375-GHz-bandwidth photoconductive detector

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We report the development of a new, integrable photoconductive detector, based on low-temperature-grown GaAs, that has a response time of 1.2 ps and a 3-dB bandwidth of 375 GHz. The responsivity is 0.1 A/W. Signal amplitudes up to 6 V can be produced with virtually no degradation in response time.

Much progress has been made over the past several years in the development of high-speed photodiode detectors. A detection bandwidth of 105 GHz together with a responsivity of 0.1 A/W have been reported for a metal-semiconductor-metal (MSM) photodiode.[1] The most common approach to increasing the bandwidth in MSM photodiodes (at least up to 100 GHz) is to shorten the carrier transit time by reducing the electrode spacing. However, achievement of bandwidths >100 GHz requires more than simply further reducing the electrode spacing. Monte Carlo simulation of the intrinsic response for a photodiode with 0.1-μm electrode spacing, for example, shows a response tail persisting for picoseconds and having an integrated energy comparable to the main signal.[2,3] This tail is caused by the long transit time of the photogenerated holes, which is almost 10 times that of electrons.

The response times of photoconductive detectors, on the other hand, can be quite fast because they are determined solely by the carrier lifetime of the material that is used. Recently, low-temperature-grown GaAs (LT GaAs) has been applied to ultrafast[4] and high-power[5] optical switching. The subpicosecond carrier lifetime,[6] high mobility (>200 cm^2/V s), and high breakdown field strength (>100 kV/cm) of LT GaAs make this material ideal for electrical pulse generation and gating. Such applications have so far required use of moderate-to-high peak optical powers.

We now report a LT GaAs-based photoconductive detector that takes advantage of the high breakdown field capability of LT GaAs to greatly improve sensitivity. In a photodiode, a reduction in electrode spacing improves speed with little change in sensitivity. In a photoconductive detector, by contrast, such a reduction increases the sensitivity with little change in speed. Decreasing the carrier transit time across the semiconductor gap to a value comparable to the carrier lifetime increases the photocurrent gain to a value of unity.[7] For a carrier lifetime of 1 ps, this condition is met when the electrode spacing, i.e., the actual gap between electrodes, is 0.1 μm. A further decrease in the electrode spacing could increase the photoconductive gain to an even higher value, provided the metal-semiconductor contacts are ohmic. With unity gain, the responsivity of a LT GaAs photoconductive detector becomes comparable to that of a photodiode.

To demonstrate this principle, we fabricated a LT GaAs photoconductive detector with interdigitated electrodes having finger widths and spacings of 0.2 μm. A 1.5-μm-thick LT GaAs layer was grown on a (100) semi-insulating GaAs substrate that has a 0.4-μm-thick conventionally grown undoped buffer layer. The LT GaAs layer growth was performed using molecular beam epitaxy at a substrate temperature of 190 °C, followed by annealing at 600 °C for 10 min in an arsenic overpressure. The interdigitated electrodes were fabricated of 300-Å/2000-Å Ti/Au using a JEOL JBX 5DIIF direct-write electron-beam lithography system. The active area of the detector is 6.5×7.6 μm^2. Coplanar transmission line electrodes of 500-Å/2500-Å Ti/Au, with 20-μm widths and spacings and 5-mm lengths, were also fabricated on the LT GaAs using conventional optical lithography.

As shown in Fig. 1, the LT GaAs photoconductive detector was placed between coplanar transmission lines ($Z_0 = 90\ \Omega$) to assure good coupling of the generated electrical pulse to the propagating mode and also to eliminate parasitic losses. The detector was not antireflection (AR) coated in this initial work. A reference transmission line of identical dimensions, but without the interdigitated-electrode detector, was also fabricated on the wafer to determine the system response. The technique of sliding-contact switching, which provides the excitation between the lines without the interdigitated-electrode detector, can have a response <0.5 ps.[8]

The photoconductive detector was characterized using the technique of external electro-optic (EO) sampling,[6] as depicted in Fig. 1. A balanced, colliding pulse, mode-locked dye laser operating at 610 nm with a repetition rate of 100 MHz was used, which produces 150-fs pump and probe pulses. Although not shown in the figure, the EO sampling crystal spanned both the detector/transmission-line assembly and the reference transmission line, so that the translation of the pump and the probe beams required to make either measurement was only ~ 200 μm.

A bias of 10 V dc was applied to the detector before breakdown occurred, corresponding to a breakdown field strength of 500 kV/cm. This value is more than twice the highest that has been reported for LT GaAs under dc-bias conditions, which was obtained using 20-μm-spaced electrodes.[9] Our result represents a better measurement of the actual breakdown field strength for LT GaAs, since our 0.2-μm electrode spacing confines the electric field to the 1.5-μm-thick LT GaAs epilayer. The dark current for 1 V applied to the detector is 100 pA. At 8 V (400 kV/cm),

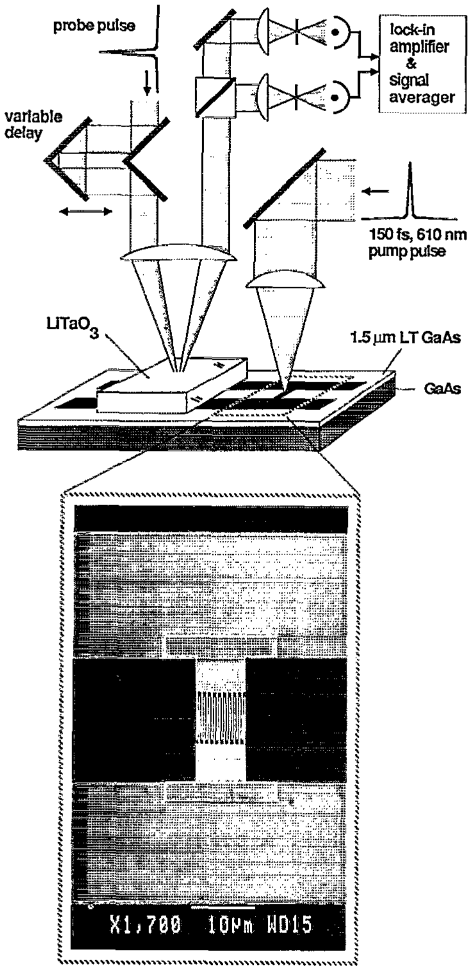

FIG. 1. Experimental apparatus for measuring response of the LT GaAs detector. The photoconductive detector is located between the coplanar transmission line (photo insert) having 20-μm-spaced electrodes.

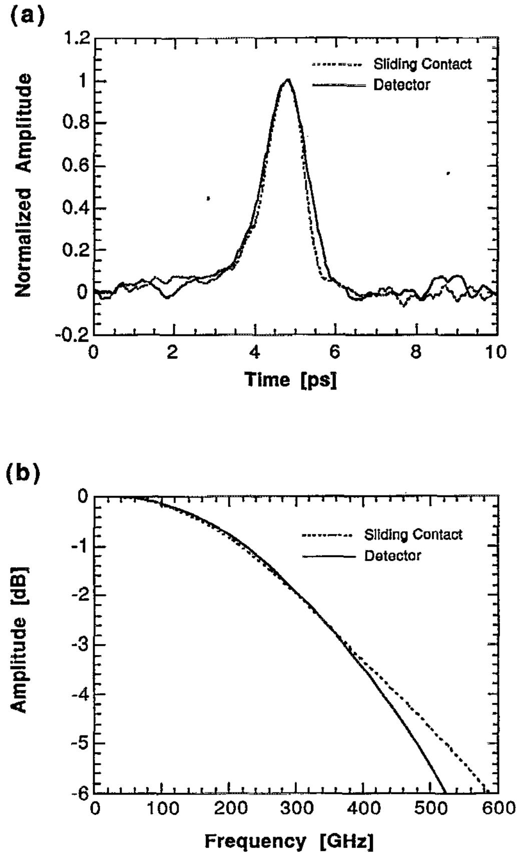

FIG. 2. (a) Temporal response of the photoconductive detector and sliding-contact switch measured 450 μm from the point of signal generation, (b) frequency response of the temporal signals shown in (a). The -3-dB point for both signals occurs at 375 GHz.

where we chose to operate, the dark current increased to 300 nA. For an average optical power of 4 μW, the responsivity is 0.1 A/W. Past work using 20-μm-spaced electrodes on LT GaAs attained a responsivity of only 10^{-3} A/W.[9] The 100-fold reduction in gap dimension therefore improves the responsivity 100 fold. The value of 0.1 A/W is comparable to that for the responsivity of high-speed photodiodes. The reflective losses at the surface from the interdigitated electrodes and the semiconductor amounted to 70% of the incident signal.

The intrinsic material response time for the LT GaAs sample has been measured previously using an all-optical pump-probe technique[10] and found to be 0.6 ps. We calculate the capacitance[11] of our structure to be 4 fF, for an RC-limited response time of 360 fs. Figure 2(a) shows the measured responses for the detector/transmission-line assembly and the sliding-contact switch on the reference transmission line. Both measurements were obtained 450 μm from the point of signal generation. The optical pulse energy on the detector is 0.04 pJ (4-μW average power). The full width at half-maximum of the detector response is 1.2 ps with no evidence of a tail. In fact, the trailing edge, with a 10%–90% fall time of 0.8 ps, is faster than the leading edge. We note a similar shape of the response for the sliding-contact switch on the reference transmission line. This is indicative of modal dispersion from quasi-TEM propagation along a transmission line having a substrate and superstrate with different permittivities.[12] Figure 2(b) shows the discrete Fourier transform of the signals shown in Fig. 2(a). The -3-dB point for both signals shown in Fig. 2(b) occurs at 375 GHz. Since the measured results shown in Fig. 2 are a convolution of the LT GaAs intrinsic response time and such system-related factors as the RC time constant, laser pulse width, and electro-optic material response, the intrinsic response time for the interdigitated-electrode detector may in fact be subpicosecond.

A set of waveforms from the photoconductive detector for several values of pulse energy is shown in Fig. 3(a). Signals A, B, C, and D correspond to peak signal amplitudes of 6, 3.5, 0.6, and 0.06 V generated using 22, 8.3, 0.83, and 0.04 pJ, respectively. We see that a 500-fold increase in intensity expands the response only slightly from 1.2 to 1.5 ps. Under similar experimental conditions, a high-speed MSM photodiode would suffer significant temporal broadening from the space charge[13] and from low-frequency gain by photoinduced band bending.[14] Thus, the LT GaAs photoconductive detector avoids the usual restriction of MSM photodiodes to pulse energies below 0.1 pJ to achieve optimum bandwidth performance.

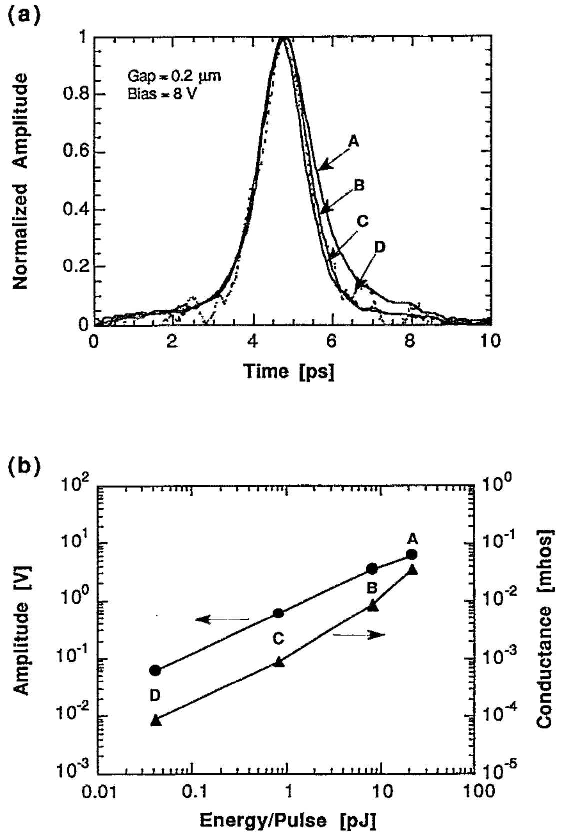

FIG. 3. (a) Set of four signals generated from the photoconductive detector. Signals A, B, C, and D correspond to peak signal amplitudes of 6, 3.5, 0.6, and 0.06 V generated using 22, 8.3, 0.83, and 0.04 pJ, respectively, representing a 500-fold decrease in the light intensity, (b) peak amplitude and conductance of signals shown in (a) plotted against incident pulse energy.

The peak amplitude versus incident pulse energy for the signals shown in Fig. 3(a) is plotted in Fig. 3(b). Also plotted in Fig. 3(b) against incident pulse energy is the derived peak conductance of the gap according to $G_{\mathrm{gap}} = V_0\,(V_{\mathrm{dc}}Z_0 - V_0Z_0 - V_0R_c)^{-1}$, where V_0 is the signal amplitude, V_{dc} is the bias voltage, Z_0 is the transmission line characteristic impedance, and R_c is the metal-semiconductor contact resistance. We find that the voltage amplitude rises sublinearly with pulse energy, changing by only 100-fold for a 500-fold increase in pulse energy. This suggests that the detector operates in the saturation regime for the transmission line impedance that was used. The 400-fold change in conductance indicates that the detector, operating alone, responds almost linearly over this energy range employed in these experiments. With a pulse energy of 22 pJ, the detector is driven from an off-state resistance of 3×10^7 Ω to an on-state resistance of 30 Ω.

In conclusion, we have developed a new MSM-type photoconductive detector, based on low-temperature-grown GaAs, that was fabricated using 0.2-μm-spaced interdigitated electrodes. The response time measured directly by EO sampling, i.e., without deconvolution, is 1.2 ps. With no AR coating on the detector, the responsivity is 0.1 A/W. To our knowledge, this is the fastest high-sensitivity photoconductive detector of any kind reported to date. In addition, it can be driven to an on-state resistance of 30 Ω with little degradation in speed. This versatility permits the device to function both as a detector and a switch. In the switching mode, the device can perform either as a high-contrast gate with a picosecond gate window or as an efficient single-picosecond electrical-pulse generator. Such unique dual functionality together with ease of integration will permit a number of detector/switch elements to be combined for acquiring and processing picosecond optical and electrical events with high efficiency and minimal temporal distortion.

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