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

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Low-temperature-grown GaAs (LT-GaAs) thin films exhibit subpicosecond relaxation time of photogenerated carriers and resistivity on the order of \( \rho > 10^8 \Omega \text{cm}^{-1} \), making them the material of choice for fabrication of ultrafast photodetectors. Typically, LT-GaAs films are grown in the temperature range 200–300 °C, followed by rapid annealing at 600 °C. As was first reported by Yablonovitch et al., the AlAs grown under the LT-GaAs film enables selective AlAs chemical etching and results in epitaxial liftoff 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. 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 were demonstrated by device patterning both before and after 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/SiO

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-thick LT-GaAs film grown in the temperature range 200–250 °C. 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:H\(_2\)O/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/SiO

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
improved performance to the substantially higher band gap energy of sapphire and SiO$_2$ ($E_g^{\text{sapphire}}=9.0$ eV, $E_g^{\text{SiO}_2}=8.0$ eV) as compared to the native GaAs substrate ($E_g^{\text{GaAs}}=1.42$ eV).

The substrates, though, have relatively poor thermal conductivity at room temperature ($a_{\text{sapphire}}' = 0.35$ W cm$^{-1}$ K$^{-1}$, $a_{\text{SiO}_2} = 0.14$ W cm$^{-1}$ K$^{-1}$, and $a_{\text{GaAs}} = 0.59$ W cm$^{-1}$ 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 substrates with high $a$. On the other hand, sapphire exhibits extremely high $\alpha$ at low temperatures ($\alpha_{\text{supp}} = 100$ W cm$^{-1}$ 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 ($a_{\text{Si}} = 1.60$ W cm$^{-1}$ 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 300 fs temporal resolution. The transients were sampled at the spot located only ~10 μm 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 photoresponse 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 $P_{ex}$ at fixed $P_{ex} = 0.46$ mW and $V_{dc} = 92.2$ V, respectively. We observe that both curves start with near-to-linear dependence and gradually reach saturation. The saturated photoresponse amplitude at constant $V_{dc} = 92.2$ V was ~1.3 V for $P_{ex} > 2.5$ 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 $P_{ex} = 0.87$ mW. The normalized photoresponse signals at $V_{dc} = 26.89$ V and $V_{dc} = 110.1$ V are shown in Fig. 4. In all cases, the signal FWHM is equal to 1.35 ps, substantially wider then 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...
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 \( \mu m \times 20 \mu m \) LT-GaAs thin-film square pieces and transferred them on top of sapphire and Si/SiO\(_2\) 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 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.

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