

Fabrication and subpicosecond optical response of low-temperature-grown GaAs freestanding photoconductive devices

R. Adam,^{a)} M. Mikulics, A. Förster, J. Schelten, M. Siegel, and P. Kordoš
Institute of Thin Films and Interfaces, Research Center Jülich, D-52425 Jülich, Germany

X. Zheng, S. Wu,^{b)} and R. Sobolewski^{c)}
*Department of Electrical and Computer Engineering and the Laboratory for Laser Energetics,
 University of Rochester, Rochester, New York 14627-0231*

(Received 23 July 2002; accepted 10 September 2002)

We have fabricated and tested *freestanding* low-temperature-grown GaAs photoconducting devices exhibiting subpicosecond photoresponse. The epitaxially grown thin-film microswitches were transferred on top of sapphire and Si/SiO₂ substrates and integrated with Ti/Au coplanar strip transmission lines. Our devices exhibited above 200 V breakdown voltages and dark currents at 100 V below 3×10^{-7} A. The photoresponse of our microswitches was measured using electro-optic sampling technique with 100-fs-wide laser pulses at wavelengths of 810 nm and 405 nm as the excitation sources. For 810-nm excitation, we measured 0.55-ps-wide electrical transients with voltage amplitudes of up to 1.3 V. The ultraviolet excitation resulted in 1.35-ps-wide transients due to the hot carriers generation and intraband relaxation. © 2002 American Institute of Physics. [DOI: 10.1063/1.1518159]

Low-temperature-grown GaAs (LT-GaAs) thin films exhibit subpicosecond relaxation time of photogenerated carriers¹ and resistivity on the order of $\rho > 10^8 \Omega \text{ cm}^{-1}$,^{2,3} making them the material of choice for fabrication of ultrafast photodetectors.⁴ Typically, LT-GaAs films are grown in the temperature range 200–300 °C, followed by rapid annealing at 600 °C.^{3,5} As was first reported by Yablonovitch *et al.*,^{6,7} the AlAs grown under the LT-GaAs film enables selective AlAs chemical etching and results in epitaxial lift-off of the LT-GaAs layer. This procedure allows for the *freestanding* LT-GaAs film to be removed from the native GaAs substrate and transferred on top of a variety of nonepitaxial substrates for material and device characterization.^{7–10} Bonding between the LT-GaAs and the new substrate surface is established through the intermolecular Van der Waals force. Excellent adhesion and durability of the *freestanding* LT-GaAs was demonstrated by device patterning both before¹¹ and after¹² the film transfer on top of sapphire or glass substrates. We must stress, however, that for successful LT-GaAs integration into practical electronic or optoelectronic circuits, we need not only a robust technique for a reliable LT-GaAs liftoff, transfer, and bonding, but also the size of the transferred structure must be microscopic, comparable with the size of the components of the circuits.

The aim of this letter is to present fabrication and optical properties of *freestanding* micrometer-size LT-GaAs devices, integrated into circuits fabricated on sapphire and Si/SiO₂ substrates. Our microswitches can serve as, e.g., femtosecond (THz bandwidth) electrical pulse generators, located at a

prescribed position on any electronic or optoelectronic circuit.

Our devices were fabricated using molecular-beam epitaxy. We started with a 300-nm-thick layer of AlAs on top of the GaAs substrate, followed by a 500-nm- to 1.5- μm -thick LT-GaAs film grown in the temperature range 200–250 °C.⁵ The AlAs/LT-GaAs bilayer was subsequently patterned by photolithography and ion-beam etching to form a set of LT-GaAs microswitches, featuring sizes from 10 $\mu\text{m} \times 10 \mu\text{m}$ to 150 $\mu\text{m} \times 150 \mu\text{m}$. The LT-GaAs devices were next lifted from the GaAs substrate by selective chemical etching of the AlAs layer in the diluted HF solution (HF:H₂O/1:9). After cleaning in deionized water, a selected microswitch was transferred on top of a chosen substrate using a metallic tip, electrostatically charged and electrically isolated from the ground. To minimize height difference between the switch and the substrate surfaces, our substrates contained 500-nm-deep, ion-etched “wells” prepositioned at the designated microswitch spots. Following the microswitch transfer, continuous coplanar strip (CPS) transmission lines crossing our devices were fabricated using Ti/Au deposition and a standard lift-off technique. A micrograph of one of our devices is shown in Fig. 1.

Figure 2 shows typical current–voltage (I – V) characteristics of *freestanding* LT-GaAs transferred on top of a sapphire and Si/SiO₂ substrates, as well as, for *as-grown* LT-GaAs on native GaAs substrate, measured in the dark. The *as-grown* samples exhibit ohmic dependence up to ~ 10 V and at higher bias nonlinear behavior is observed. On the other hand, the *freestanding* devices show ohmic behavior in the whole range of applied voltages up to 200 V (corresponding to average electric field of 200 kV/cm). Furthermore, Fig. 2 demonstrates that our *freestanding* structures exhibit more than a ten-fold decrease of the dark current as compared to the *as-grown* devices, and they show no sign of electrical breakdown up to 200 V of dc bias. We ascribe this

^{a)}Author to whom correspondence should be addressed; electronic mail: r.adam@fz-juelich.de

^{b)}Also at the Department of Physics, University of Rochester, Rochester, NY 14627.

^{c)}Also at the Institute of Physics, Polish Academy of Sciences, PL-02668 Warszawa, Poland.

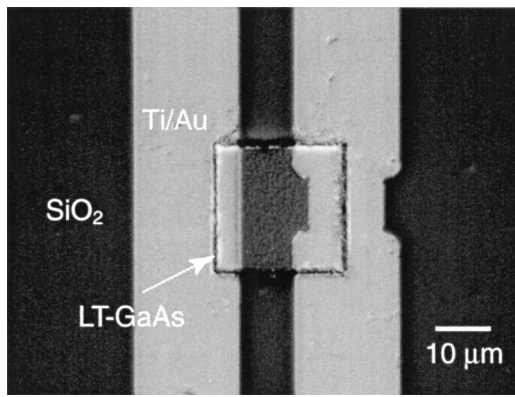


FIG. 1. Photograph of an Au/Ti CPS transmission line with a $20\text{ }\mu\text{m}\times 20\text{ }\mu\text{m}$ LT-GaAs microswitch placed in the CPS gap.

improved performance to the substantially higher band gap energy of sapphire and SiO_2 ($E_g^{\text{sap}}=9.0\text{ eV}$, $E_g^{\text{SiO}_2}\sim 8.0\text{ eV}$) as compared to the native GaAs substrate ($E_g^{\text{GaAs}}=1.42\text{ eV}$). The substrates, though, have relatively poor thermal conductivity at room temperature ($\alpha^{\text{sap}}\approx 0.35\text{ W cm}^{-1}\text{ K}^{-1}$, $\alpha^{\text{SiO}_2}\approx 0.14\text{ W cm}^{-1}\text{ K}^{-1}$, and $\alpha^{\text{GaAs}}\approx 0.59\text{ W cm}^{-1}\text{ K}^{-1}$). Thus, the further improvement in room-temperature performance of our *freestanding* LT-GaAs devices (e.g., higher device biasing and increased optical illumination power) can be achieved by the film transfer on top of a substrates with high α . On the other hand, sapphire exhibits extremely high α at low temperatures ($\alpha^{\text{sap}}\sim 100\text{ W cm}^{-1}\text{ K}^{-1}$ at 20 K) and is an ideal choice for cryogenic devices. LT-GaAs coupling with Si substrates is attractive as well, since it offers the combination of good thermal conductivity of Si ($\alpha^{\text{Si}}\approx 1.60\text{ W cm}^{-1}\text{ K}^{-1}$) and a large range of integration options with existing electronic devices.

Photoresponse of our *freestanding* LT-GaAs microswitches was measured using 100-fs-wide, optical pulses from Ti:Sapphire laser at 405-nm and 810-nm wavelength. Electrical transients were recorded with the help of an electro-optic sampling system, featuring $\sim 300\text{ fs}$ temporal resolution.¹³ The transients were sampled at the spot located only $\sim 10\text{ }\mu\text{m}$ away from the device. Thus, the signal distortion caused by pulse dispersion effects in the CPS line was minimized enabling the measurement of near-to-intrinsic carrier dynamics in our LT-GaAs films. The time-resolved pho-

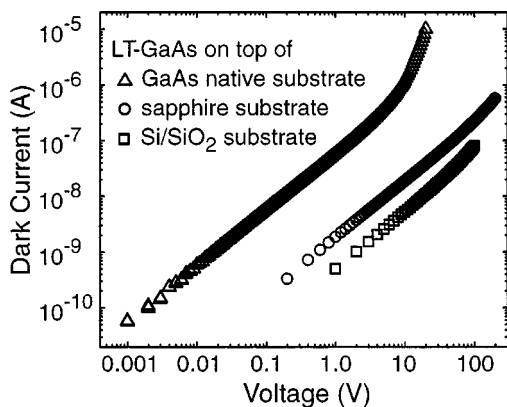


FIG. 2. I - V characteristics of an *as-grown* LT-GaAs-on-GaAs device and the LT-GaAs microswitch transferred on top of the sapphire and Si/SiO_2 substrates.

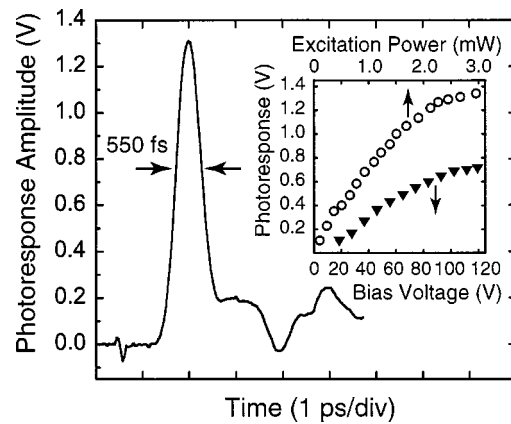


FIG. 3. 0.55-ps-FWHM photoresponse of a *freestanding* LT-GaAs switch exposed to 100-fs-wide, 810-nm-wavelength optical pulses. The inset shows the photoresponse amplitude as functions of V_{dc} and P_{ex} at fixed $P_{\text{ex}}=0.46\text{ mW}$ and fixed $V_{\text{dc}}=92.2\text{ V}$, respectively.

toresponse signal of our *freestanding* LT-GaAs switch transferred on the Si/SiO_2 substrate and illuminated by 810-nm photons is shown in Fig. 3. The transient exhibits a 550-fs full-width-at-half-maximum (FWHM) with 380-fs rise time and 400-fs carrier relaxation time obtained from signal amplitude drop to its $1/e$ value. The inset of Fig. 3 shows the photoresponse amplitude as functions of V_{dc} and P_{ex} with fixed $P_{\text{ex}}=0.46\text{ mW}$ and $V_{\text{dc}}=92.2\text{ V}$, respectively. We observe that both curves start with near-to-linear dependence and gradually reach saturation. The saturated photoresponse amplitude at constant $V_{\text{dc}}=92.2\text{ V}$ was $\sim 1.3\text{ V}$ for $P_{\text{ex}}>2.5\text{ mW}$. At low P_{ex} levels, the device voltage responsivity, defined as the ratio of photoresponse voltage amplitude to the corresponding photoexcitation power P_{ex} exceeds 10^3 V/W .

The 405-nm-wavelength excitation beam was obtained by frequency doubling the 810-nm-wavelength laser pulses. The LT-GaAs microswitch photoresponses were then recorded for several V_{dc} ranging from 18.5 to 119.1 V at fixed $P_{\text{ex}}=0.87\text{ mW}$. The normalized photoresponse signals at $V_{\text{dc}}=26.89\text{ V}$ and $V_{\text{dc}}=110.1\text{ V}$ are shown in Fig. 4. In all cases, the signal FWHM is equal to 1.35 ps, substantially wider than for 810-nm photoexcitation. In addition, we observe a signal trailing shoulder that grows with the increase of V_{dc} . In Ref. 14, the authors attributed the shoulder-growth

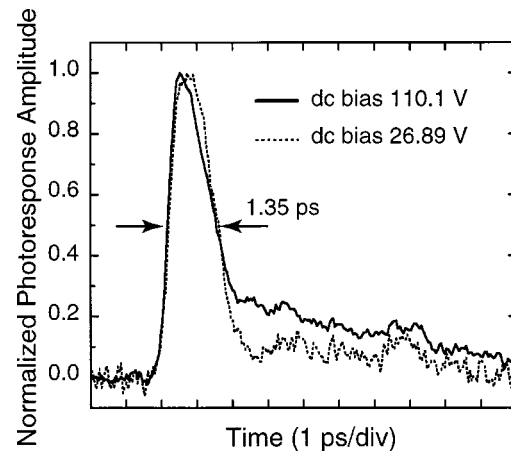


FIG. 4. Normalized photoresponse of a *freestanding* LT-GaAs switch exposed to 100-fs-wide, 405-nm-wavelength optical pulses for dc bias 26.89 V and 110.1 V.

effect to generation of additional carriers due to local heating and to limited effectiveness of recombination centers due to the ionization of carrier traps. Both latter effects could contribute to the trailing shoulder increase in our photoresponse signal at higher dc biases. Regardless of the dc bias, 405-nm excitation (3.0 eV) generates a population of hot carriers, well above the GaAs bandedge. Longer photoresponse time at UV excitation can be, therefore, attributed to intraband hot carrier relaxation.

In conclusion, we selectively etched $20\text{ }\mu\text{m}\times 20\text{ }\mu\text{m}$ LT-GaAs thin-film square pieces and transferred them on top of sapphire and Si/SiO₂ substrates. The thin films were, subsequently, integrated with Ti/Au CPS transmission lines, forming *freestanding* photoconductive microswitches. The *freestanding* devices exhibited ten-fold lower dark currents and higher breakdown voltages, as compared to the devices patterned on native GaAs substrates. EO sampling measurements showed 0.55-ps- and 1.35-ps-wide response at 810-nm- and 405-nm-wavelength excitations, respectively, with up to 1.3 V photoresponse amplitude and above 10^3 V/W responsivity. The ultraviolet excitation resulted in a significantly longer photoresponse, due to the additional intraband relaxation of hot carriers excited $\sim 1.5\text{ eV}$ above GaAs bandedge. The *freestanding* LT-GaAs microswitches, reported herein, are suitable for hybrid optoelectronic applications, as well as for on-chip femtosecond-pulse generators, since they can be placed at any chosen position of the test circuit.

This work was supported by the NSF (Grant No. INT-0078949), the ONR (Grant No. N00014-02-1-0026), and by Corning Inc.

- ¹P. Kordoš, A. Förster, M. Marso, and F. Rüders, *Electron. Lett.* **34**, 119 (1998).
- ²D. C. Look, *Thin Solid Films* **231**, 61 (1993).
- ³P. Kordoš, M. Marso, A. Förster, J. Darmo, J. Betko, and G. Nimtz, *Appl. Phys. Lett.* **71**, 1118 (1997).
- ⁴J. F. Whitaker, *Mater. Sci. Eng., B* **22**, 61 (1993).
- ⁵J. Betko, M. Morvic, J. Novak, A. Förster, and P. Kordoš, *J. Appl. Phys.* **86**, 6243 (1999).
- ⁶E. Yablonovitch, T. Gmitter, J. P. Harbison, and R. Bhat, *Appl. Phys. Lett.* **51**, 2222 (1987).
- ⁷E. Yablonovitch, D. M. Hwang, T. J. Gmitter, L. T. Florez, and J. P. Harbison, *Appl. Phys. Lett.* **56**, 2419 (1990).
- ⁸J. Novak, M. Morvic, J. Betko, A. Förster, and P. Kordoš, *Mater. Sci. Eng., B* **40**, 58 (1996).
- ⁹D.-S. Jiang, X.-P. Li, B.-Q. Sun, and H.-X. Han, *J. Phys. D* **32**, 629 (1999).
- ¹⁰Y. Sasaki, T. Katayama, T. Koishi, K. Shibahara, S. Yokoyama, S. Miyazaki, and M. Hirose, *J. Electrochem. Soc.* **146**, 710 (1999).
- ¹¹H.-M. Heiliger, M. Vöseburger, H. G. Roskos, H. Kurz, R. Hey, and K. Ploog, *Appl. Phys. Lett.* **69**, 2903 (1996).
- ¹²U. D. Keil, J. M. Hvam, S. Tautz, S. U. Dankowski, P. Kiesel, and G. H. Döhler, *Appl. Phys. Lett.* **70**, 72 (1996).
- ¹³M. Lindgren, M. Curie, C. Williams, T. Y. Hsiang, P. M. Fauchet, R. Sobolewski, S. H. Moffat, R. A. Hughes, J. S. Preston, and F. A. Hegman, *IEEE J. Sel. Top. Quantum Electron.* **2**, 668 (1996).
- ¹⁴M. Y. Frankel, J. F. Whitaker, G. A. Mourou, F. W. Smith, and A. R. Calawa, *IEEE Trans. Electron Devices* **37**, 2493 (1990).