Femtosecond Response of a Freestanding LT-GaAs Photoconductive Switch

The use of semiconductor photoconductive devices to generate picosecond and subpicosecond electrical signals has been the subject of intense research for the last two decades, primarily motivated by the fast-growing demand for ultrafast, integrated optoelectronic photoswitches and photodetectors. Photoconductive devices based on ion-implanted InP,[1,2] ion-implanted silicon-on-sapphire,[3] amorphous silicon, low-temperature-grown GaAs (LT-GaAs),[4–7] as well as metal-semiconductor-metal diodes,[8] have been studied thoroughly. Unfortunately, due to either their nonstandard active material or the need for nanolithography, it is difficult to integrate any of the above devices into advanced optoelectronic systems or high-performance digital electronics circuits (conventional or superconducting) fabricated on Si substrates. The existing semiconductor photoswitches usually require hybrid integration, which drastically reduces their intrinsic multigigahertz bandwidth.

This article reports on a new method of making a freestanding LT-GaAs photoconductive switch that can be placed at virtually any point on any circuit containing a coplanar strip (CPS) transmission structure. Our device is characterized by <0.5-ps response time and ~23-V/W responsivity (typical for Si or GaAs photodetectors) for 810-nm radiation.

The fabricating process of freestanding LT-GaAs photoconductive devices is described in detail elsewhere.[9] Briefly, 1-μm-thick LT-GaAs films were grown by molecular beam epitaxy on semi-insulating GaAs substrates covered with a layer of AlAs, at a temperature range of 200°C to 250°C and at a growth rate of 1 μm/h.[10] The 0.5-μm-thick AlAs etch-stop interlayer was grown first to enable the separation of the LT-GaAs film from the substrate. After the growth, wafers with LT-GaAs layers were annealed *in situ* at 600°C for 10 min under local As overpressure.

The multiple-step process was used to lift and transfer the LT-GaAs layer from the GaAs substrate.[9–11] First, LT-GaAs was covered with a photoresist, and the photoswitch structures, approximately 5 μm wide and 15 μm long, were defined by photolithography. Next, the wafer was placed into the diluted HF solution (HF:H_2O = 1:9) for selective AlAs etching, which led to separation of the LT-GaAs film from the substrate. The separated LT-GaAs switch was then placed gently on a predetermined spot on the Si substrate. Special care was taken to ensure that the contacting surfaces were exceptionally clean so the LT-GaAs would adhere to the Si through molecular bonding. In the final step, the 10-nm/300-nm-thick, Ti/Au CPS lines were fabricated on top of the switch, resulting in the structure shown in the inset in Fig. 90.36. The final two steps could be easily reversed, i.e., in many fabrication runs the Ti/Au CPS lines were fabricated first, and the switch was placed on top of them, again attached by molecular forces.

The femtosecond response of our LT-GaAs photoconductive switches was measured with an electro-optic (EO) sampling system,[12] using a $LiTaO_3$ total-internal-reflection (TIR) probe,[4,13,14] as shown in Fig. 90.36. The TIR configuration allowed us to position the excitation and sampling spots only ~10 μm away, eliminating the signal distortion caused by propagation effects and enabling the measurement of close-to-intrinsic electrical transients. A commercial Ti:sapphire laser with a repetition rate of 82 MHz was used to generate 110-fs-wide, 810-nm-wavelength optical pulses. Both the excitation and sampling beams were focused to ~5-μm spots with a single 10×, long-focal-length microscope objective. The same objective also collected the sampling beam reflected by the TIR probe.[4,13,14]

The time-resolved photoresponse signals of our freestanding LT-GaAs photoconductive switch, dc biased at 30 V and illuminated by the average optical excitation power P_{ex} of 2.7 mW, 3.2 mW, 3.9 mW, and 4.6 mW, respectively, are shown in Fig. 90.37. The transient amplitudes were normalized to demonstrate that although measurements for each P_{ex} were optimized separately, the response was very reproducible, with a 470-fs full-width-at-half-maximum (FWHM) pulse width, a rise time (10% to 90%) of 340 fs, and a fall time (90% to 10%) of 460 fs. Small ripples on top of the ~5-ps-long shoulder after the main peak were also present in each measurement.

Following Ref. 14, we believe that these ripples were caused by electrical signal reflections of the interfaces of our >50-μm-thick $LiTaO_3$ crystal at the bottom of the TIR probe. The latter was confirmed by measuring the transients when the sampling spot was moved ~100 μm. In this case, the measured pulse was broadened to a FWHM of 1.1 ps (due to the CPS dispersion), and post-pulse ripples were shifted in time with the respect of main pulse.

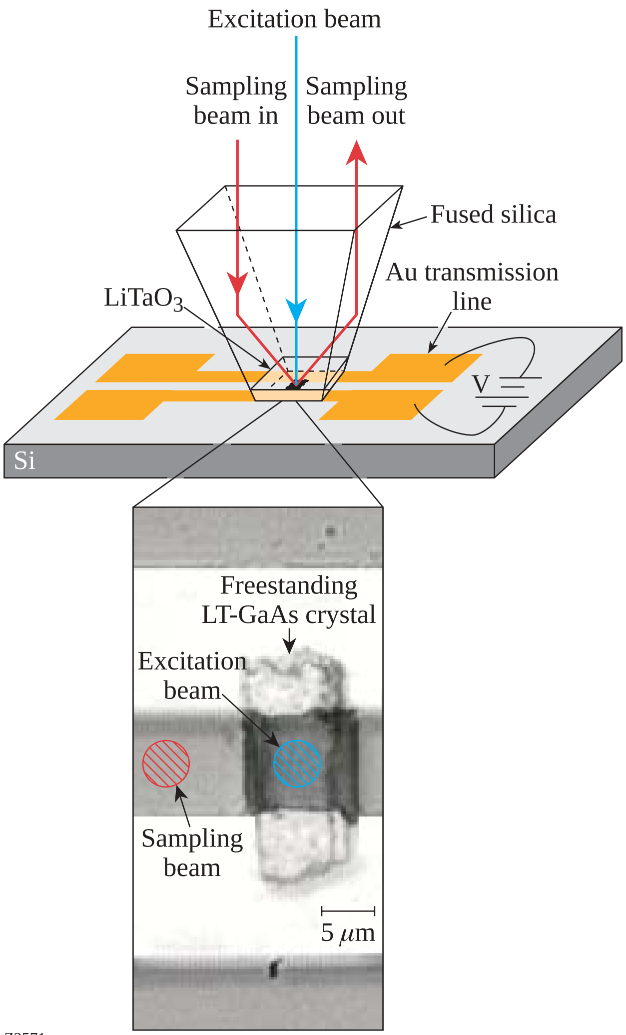

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Figure 90.36
Schematics of the electro-optic TIR probe placed on top of the Au CPS line fabricated on a Si wafer (the figure is not to scale). The inset shows the micrograph of an actual LT-GaAs freestanding switch and the positions of the excitation and sampling beams.

The electrical transient generated by the photoconductive device results from the temporary increase of conductivity due to photogenerated free carriers in the illuminated region of the semiconductor. The signal's intrinsic rise time is limited by how fast the optical energy is delivered, which corresponds to the integral of the laser pulse (in our case, ~120 fs). Our measured, 340-fs rise time is broadened by the EO system time response τ_s, which includes such factors as the finite spot size of the sampling beam, the thickness of the $LiTaO_3$ crystal, and the equivalent lumped-element circuit parameters.[7] The value of τ_s can be estimated as

$$\tau_s = \sqrt{340^2 - 120^2} \approx 320 \text{ fs}.$$

Owing to the existence of a very large concentration of deep-level traps in LT-GaAs, which originated in the fabrication procedure, the signal's fall time is limited by the free-carrier lifetime. Knowing that the measured fall time is 460 fs and taking into account τ_s, we can derive the carrier lifetime as

$$\tau = \sqrt{460^2 - 320^2} \approx 330 \text{ fs}.$$

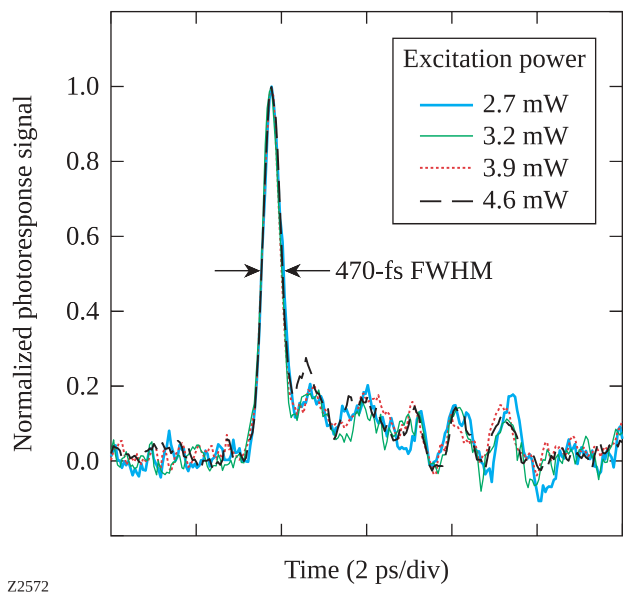

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Figure 90.37
A 470-fs FWHM electrical photoresponse of our freestanding LT-GaAs photoconductive switch biased at 30 V and excited by 810-nm radiation, for several values of the optical excitation power. The optical power was measured at the sample plane, including all the optics and the TIR probe.

This latter value fits very well with the literature data on LT-GaAs, measured using the EO systems, e.g., $\tau < 400$ fs reported by Gupta *et al.*[6] We note that the all-optical, pump/probe experiments tend to give much shorter, $\tau \approx 150$ fs, values.[15] We must remember, however, that for all-optical experiments, the probe beam tests dynamics of very hot carriers, at much higher optical frequencies, as compared to the voltage response, measured by the EO sampling.

Figure 90.38 shows the dependence of the photoresponse amplitude on P_{ex} when the bias voltage V_b was set at 30 V. We observe a linear dependence for moderate P_{ex} values with a slope of ~23 V/W, which can be interpreted as the voltage responsivity of our photoconductive device. For $P_{ex} > 4.5$ mW, the signal amplitude saturates. The photoresponse amplitude versus V_b, measured at P_{ex} = 4.6 mW, is also linear (inset in Fig. 90.38), with a few volts offset at low biases, apparently, due to nonohmic contacts at the Au/LT–GaAs interface.

The photoswitch behavior presented in Fig. 90.38 is expected. With no light incident on the device, the resistance of the LT-GaAs bar is above 40 MΩ; thus, we can safely assume that the measured signal is entirely due to photogenerated carriers inside our 1-μm-thick sample (optical penetration depth of 810-nm photons is 0.86 μm). The background signal recovered to 0 V after each pulse, which indicated that the underlying Si substrate with its long recombination time was not being excited. With the gradual increase of P_{ex}, more and more electron-hole pairs are generated, increasing conductivity and leading to the proportional increase of the electrical response. Above a certain excitation level, however, all available carriers (for a given photon energy) are excited, so the further increase in P_{ex} does not produce more carriers and the signal reaches saturation. Similarly, for a given P_{ex}, the increase of the switch V_b leads to the linear (due to the Ohm's law) increase of the amplitude of the photocurrent.

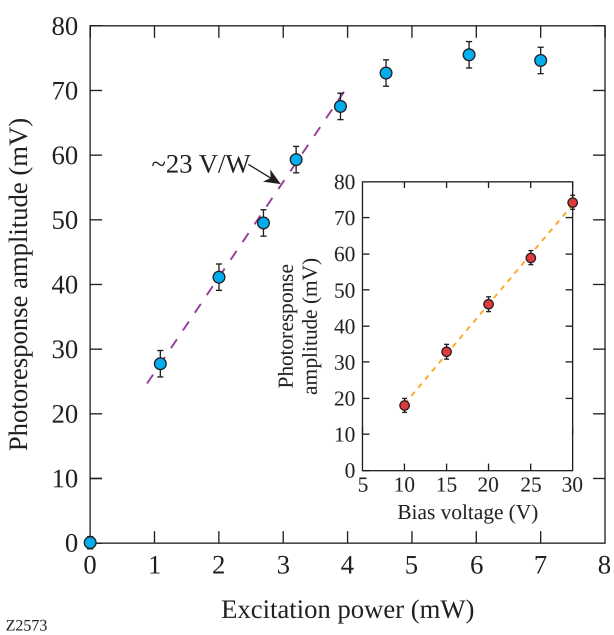

Figure 90.38
The amplitude of the photoresponse signal as a function of P_{ex} for the fixed, 30-V switch bias. The inset shows the signal amplitude versus the bias voltage for P_{ex} = 4.6 mW.

To provide more quantitative interpretation and to check if our experimental data are consistent with theoretical predictions, we calculated the amplitude of the photocurrent pulse generated in our experiment as $I_s = V_s/Z_0$, where V_s is the voltage pulse amplitude and $Z_0 = 30\,\Omega$ is the CPS characteristic impedance. For P_{ex} = 3.9 mW, the measured V_s is 70 mW, leading to I_s = 2.33 mA. Taking into account that the signal FWHM is 470 fs, the total number of carriers involved in the transient photocurrent pulse is $N \approx 7 \times 10^3$. This value can be inserted into the theoretical formula,[7] which returns the number of carriers generated in a semiconductor by a laser pulse and collected by the photoswitch electrodes, to see if the measured data is consistent with reasonable values of the quantum efficiency:

$$N = \eta(1-R)E_0[1-\exp(-\alpha d)]\frac{1}{\hbar\omega}\mu\tau\frac{V_b}{l^2}, \qquad (1)$$

where η is the quantum efficiency, R is the reflectivity, E_0 is the laser energy per pulse of $\hbar\omega$ photons impinging on the LT-GaAs layer, α is the optical absorption coefficient at the excitation wavelength, d is the thickness, μ is the mobility of the LT-GaAs layer, and l is the spacing between the CPS electrodes. Substituting into Eq. (1) parameters relevant for our experimental situation, namely, E_0 = 68 pJ (corresponding to P_{ex} = 3.9 mV), V_b = 30 V, l = 10 μm, α (810 nm) = 1.16 μm^{-1}, d = 1 μm, τ = 330 fs, and estimating $R \approx 0.4$ and $\mu \approx 100$ cm^2/V-s, we finally obtain $\eta \approx 0.1$. We also note that Eq. (1) predicts experimentally observed (Fig. 90.38) linear dependences for both P_{ex} ($P_{ex} \sim E_0$) and V_b. For P_{ex} = 4.6 mW, the number of photogenerated carriers corresponds to a total carrier density of ~10^{18} cm^{-3}, which is a reasonable value for LT-GaAs near the saturation (see Fig. 90.38).

Conclusion

In conclusion, a freestanding LT-GaAs photoconductive device has been successfully fabricated and demonstrated to have a femtosecond time resolution, voltage responsivity of ~23V/W, and a quantum efficiency of the order of 10%. The time-resolved, 470-fs FWHM of our pulses corresponds to ~640-GHz, 3-dB bandwidth for the photodetector. For moderate P_{ex} and V_b, the photoresponse signal was found to increase linearly, in very good agreement with theoretical predictions. The LT-GaAs excess carrier lifetime was measured to be 330 fs, in agreement with the literature data. The freestanding photoswitch is best suited for hybrid optoelectronic and ultrafast electronic systems since it can be placed at virtually any point on the test circuit.

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