High-Speed Photoconductive Switch Based on Low-Temperature GaAs Transferred on SiO_2–Si Substrate

Martin Mikulics, Xuemei Zheng, Roman Adam, Roman Sobolewski, and Peter Kordoš

***Abstract*—In this letter, we report high-speed photoconductive switches based on low-temperature (LT) grown GaAs on Si substrate. Epitaxially grown LT GaAs was separated from its substrate, transferred on an SiO_2-coated Si substrate and integrated with a transmission line. The 10×20-μm^2 switches exhibit high breakdown voltage and low dark currents ($<10^{-7}$ A at 100 V). The photoresponse at 810 nm shows electrical transients with $\sim$0.55-ps full-width at half-maximum and $\sim$0.37-ps decay time, both independent on the bias voltage up to the tested limit of 120 V. The photoresponse amplitude increases up to $\sim$0.7 V with increased bias and the signal bandwith is $\sim$500 GHz. The freestanding LT GaAs switches are best suited for ultrafast optoelectronic testing since they can be placed at virtually any point on the test circuit.**

***Index Terms*—Coplanar waveguide, gallium arsenide, liftoff technique, molecular beam epitaxy, photoconductive device, photodetector.**

I. Introduction

MOLECULAR-BEAM epitaxial (MBE) GaAs grown at low substrate temperature (LT GaAs) of about 200 °C–400 °C is a promising material for the preparation of ultrafast photoconductive switches [1] and broad-band photodetectors (PDs) [2], as well as tunable sources of terahertz radiation by photomixing [3]. Dynamic behavior of these devices is based on nonstoichiometric nature of LT GaAs accompanied with high density of defects resulting in low carrier lifetime. However, further improvements of the device performance are needed to be useful in applications. Therefore, various modifications in device configuration, like vertical-illuminated traveling wave (TW) [4] and resonant-cavity enhanced (RCE) [5] structures, have been demonstrated. Besides an increase of the absorption efficiency, one can simply overcome the problem of efficient light absorption versus critical LT GaAs thickness [6]. The major difficulties in the use of such PDs are efficient light coupling into the active region and higher requirements on the epitaxial growth. GaAs PDs with recessed metal contacts, which improve electric field distribution in the active region, have also been reported [7]. Another alternative to improving the properties of LT GaAs switches and PDs is the use of a host substrate. In such a way, some of the unwanted effects related to the native GaAs substrate can be suppressed or eliminated. Structures with LT GaAs transferred by liftoff technique onto optically transparent substrates like glass and sapphire have been reported [8], [9]. However, silicon substrate can be another alternative because of the possible integration of LT GaAs switches and PDs with advances in Si-based electronics.

In this letter, we demonstrate a high-speed photoconductive switch based on freestanding LT GaAs transferred on an SiO_2 coated Si substrate and integrated with a coplanar-strip (CPS) transmission line. Low dark currents, high breakdown voltage, subpicosecond response of up to 120 V dc bias, and the ability to place the switch at any chosen position at the host substrate indicate that the developed devices can be useful for femtosecond-pulse generation and on-chip ultrafast optoelectronic testing.

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II. Device Preparation

The device structures with LT GaAs active layer were grown on 2-in semi-insulating GaAs wafer by MBE technique using a Varian GEN-II equipment [2], [6]. They were prepared as follows: at first a 300-nm-thick AlAs layer was grown on top of the GaAs substrate, followed by a 0.5- to 1.5-μm-thick LT GaAs grown at the substrate temperature of 220 °C–250 °C (thermocouple reading only). The structures were in-situ isothermally annealed at $\sim$600 °C for 10 min under local As overpressure.

The device processing consisted of a multiple-step process in which LT GaAs layer was lifted from the GaAs native substrate and transferred on top of an SiO_2-coated Si substrate. Selective chemical etching of the AlAs layer ($HF : H_2O$, 1 : 9) was used to separate the LT GaAs layer from the GaAs substrate [10]. The separated LT GaAs with a featuring size from 10×10 to 150×150 μm^2 was then transferred on top of an SiO_2-coated Si substrate. Special care was taken to ensure that the contacting surfaces were exceptionally clean so that the LT GaAs would adhere to the SiO_2 through molecular bonding. To minimize height difference between the LT GaAs and the substrate surface, the Si substrates contain ion-etched "wells" prepositioned at the designated switch spots. Following the LT GaAs transfer, continuous CPS lines crossing the device were fabricated using Ti–Au evaporation and a standard liftoff technique. An SiO_2 interface layer ensures insulation of the LT GaAs and the CPS lines from Si substrate and improves absorption effciency in the LT GaAs. No antireflection coating of the LT GaAs surface was applied. A photograph of one of the prepared LT GaAs microswitches with an active area of 10×20 μm^2 placed in the 10-μm-wide CPS gap on SiO_2–Si substrate is shown in the inset of Fig. 1.

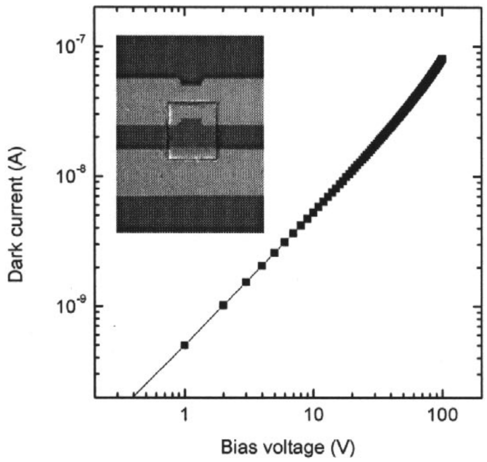

Fig. 1. Dark current as a function of applied bias for the LT GaAs microswitch on an SiO_2–Si substrate. Photograph of the microswitch and CPS lines with 10-μm gap is shown in the inset.

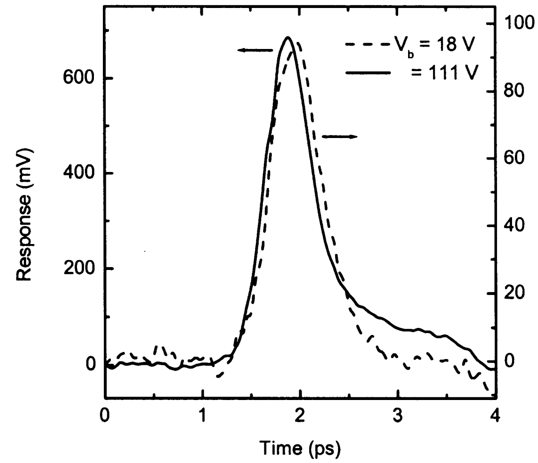

Fig. 2. Temporal response of the LT GaAs-on-SiO_2–Si microswitch at the applied bias voltage of 111 V (full line, left axis) and 18 V (dashed line, right axis).

III. Experimental Results

The current–voltage (I–V) characteristics in the dark of LT GaAs-on-SiO_2–Si microswitches were measured at first. They exhibit ohmic behavior in the wide range of biases, and low dark currents ($<10^{-7}$ A at 100 V), as shown in Fig. 1. Space-charge effects (i.e., nonohmic I–V region) are not observed, which indicates an efficient suppression of the high-field region near the contacts [11]. The breakdown voltage was estimated to be higher than 200 V, which confirms for LT GaAs known typical average breakdown field of $>$200 kV/cm.

The photoresponse of our LT GaAs-on-SiO_2–Si photoconductive microswitches was measured with an electrooptic sampling system using $\sim$110-fs-wide optical pulses from a Ti : sapphire laser at 810 nm. Both the excitation and sampling beams were focused with a long-focal-length (49 mm) microscope objective to $\sim$5-μm spots, positioned on the same place of 10-μm-wide CPS gap on LT GaAs. The electrical transients were measured at various dc bias voltages up to the tested limit of 120 V and laser beam excitation powers up to 3 mW. All records show the same full-width at half-maximum (FWHM) of $\sim$0.55 ps. Two examples for 18- and 111-V bias are shown in Fig. 2. Even more important is the observation that the response time ($1/e$ decay time) does not depend on the applied bias up to 120 V and is $\sim$0.37 ps (Fig. 3, right axis). This is in contradiction to the experiments on LT GaAs switches on GaAs substrates [1], [12] showing response time increase with applied bias voltage (e.g., $\sim$0.3 ps at $<$10 V and $\sim$5 ps at $\sim$50 V [12]). Data given in [12] are shown in Fig. 3 too, and because of different contact spacing an average electric field is used instead of applied bias voltage. The response-time increase was attributed to thermal effects [1] or to a reduction of the electron capture cross section with increased electric field as reported recently [12]. Another explanation might be that the high field region, which is located near the contacts, penetrates partially into the GaAs substrate at high biases and subsequently some "slow" carriers contribute to the photoresponse. However, this effect is absent in our structures and this underlines the advantage of presented LT GaAs-on-SiO_2–Si structures to achieve short response times even at high bias voltages.

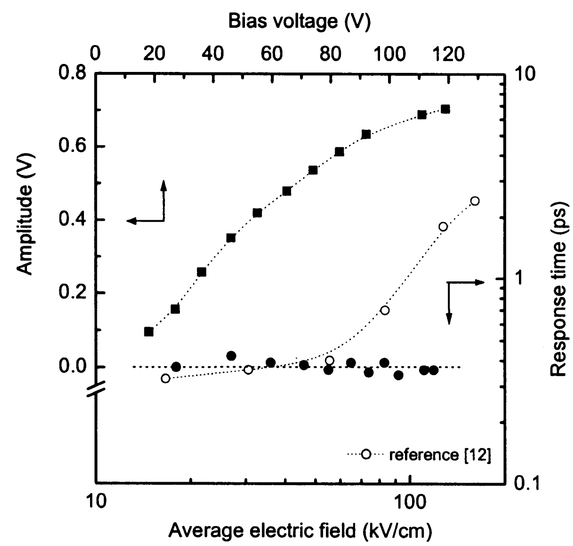

Fig. 3. Response time as a function of average electric field (lower and right axes) and amplitude as a function of applied bias voltage (upper and left axes) for the LT GaAs-on-SiO_2–Si microswitch (open dots are response times for LT GaAs-on-GaAs given in [12]).

The response amplitude as a function of applied bias, measured at the excitation power of $\sim$0.46 mW, is shown in Fig. 3 (left and upper axes). At low biases, the pulse amplitudes increase linearly with voltage, as expected. At higher biases, the amplitude saturates, indicating the decrease in the device collection efficiency. Similar dependencies have also been observed for other excitation powers and the saturated amplitudes exceeded 1 V at higher illumination powers.

Fig. 4 shows the frequency response of the LT GaAs-on-SiO_2–Si microswitch obtained from the uncorrected transient measurements using the fast Fourier transform (FFT). The FFT results for signals recorded at 27, 55, and 119 V bias voltage are shown as examples. The -3-dB bandwidth for the bias up to 119 V is about 500 GHz. This is nearly the same bandwidth as obtained for LT GaAs-on-GaAs substrate [2]. Some peaks observed in the frequency responses above $\sim$200 GHz are apparently due to nonoptimized CPS lines.

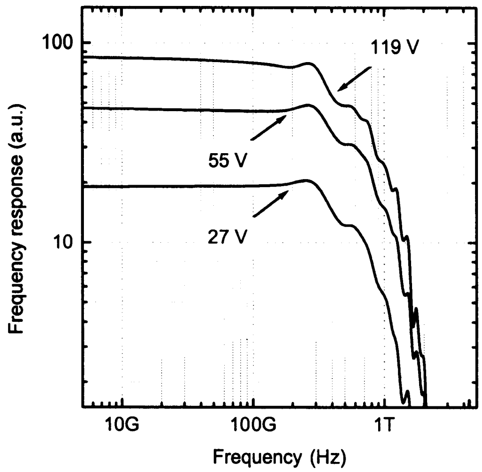

Fig. 4. Frequency response of the LT GaAs-on-SiO_2–Si microswitch at three different bias voltages.

IV. Conclusion

We have demonstrated a high-speed photoconductive switch on LT GaAs transferred on SiO_2–Si substrate and integrated with CPS lines. The devices show low dark currents ($<10^{-7}$ A at 100 V) and high breakdown voltages ($\sim$200 V). Photoresponses with $\sim$0.55-ps FWHM, $\sim$0.37-ps response time, and up to 0.7-V amplitudes for bias voltages up to 120 V were obtained. The decay time did not increase with the applied voltage, in contradiction to LT GaAs-on-GaAs switches. The $-$3-dB bandwidth of $\sim$500 GHz was obtained from as-measured transients using FFT. The developed technology and the properties of LT GaAs-on-SiO_2–Si switches indicate that these devices can be useful for high-voltage femtosecond-pulse generation and on-chip ultrafast optoelectronic testing.

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