Low-temperature-grown gallium arsenide photoconductors with subpicosecond carrier lifetime and photoresponse reaching 25 mA/W under 1550 nm CW excitation

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C. Tannoury, M. Billet, C. Coinon, J-F. Lampin and E. Peytavit✉

The authors show in this Letter that photoconductors based on GaAs grown at low temperatures can exhibit photoresponses as high as 25 mA/W under continuous-wave 1550-nm-wavelength illumination. It is achieved by using an optical Fabry–Pérot cavity in order to improve the external quantum efficiency and by decreasing the post-growth annealing temperature down-to 450°C.

Introduction: Low-temperature-grown GaAs (LT-GaAs) photoconductors have served as THz sources or detectors in time-domain THz spectroscopy systems based on Ti: Sa mode-locked lasers operating around 800 nm [1]. They have also been used as photoconductive switches to sample millimetre wave signals [2, 3], as optoelectronic homodyne mixers in CW THz spectroscopy systems [4] and also as optoelectronic heterodyne mixers in THz detectors [5, 6]. We have recently shown that LT-GaAs ultrafast photoconductors can operate at $\lambda = 1550$ nm, despite a photon energy $E_{ph} \approx 0.75$ eV, i.e. lower than the energy gap of GaAs ($E_g = 1.42$ eV), by placing the LT-GaAs layer inside an optical resonant cavity [7]. This photoconductor has been then successfully used to sub-sample continuous waves at frequencies up to 300 GHz, demonstrating a sub-picosecond response time of photocurrents generated by 1550 nm illumination [8]. However, the much higher dark resistivity of LT-GaAs material (>10^3 kΩ cm) in comparison with LT-InGaAs/InAlAs multilayers material [9] or Fe-doped InGaAs layers [10] (<2 kΩ cm) employed in 1550-nm ultrafast photoconductors is far from compensating the low photoresponse despite the use of an optical cavity (≈ 1 mA/W under CW illumination [7]).

These first results have been obtained by using an LT-GaAs layer grown at a temperature of 250 ± 5°C and annealed at 580°C during 60 s. The post-grown annealing is performed in order to decrease the number of point defects (As_{Ga}, As_i, V_{Ga}) related to the incorporation of excess arsenic in the layer by forming As clusters. It has been demonstrated several times that it leads mainly to a higher dark resistivity, a lower sub-bandgap absorption [11] and a slight increase of the carrier-lifetime. In this Letter, we show that a photoresponse under CW illumination reaching 25 mA/W can be achieved by decreasing the post-growth annealing temperature down to 450°C. This is 25% of the value obtained using the same type of resonant-cavity-enhanced LT-GaAs photoconductor under 800-nm-wavelength illumination. Under this condition, a dark resistivity of 200 kΩ cm has been measured, which is still two orders of magnitude greater than that of best InGaAs-based ultrafast photoconductive materials [10]. In addition, a clear dependence of the photoresponse and dark resistivity on the post-annealing temperature is shown in the temperature range 450–580°C.

Optical cavity design: As shown schematically in Fig. 1*a*, the LT-GaAs photoconductors designed for 1550 nm operation consist of an optical cavity formed by an LT-GaAs thin layer of thickness $t = 450$ nm, sandwiched between two gold layers which are used at the same time as contact electrodes and cavity mirrors. The top mirror is a nanostructured optical gold grating of thickness $h = 300$ nm, sub-wavelength periodicity $p = 900$ nm, and slit width $a = 500$ nm. This was designed using a rigorous coupled-wave analysis (RCWA) in order to excite a Fabry–Pérot (FP) resonance for $t = 450$ nm under 1550 nm illumination (polarisation parallel to the grating direction as shown Fig. 1*a*) [7].

Epitaxial growth and fabrication: The samples were fabricated using the following procedure: starting from a 450-μm-thick semi-insulating GaAs substrate, a 0.1-μm-thick GaInP etch-stop layer was grown by gas-source molecular beam epitaxy (GS-MBE) followed by a 500-nm-thick layer of low temperature grown (250°C) GaAs. The GaAs wafer is subsequently cleaved into four pieces, which are annealed at temperature $T_A = 450$, 500, 540 and 580°C, respectively. Four different samples (S_1, S_2, S_3, S_4) were then processed. On each one, the buried gold layer shown in Fig. 1*a* was obtained by transferring the LT-GaAs epitaxial layers onto 2-in.-diameter silicon wafer. This is done by using an Au–Au thermocompression layer bonding technique [7]. The gold grating was patterned on the LT-GaAs layer by using electron lithography, electron beam evaporation, and lift-off techniques. As shown in the SEM picture of Fig. 1*b*, test structures for photocurrent measurement consist of a 60 × 55 μm^2 area optically opaque Au contact pad and a 60 × 75 μm^2 area array of 300-nm-thick Au electrodes ($p = 900$ nm and $a = 500$ nm).

Electron dynamics characterisation: Fig. 2 shows the time-resolved photoreflectance measurements performed after the epitaxial layer transfer using 200 fs optical pulses at a wavelength of $\lambda = 820$ nm provided by a Ti: Sapphire laser. It shows clearly an electronic carrier trapping lying in the subpicosecond time scale suitable for THz applications. It is worth noting that an accurate extraction of carrier lifetime from the rough data is not easily achievable in this experiment because of interferences induced by the metallic back mirror.

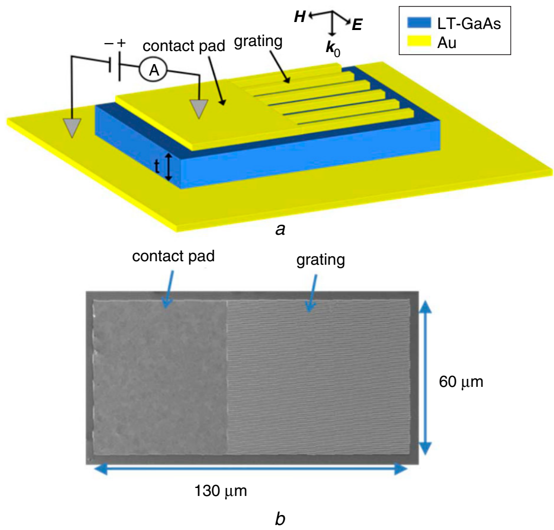

Fig. 1 *Optical cavity LT-GaAs photoconductor*

a Schematic view of the resonant cavity photoconductors
b SEM picture of the dc photocurrent test devices

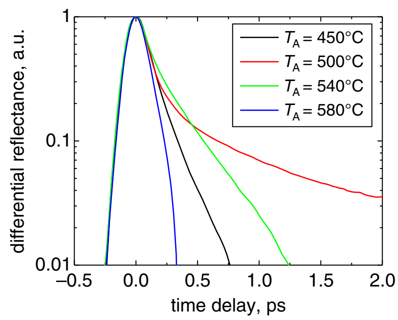

Fig. 2 *Time-resolved photoreflectance measurements obtained on the LT-GaAs layers grown at 250°C and annealed at T_A = 450, 500, 540 and 580°C*

Dark resistivity and photoresponse measurements: First, the dependence of the dark resistivity ρ_d on the post-growth annealing temperature (see Fig. 3) was evaluated by measuring the dark currents on the four samples as a function of bias voltage (see inset of Fig. 3) and by calculating the slope of the current–voltage characteristic at zero bias voltage ($dI/dV = G_0$). The dark resistivity ρ_d is then calculated by assuming a 1D resistor of thickness $t = 450$ nm and an area $A = 60 \times 130\ \mu m^2$

$$\rho_d = \frac{A}{t \times G_0} \tag{1}$$

The photoresponse experiment was conducted using a fibre coupled external cavity laser emitting at $\lambda = 1550$ nm and focused through a cleaved fibre (for S_2, S_4) or a lensed fibre (for S_1, S_3) into a Gaussian spot of mode field diameter, $w \approx 10.5$ μm and $w \approx 2.5$ μm, respectively. It is worth noting that the spot width variation is unlikely to affect the results of this study since it has been previously shown that under CW illumination, in linear absorption regime, the spot diameter does not influence the photoresponse of the optical cavity photoconductors as far it is smaller than the active area [7]. The polarisation is adjusted by means of a fibre polarisation controller in order to align the electric field orthogonally to the grating electrodes. Fig. 4 shows the photoresponse (R) as a function of bias voltage obtained for the four different samples for a CW optical power $P_{opt} = 5$ mW. The photoresponse is deduced from the photocurrent I_{ph} as follows:

$$R(V) = \frac{I_{ph}(V)}{P_{opt}} \tag{2}$$

where I_{ph} is given by the difference between the current obtained under illumination I_{tot} and the dark current I_d: $I_{ph} = I_{tot} - I_d$. It can be seen that at the maximum bias voltage, both sample S_1 ($T_A = 450°C$) and sample S_2 ($T_A = 500°C$) show a photoresponse approximately ten times larger than the sample S_4 ($T_A = 580°C$). In addition, we calculated that the slope of the photoresponse–voltage curve of S_1at zero bias voltage is also ten times higher than that of S_4 (17 mS/W versus 1.7 mS/W). This last figure is also essential in THz optoelectronics applications since it shows the capability of a photoconductor to reach a value of photoconductance sufficiently high to achieve reasonable impedance matching with free space antennas or standard 50-Ω input impedance of RF waveguides instruments. The increase of photoresponse is seen as a consequence of the increase of the optical absorption in the LT-GaAs layer due to a higher defect density. By comparison with the photoresponse obtained in our previous works at 1550 and 780 nm [7, 12], we can estimate that in S_1, ∼25% of the incoming light is absorbed in the active layer and that the absorption depth is as low as ∼30 µm in the LT-GaAs layer annealed at 450°C.

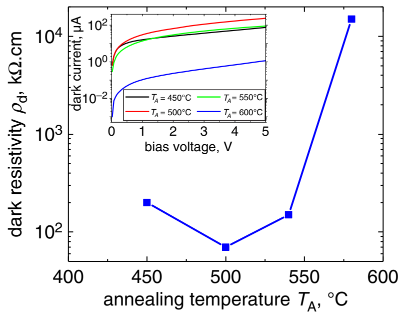

Fig. 3 *Dark resistivity dependence on post-growth annealing temperature T_A. Inset: Dark current versus bias voltage obtained on the 60 × 130 µm^2 area test structures*

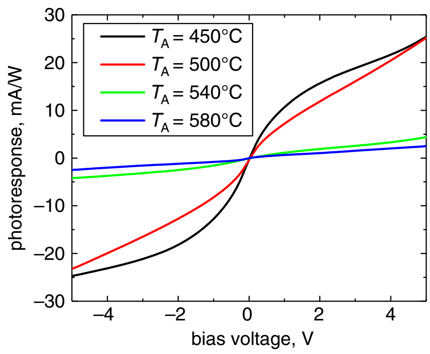

Fig. 4 *Photoresponse-bias voltage characteristics measured on optical cavity photoconductors fabricated using LT-GaAs layers grown at 250°C and annealed at T_A = 450, 500, 540 and 580°C*

Conclusion: It has been shown that LT-GaAs photoconductors can be seen as a credible alternative to InGaAs-based ultrafast photoconductors for CW and pulsed THz optoelectronics application since they can potentially exhibit simultaneously a very high dark resistance and a high photoresponse under 1550-nm illumination. It is achieved by enhancing the optical sub-bandgap absorption in the LT-GaAs layer by decreasing the post-growth annealing and by using an optical cavity based on metallic mirrors.

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One or more of the Figures in this Letter are available in colour online.

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