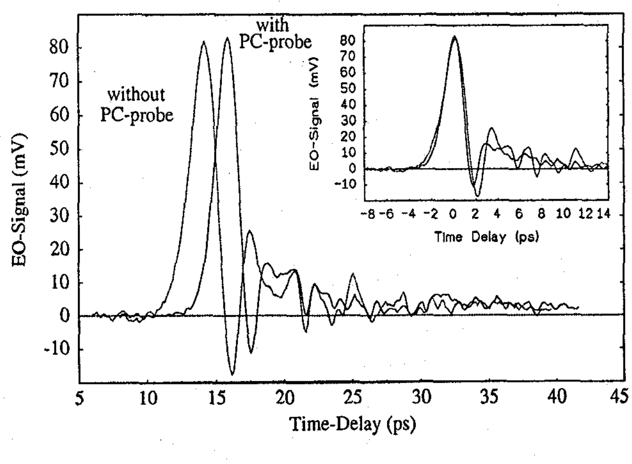

Fig. 5: Electro–optically detected electric pulses on a CPW with (—) and without (- - - -) a PC probe contacted to the CPW. In the inset, the peak amplitude of the pulses is shifted to zero time delay.

Waveforms are detected electro-optically[5] 1.92 mm away from the point of excitation (Fig. 5). The electric pulse remains undisturbed in shape when the PC probe is in full contact with the signal conductor 0.73 mm from the generation gap. The shift of 1.6 ps towards longer time delays is explained with a 15-% increase of the effective refractive index of the CPW by the sapphire substate of the PC probe itself (substrate width 1.33 mm).

In the last experiment we demonstrate that flexible PC probes are not only capable to detect but also to generate ps electric transients. For this reason, we contact the PC probe to the signal conductor at the open end of a 10 mm long CPW on GaAs-substrate (signal conductor width 52 μm, spacing 40 μm). In contrast to the experiments presented above, the gap of the flexible PC probe is biased and is illuminated by the pump laser pulse instead of the probe pulse. The electric transients launched on the CPW are detected via EO sampling technique[5] employing a $LiTaO_3$-crystal approx. 400 μm away from the PC switch.

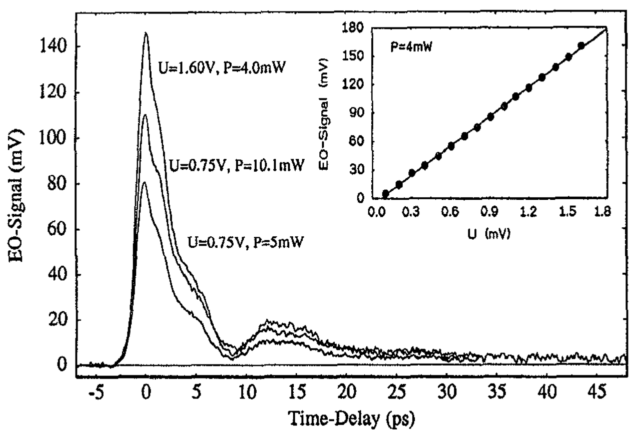

Fig. 6: Electro-optically detected electric transients generated by a PC probe on a CPW for various average pump pulse powers and bias voltages of the PC switch. In the inset: Peak amplitude of the electric signals for various bias voltages of the PC probe at constant pump power of 4 mW.

Figure 6 depicts electric transients launched on the CPW for various bias voltages (U) and average pump powers (P). The amplitude of the generated pulses rises linearly with increasing bias voltage (see inset of Fig. 6) and an electric pulse duration of 3.3 ps (FWHM) is obtained. The bump at approx. 14 ps delay is due to a reflexion of the electric pulse at the $LiTaO_3$ crystal. The reflected part of the electric pulse is subsequently reflected at the open end of the CPW and returns to the EO-crystal, where it is detected. This interpretation is corroborated by the observation, that the time delay between the initial signal and the reflexion increases when positioning the EO-crystal to larger distances away from the open end of the CPW (data not shown).

Conclusion

In conclusion, we have described in detail the fabrication of freely positionable PC probes and have investigated the main characteristics such as linearity, sensitivity, time resolution and invasiveness. We have shown that free-standing PC switches are suited as efficient ps-electric signal generators. This opens the way for high-frequency PC testing at any electrically accessible point on a circuit without the need for integration of switches into the chip.

References

1 J. Kim, S. Williamson, J. Nees, S.-I. Wakana, and J. Whitaker, Appl. Phys. Lett. **62**, 2268 (1993).

2 T. Pfeifer, H.-M. Heiliger, E. Stein von Kamienski, H. G. Roskos, and H. Kurz, J. Opt. Soc. Am. B **11**, 2547 (1994)

3 F. E. Doany, D. Grischkowsky, and C.-C. Chi, Appl. Phys. Lett. **50**, 460 (1987)

4 H. G. Roskos, Lithuan. J. Phys. **34** 175 (1994).

5 M. Y. Frankel, J. F. Whitaker, and G. Mourou, IEEE J. Quantum Electron. **28**, 2313 (1992)

6 D. H. Auston, "Picosecond Photoconductors", in *Picosecond Optoelectronic Devices*, C. H. Lee, ed., (Academic Press, Orlando, San Diego, New York, London, Toronto, Montreal, Sydney, Tokyo, 1984), p.73-117.