# THz Signal Generators Based on Lift-Off LT-GaAs on Transparent Substrates

**H.-M. Heiliger, M. Voßebürger, H. G. Roskos,**
**R. Hey†, K. Ploog†, and H. Kurz**

Institut für Halbleitertechnik II, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, D-52056 Aachen, Germany

†Paul-Drude Institut, Hausvogteiplatz 5-7, D-10117 Berlin, Germany

## Abstract

Low-temperature molecular-beam-epitaxy-(MBE)-grown GaAs (LT-GaAs) is recognized as a superior photoconductive material because of the combined advantages of high carrier mobility, short conductance lifetime and high dark resistivity. Here, LT-GaAs is employed for the fabrication of (sub)picosecond photoconductive switches for THz guided-wave and free-space-radiation applications. The switches are realized on LT-GaAs-on-glass and LT-GaAs-on-sapphire substrates after transfer of the LT-GaAs films via epitaxial lift-off (ELO) and van-der-Waals-bonding procedure from the GaAs growth substrate to glass or sapphire, respectively.

## 1. Introduction

Within the last few years, many publications have shown how to employ photoconductive (PC) Auston switches in the field of THz guided-wave and free-space-radiation applications [1-7]. These switches are most often realized either with LT-GaAs on semi-insulating GaAs or with ion-damaged (ID) silicon-on-sapphire (SOS) substrates because the ultrashort lifetime of photogenerated carriers of about 600 fs in both materials allows generation and detection of (sub)picosecond electric pulses. The choice of the best material for a specific application is based on the following criteria. On one hand, LT-GaAs has a much higher dark resistivity and superior charge carrier mobility compared to ID Si, which leads to larger breakdown fields, larger signal amplitudes and greater signal-to-noise ratios [3]. On the other hand, optically transparent sapphire makes switches on ID SOS much more flexible than those on LT-GaAs on GaAs because they can be illuminated from the front and the backside. Illumination from the back is necessary for freely positionable PC probes utilized in on-wafer testing of microelectronic devices (see, e.g., Fig. 1). Furthermore, as sapphire is an insulator, no charge carriers are generated when illuminated with light pulses in the visible or near-infrared wavelength regime (630 - 840 nm). With PC switches on LT-GaAs on GaAs substrate, electron-hole pairs can be photogenerated in the GaAs depending on the employed wavelength of light and the thickness of the LT-GaAs film (light absorption depth in GaAs at 630 nm: 250 nm, and at 840 nm: 1 $\mu$m [8]). The charge carriers generated in the GaAs substrate have a much longer conductance lifetime than the carriers photogenerated in the LT-GaAs epilayer above. Diffusive transport of the carriers induces background currents that make the alignment of the laser beams onto that switches in THz antennas and on-wafer probes difficult and additionally add to the noise level of the switches. The problem of substrate excitation is already known from early attempts to realize PC switches on single-crystalline Si substrate [9]. The large penetration of the laser light in Si led to a failure of this approach so that only switches based on Si derivatives with transparent insulating substrates such as SOS are in use today.

One can expect that optical-switching devices made from LT-GaAs on sapphire will combine the advantages of both systems, i.e., large-signal generation, optical transparency of the substrate and reduced noise levels. When, moreover, sapphire is exchanged for glass, the dielectric invasiveness of probes for high-frequency testing applications [4,5] is diminished additionally owing to the lower permittivity. Because of the small thermal conductivity, glass is limited to applications at low illumination power in order to avoid thermal destruction of the switches.

The realization of devices made from LT-GaAs on various substrates has become possible by the ELO technique in combination with van-der-Waals bonding [10]. Here, we report on the fabrication and characterization of (i) high-frequency on-wafer PC probes made from ELO LT-GaAs on glass for generation of picosecond electric pulses, and (ii) of PC dipole antennas made from ELO LT-GaAs on sapphire. Both glass and sapphire are suited for van-der-Waals bonding of ELO LT-GaAs and fulfill the requirements of being electric insulators with high optical transparency.

## 2. Device Fabrication

The PC material is grown by MBE on commercial semi-insulating <100> GaAs. The epitaxial layers consist of 100 nm sacrifical AlAs deposited at 550°C, and the 500-nm-thick LT-GaAs film grown at 200°C and annealed at 615°C for 15 minutes in an As-rich atmosphere. The ELO and bonding of LT-GaAs on glass and sapphire follow the procedure first presented by Yablonovitch et al. [10]. Small pieces (2 x 10 $mm^2$) are cut from the wafer, heated to 125°C and coated on top with Apiezon W (thickness: about 250 $\mu$m) for better handling of the LT-GaAs films after ELO. Care has to be taken to keep the edges of the samples free from Apiezon for the subsequent etch process where the LT-GaAs/Apiezon stack is lifted off by dissolving the AlAs layer in diluted (10%) HF acid at 0°C. The etch process lasts several hours. The LT-GaAs/Apiezon film is then rinsed in DI water, placed onto the glass or sapphire substrate and van-der-Waals bonded during a drying step at 85°C (duration: about half an hour). After removal of the Apiezon layer in $CHCl_3$ and cleaning in acetone and DI water, the LT-GaAs-on-insulator samples are ready for preparation of metal structures via optical lithography and metal lift-off. The metallization (50 nm Ti and 600 nm Au, deposited via electron-beam evaporation) is chosen to be rather thick to ensure good coverage of the 500-nm-high step from the transparent substrate to the LT-GaAs film.

# 3. Application of Lift-Off LT-GaAs Switches for High-Frequency PC Probes

PC probes are useful tools for the injection and time-resolved detection of picosecond electric pulses in microelectronic circuits [4]. They are realized as single-strip lines with a PC switch close to the end of the line. On the short arm of the line, a metallic probe tip facilitates contacting of the device under test (DUT). PC probes are operated in flip-chip geometry. As emphasized above, positioning and alignment as well as optical gating with ultrashort laser pulses impose the requirement of an optically transparent substrate.

The probes presented here utilize a 15-$\mu$m-wide metal-semiconductor-metal interdigitated electrode structure as PC switch (see inset of Fig. 1). The finger width and the spacing are about 3 $\mu$m. The overall length of the metallization is several mm. A 75-$\mu$m-high electrically conductive epoxy tip (25-$\mu$m-wide at the top) is located at the end of the short electrode [4].

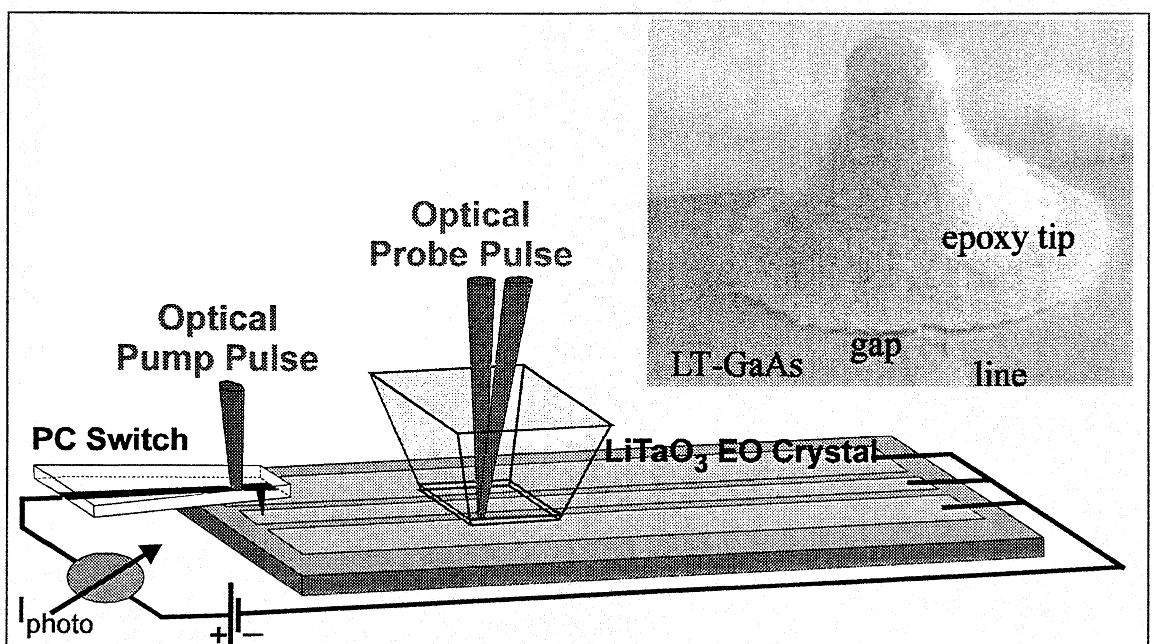


Fig. 1: Experimental setup with high-frequency PC probe for pulse injection and electro-optic tip for detection of the signals on the CPW. Inset: SEM micrograph of the interdigitated gap with an epoxy-tip on one electrode.

The high-frequency properties of the probe are tested with the help of a simple waveguide structure, as illustrated in Fig. 1. As a DUT, we use a 20-nm-Cr/400-nm-Au coplanar waveguide (CPW, signal conductor: 20 $\mu$m, spacing: 15 $\mu$m, length: 20 mm) fabricated by standard lift-off technique on high-resistivity (>2000 $\Omega$cm) Si substrate.

In the experiment, the tip of the probe is placed onto the signal conductor of the CPW (compare Fig. 1). Time-resolved optoelectronic characterization is performed with a 150-fs Ti:sapphire laser (wavelength: 780 nm, repetition rate: 76 MHz) in a pump-probe setup. The laser beam is split into two parts by a polarizing beam splitter, the pump beam for pulse generation in the probe, and the probe beam for electro-optic pulse detection with a $LiTaO_3$ crystal of dimensions $100 * 100 * 20\ \mu m^3$ placed above the CPW at a position approximately 700 $\mu$m from the excitation gap of the pulse generator. The two beams are time-delayed relative to each other via a stepper-driven translation stage. A lock-in detection scheme is employed to reduce the signal noise. The PC switch is biased at various voltages (5 - 50 V), while the optical power is kept constant (power density: 1.3 $kW/cm^2$). Fig. 2 depicts the measured waveforms normalized to the maximum. The shoulder in the pulse tail is due to a pulse reflection at the backside of the electro-optic crystal. The decay time of the pulses increases with increasing bias voltage and thus with increasing electric field across the switch. The temporal pulse width (full width at half maximum) at 5 V and 50 V is about 2.2 ps and 3.4 ps, respectively (for estimating the pulse width at 50 V bias, the shoulder is replaced by an exponential decay). The pulse width at low bias is comparable to that of pulses from SOS switches [4]. The shape of the pulses does not change when the incident laser power is reduced from 1 mW to 0.5 mW to 0.25 mW keeping the bias voltage at 50 V.

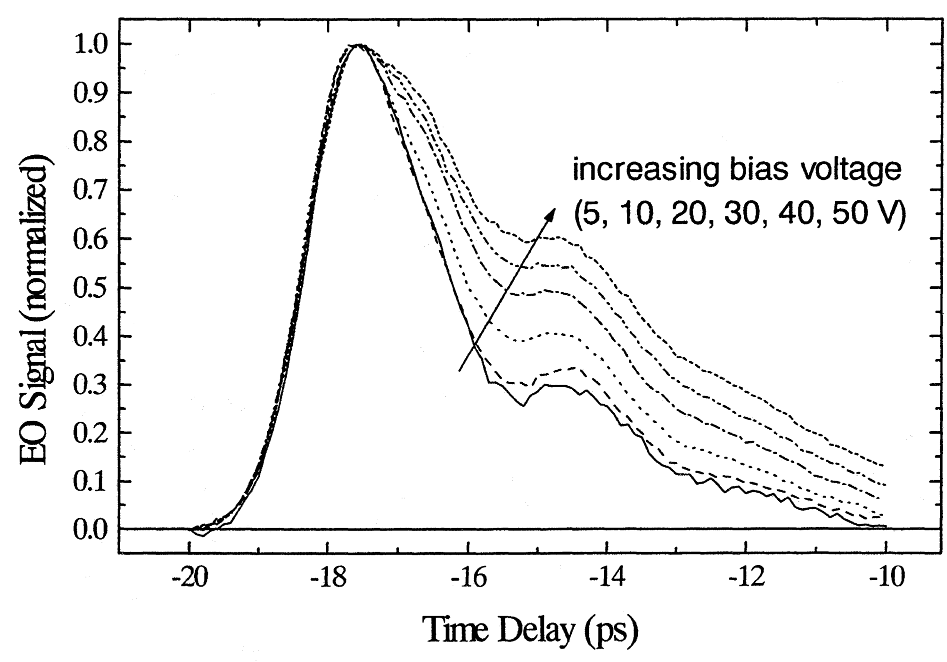


Fig. 2: Normalized signals detected electro-optically at a position 700 $\mu$m away from the excitation gap for various bias voltages.

The dependence of the pulse amplitude on the applied electric field is displayed in Fig. 3 (incident light power: 1 mW, photocurrent always less than 3 $\mu$A). The amplitude increases sublinear with voltage and seems to saturate at a voltage > 50 V. The maximum switched voltage is 400 mV at 50 V. With higher optical excitation power (3 mW) and optimized alignment (measured photocurrents: 16 $\mu$A), amplitudes as high as 2 V are achieved with the same probe. These pulses are broader (FWHM> 6 ps) but with a weaker voltage dependence of the broadening. The attainable amplitudes are significantly higher than those from SOS probes and are sufficient to investigate the large-signal behavior of a DUT up to several hundreds of GHz.

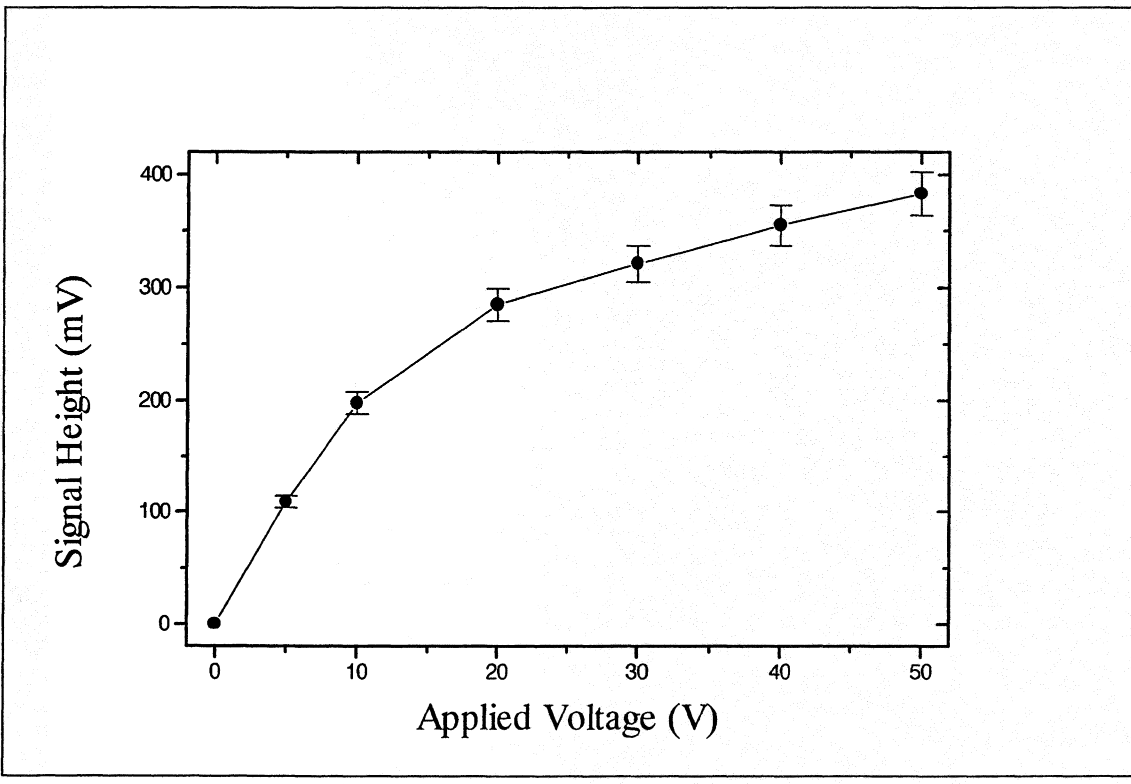


Fig. 3: Measured signal amplitudes for various bias voltages applied to the switch

Qualitatively similar behavior of LT-GaAs switches on GaAs substrate like the increasing decay time or the sublinear rise of the pulse amplitude with increasing electric field has been observed by Frankel et al. [1] indicating that the properties of the LT-GaAs remain unchanged during the ELO and bonding process. The pulse broadening has been explained in Ref. 1 by local heating at the high current densities that can contribute to the ionization of shallow carrier traps so that they are less efficient as recombination centers. Because of the low thermal conductivity of the glass, the local heating by the relatively small current density through the PC switch (peak density $< 2 * 10^5$ A/cm$^2$) might have a stronger influence on the LT-GaAs than with other substrates.

# 4. Application of Lift-off GaAs for the Fabrication of THz Antennas

Auston switches are not only applied for guided-wave purposes but also for the generation and detection of free-space THz radiation. PC antennas are the core element of time-resolved THz spectroscopy covering the frequency range from 50 GHz to 4 THz. The spectroscopy is used for the characterization of GHz electronic components, but has an even wider impact in the investigation of fundamental excitations in physics and chemistry in the energy range from 0.2 to 16 meV.

The ELO LT-GaAs antennas on sapphire introduced here consist of a 40-$\mu$m-long and 10-$\mu$m-wide dipole with a 6 $\mu$m slot in the center. The dipole arms are connected to a coplanar transmission line with 5 $\mu$m linewidth and 10 $\mu$m spacing. In contrast to the glass substrate of the photoconducting switches used in the electro-optic measurements discussed above, the antennas realized on sapphire as substrate allow operation at higher optical excitation densities because of the good thermal conductivity of sapphire.

For the characterization of the emission properties, the antennas are dc biased and excited from the backside (sapphire side) by 150 fs pulses from a Ti:sapphire laser with a wavelength of 768 nm. The excitation beam (150 mW average power) is focussed to a spot diameter of approximately 10 $\mu$m. The emitted radiation is collected with two off-axis paraboloidal mirrors and detected with an ID SOS antenna. While a hyperhemispherical substrate lens is glued to the detector antenna, no lens is attached to the emitter.

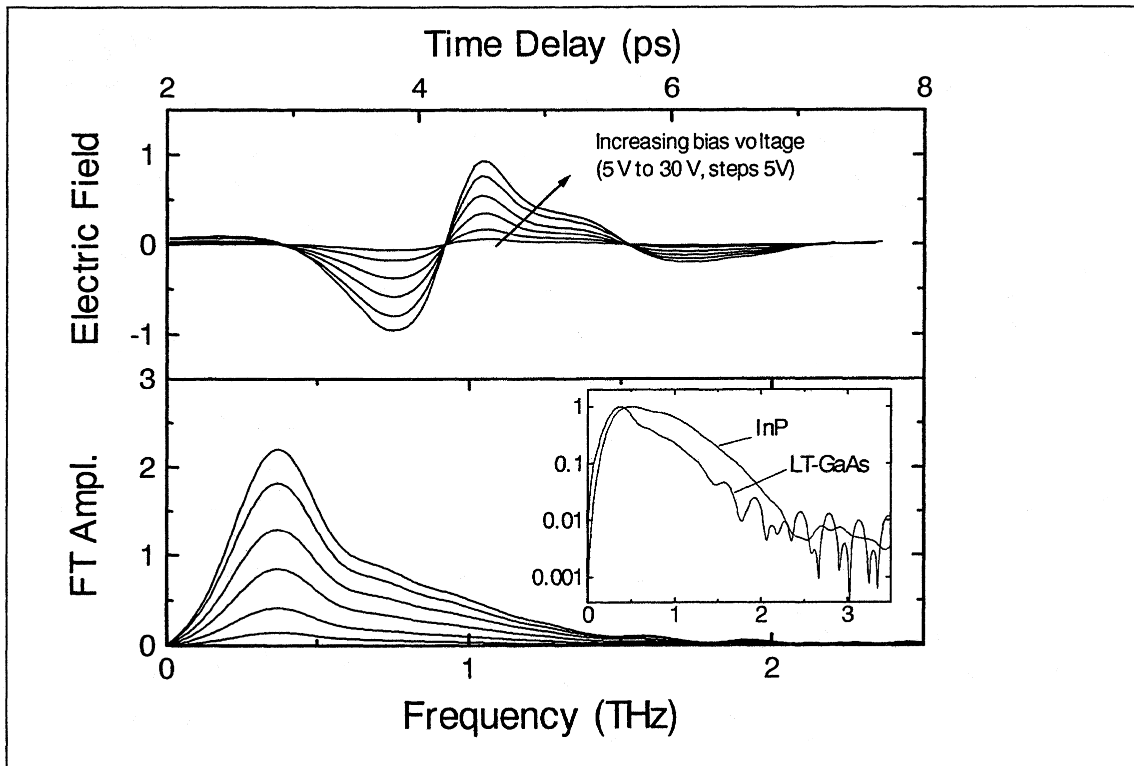


Fig. 4: Dependence of the emitted THz radiation on the bias voltage. In the upper part, the time-domain data are shown. Their Fourier transforms are displayed in the lower part. In the inset, the spectral sensitivity of the detector measured with an InP quasi-white-light emitter, is displayed.

Figure 4 displays detected THz transients obtained at various bias voltages. In the upper part of Fig. 4, time-domain data are presented. The electric field of the THz radiation shows an oscillation of one and a half cycles after optical excitation. The amplitude of the emitted electric field increases with increasing bias voltage without affecting the form of the transients. In the lower part of Fig. 4, the corresponding Fourier transforms are depicted. The shape of the spectra is independent of the applied voltage. The spectra peak at 0.35 THz. The peak is at lower frequencies than the maximum sensitivity of the

ID SOS detector. The spectral characteristics of the detector are calibrated with an InP surface emitter radiating with a quasi-white-light spectrum [11]. The detector response peaks at 0.5 THz. The spectra of the radiation from the LT-GaAs antenna are significantly weaker at the high-frequency side than expected from the spectral sensitivity of the detector. At 2.3 THz, the spectra of the LT-GaAs emitter reach the 40 dB point ($10^{-4}$ of the peak power).

The observation that the waveform of the THz transients does not change with field and that the amplitude rises linearly with the bias field seems to contrast with the change in shape and the sublinear bias dependence of the guided-wave signal of Fig. 2. The different behavior is explained with the different field regimes for the two measurements. The antenna characterization was performed for fields up to 50 kV/cm whereas the guided-wave probe was tested up to 170 kV/cm. The pulse amplitude of the probe has a linear field dependence up to 50 kV/cm in agreement with the behavior of the antenna. The THz signal should have a waveform given in first-order approximation by the time derivative of the guided-wave transients. Up to 50 kV/cm, the time derivative of the guided-wave signal hardly changes in accordance with the observed independence of the THz signal from the bias field.

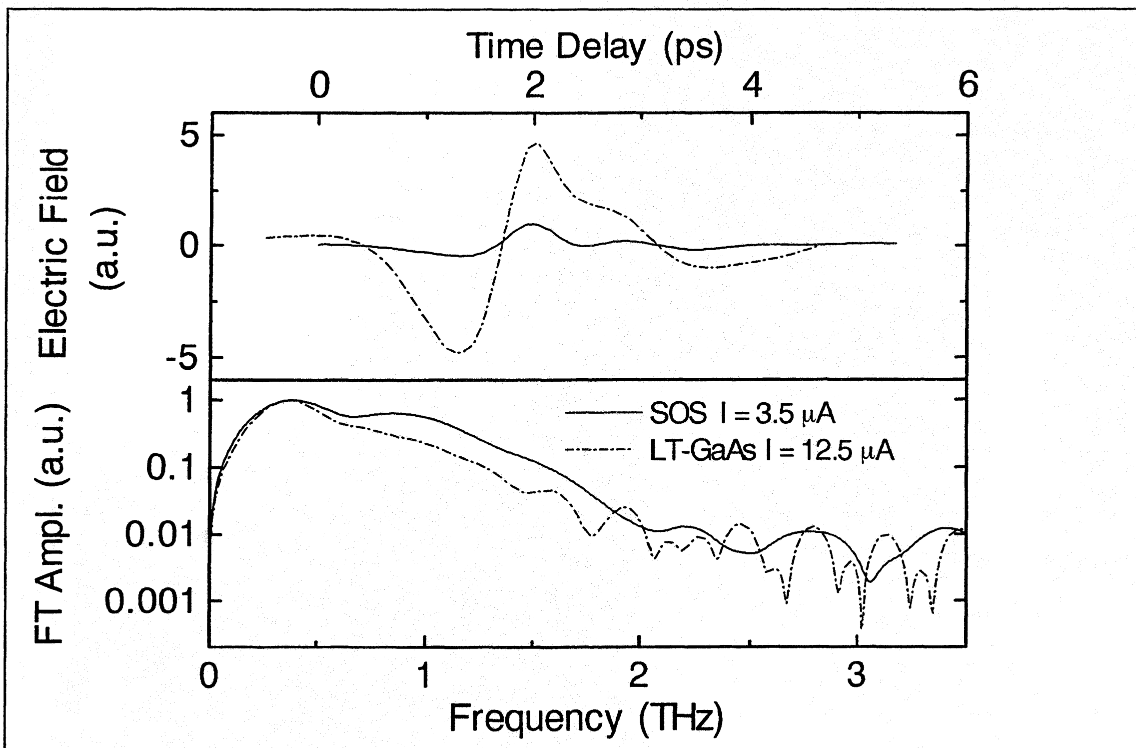


Fig. 5: Comparison of the emission efficiency of the ELO LT-GaAs-on-sapphire antenna with an ID SOS antenna under similar excitation properties. Upper part: time-domain data, lower part: normalized Fourier spectra.

In order to specify the emission efficiency of LT-GaAs antennas, an LT-GaAs antenna is tested in direct comparison with a standard ID SOS antenna. Both antennas are biased at 50 kV/cm, the incident optical power density is 160 kW/cm$^2$. The detected THz transients are displayed in Fig. 5. The ELO LT-GaAs antenna shows a five times higher amplitude than the ID SOS antenna. This is not explained with the weaker light absorption in ID Si as compared to GaAs because the absorption of ID Si is comparable to that of GaAs at the laser wavelength of 768 nm.

It should be mentioned that the ID SOS antenna is operated at a voltage which is already too high for a prolonged lifetime of the antenna. At these fields, it does not survive for more than a few hours as compared to average lifetimes of months at bias fields of 15 kV/cm. The destruction at fields above 15 kV/cm can generally be traced back to electromigration revealed by the telltale metallic shorts in the PC gap that are observed after antenna failure. The lifetime of LT-GaAs antennas, on the other hand, is not yet compromised at these operation conditions. Obviously, the activation of electromigration has a much higher threshold for the metallization on LT-GaAs as compared to that on ID SOS. The functional lifetime of LT-GaAs antennas is reduced to half an hour, when they are operated at fields of 120 kV/cm, although the regime of abrupt breakdown is not yet reached at the highest electric fields of the experiment of 200 kV/cm [1]. We estimate that a maximum applied electric field of 50-60 kV/cm should not be exceeded in day-to-day operation to ensure normal lifetimes (of months) of the antennas.

## 5. Conclusions

In summary, we have demonstrated application of lift-off LT-GaAs for the realization of photoconductive switches in both guided-wave probes for circuits testing as well as in microantennas for time-resolved free-space THz spectroscopy. The devices are tested as THz signal generators. The lift-off and van-der-Waals bonding process allows transfer of the LT-GaAs films to nearly any substrate of choice. For the guided-wave probes, optically transparent substrates, that allow backside illumination of the switch, are needed. Here, glass substrates with low dielectric constant are chosen to reduce the invasiveness of the probes. Although the low thermal conductivity of glass limits the optical power that can be used to drive the switch, voltages pulses as high as 2 V are generated. For the microantennas, sapphire is chosen as a substrate with good thermal conductivity. Compared to antennas realized with silicon-on-sapphire, much higher amplitudes of the emitted THz pulses are achieved. The amplitude advantage is a factor of five at the same bias fields. The LT-GaAs antennas can, however, be operated at much higher bias fields than the silicon-on-sapphire antennas because of the higher threshold for electromigration. Compared to LT-GaAs antennas fabricated directly on the GaAs growth substrates, the antennas on lift-off LT-GaAs are much easier to align optically because light absorption in the substrate and the concomitant background currents are eliminated.

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