Subpicosecond, freely propagating electromagnetic pulse generation and detection using GaAs:As epilayers

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Using GaAs epilayers with arsenic precipitates (GaAs:As) as the photoconductive material in a broad-band optoelectronic terahertz beam system, we have generated and detected freely propagating, subpicosecond electromagnetic pulses. The receiver signal gave a measured integrated pulse width of 0.71 ps. Fast photoconductive rise times have been achieved which are characteristic of good mobility GaAs. In addition, the material exhibits a short "effective" carrier lifetime of several ps due to the embedded, closely spaced (about 20 nm) arsenic precipitates.

The use of subpicosecond pulsed laser technology to drive photoconductive switches [1] has led to a widespread interest in the development of ultrafast optoelectronic materials and devices which can generate and detect subpicosecond electrical pulses.[2–10] Generally, achieving ultrafast optoelectronic performance depends on both the properties of the photoconductive material and the configuration of the sampling device. Nonetheless, it is well understood that the ideal photoconductive material would have high dark resistivity, high carrier mobility, and short carrier lifetimes. Such material would exhibit a fast rise time, high output signal, and a fast turn-off time. The best previously studied subpicosecond material, namely, implanted silicon-on-sapphire (SOS), achieved short carrier lifetimes via high defect densities—this results in excellent receiver noise characteristics, but compromises somewhat the carrier mobility and pulse rise time, and thereby the ultimate high-frequency performance.

An alternative photoconductive material is GaAs grown by molecular beam epitaxy (MBE) at 200–250 °C (LT GaAs). As grown, this material contains roughly 1% excess As, producing an extreme concentration of bulk defects.[11] When used as the photoconductive material in a transmission line, electrical pulse "launcher,"[9] it produced an electrical pulse width of 1.6 ps and a large improvement in signal amplitude over SOS-based structures. From that study, its authors surmised an electron mobility of 200 cm^2/V s. Since then, electrical pulses as short as 0.6 ps have been generated on coplanar transmission lines with this material.[10]

Recently, it has been shown that under certain annealing conditions, the excess arsenic in LT GaAs will coalesce into arsenic precipitates (GaAs:As) about 6 nm in diameter with an average spacing of about 20 nm.[12] In this letter we demonstrate the relatively large signal generation and detection of subpicosecond freely propagating electromagnetic pulses using these GaAs:As epilayers as the photoconductive emitters and detectors in a complete, broadband optoelectronic terahertz beam system.[5,6] Our results indicate that the photoconductive response of the GaAs:As material consists of an ultrafast, subpicosecond turn-on time similar to that for "normal" GaAs, but followed by a turn-off time of several picoseconds. Consequently, for the transmitter the emitted THz pulse is produced by the leading transient. Similarly, this photoconductive response "gates" the receiver so that it operates in an integrating mode, where the high-frequency limit is determined by the sharpness of the photoconductive rise time.

Since the process windows which produce GaAs:As are not yet well established, the details of the relevant epigrowth procedure will be described. The epilayers used in this study were grown in a Varian GEN II molecular beam epitaxy (MBE) system on a 2-in. diam, liquid-encapsulated-Czochralski (100) GaAs substrate. The substrate was degreased, etched in a 60 °C solution of 5:1:1 of H_2SO_4:H_2O_2:H_2O for 1 min and placed in a nonbonded substrate mount. The substrate was outgassed for 2 h at 200 °C in the entry chamber of the MBE, moved to the buffer chamber where it was outgassed for 1 h at 300 °C, and then loaded into the growth chamber. In the growth chamber, the sample was heated to 615 °C for 2 min (the surface oxides desorbed at 580 °C) and then lowered to the initial growth temperature of 600 °C.

The growth rate for all layers was 1 μm/h, with a group V to group III ratio (beam equivalent pressure) of 22. The arsenic source used was the dimer As_2. First, 0.75 μm of undoped GaAs buffer was grown. Then the substrate temperature was ramped from 600 °C to 250 °C, during the growth of the next 0.25 μm of GaAs. After reaching a substrate temperature of 250 °C, 1 μm of undoped GaAs was grown. The substrate temperature was then ramped back to 600 °C during the growth of the next 500 Å of GaAs, and the structure was capped with an additional 100 Å of undoped GaAs. The structure growth was followed by an *in situ* anneal in the As_2 flux for 1 h at 600 °C. The substrate was rotated at 5 rpm during the growth of all layers and during the one hour 600 °C anneal. Transmission electron microscopy revealed arsenic precipitates (6

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nm average diameter) in samples grown by this procedure. A similar procedure using an As_4 source has also been shown to produce arsenic precipitates.[12]

The performance of GaAs:As as an ultrafast photoconductive switch was demonstrated using the same broadband optoelectronic THz beam system as described in Refs. 5 and 6. The only difference between that study and the work reported here is the substitution of GaAs:As (with Au:Ge:Ni contacts and antennae) for the implanted SOS. As described in Ref. 6, the patterned photoconductive gaps and transmission lines had spacings of 5 and 30 μm, respectively. The transmitter is biased at 9 V and driven with 70 fs optical pulses with a 100 MHz repetition rate and coming from a colliding-pulse, mode-locked dye laser to generate the terahertz pulse radiation. This radiation is then focused on the receiver antenna which is being gated by identical, but time-delayed, photoexcitation pulses. While SOS has a "delta function" type photoconductive response enabling a "sampling" mode of operation, the GaAs:As photoconductive response is more like a step function, i.e., an ultrafast subpicosecond rise time followed by a relatively slow decay of several picoseconds. Thus, the temporal overlap between the incident teraHz pulse which biases the gap of the receiver antenna and the step-function photoconductive response of the receiver results in a transfer of charge (current) across the photoconductive gap proportional to the *negative integral* of the electric field across the gap.[13]

We will now relate the above discussion to our particular system in the limit that the transmitter and receiver have identical antennas which are small compared to the wavelengths of the emitted radiation (the Hertzian dipole approximation). For this case the electric field of the emitted radiation is proportional to the time derivative of the current pulse in the transmitting antenna, and the voltage induced across the receiving antenna gap is proportional to the time derivative of the electric field of the incoming THz pulse. Thus, the voltage on the gap is proportional to the second derivative of the current pulse in the transmitting antenna. This situation is mathematically equivalent to the measured signal being proportional to the autocorrelation of the derivative of the current pulse, in agreement with the reciprocity theorem for antennas. This is not precisely the case here, due to the transfer function of the THz optical system and due to the absorption and dispersion of the GaAs chips and to a small extent the Si lenses. However, this fact shows the sensitivity to the fast turnon as compared to the relative insensitivity to the much slower turnoff of the current pulse. Therefore, whether the turn-off time is 1 or 3 ps does not make much difference, if the turn-on time is is only a few hundred femtoseconds.

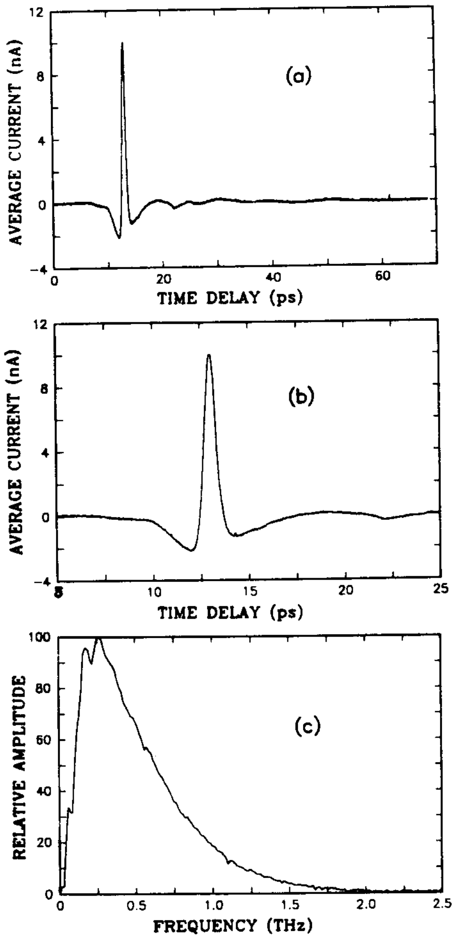

FIG. 1. Measurement results using GaAs:As transmitter and receiver on an extended (a) and expanded (b) time scale, and the resulting amplitude spectrum (c).

A typical measured pulse, proportional to the *negative integral* of the voltage across the receiving antenna induced by the incoming pulse, is shown in Fig. 1(a) and again in Fig. 1(b) on an expanded time scale. Figure 1(c) shows the amplitude spectrum of this pulse, illustrating a bandwidth significantly under 2 THz. The full width at half maximum (FWHM) of the integral pulse, using GaAs:As as both transmitter and receiver, is 0.71 ps as compared to 0.54 ps for sampling mode measurements using ion-implanted SOS throughout.[6] The principal difference, however, is that the measured peak signal (current) in Fig. 1(a) is more than five times larger than that obtained from an all-SOS system. In order to clarify the contributions of the different materials at the different transceiver components, GaAs:As, SOS and intrinsic GaAs were tried in various combinations, producing several informative results. First, it was found that the substitution of intrinsic GaAs for the GaAs:As transmitter produced essentially no differences in the signals measured with a given receiver, using either SOS or GaAs:As receivers (intrinsic GaAs could not be used for the receiver because of its long carrier lifetime). The fact that the GaAs and GaAs:As transmitters gave the same signals is indicative of the high quality of the GaAs matrix in the low-temperature material and lack of mobility degradation. Second, while exact numbers are unclear, it is certain that the signal strength for the GaAs:As is larger than for SOS for both the transmitter and receiver sides, resulting in the above factor of 5 between the all-GaAs:As and all-SOS transceiver configurations. With respect to such amplitude comparisons, typical variations in photocurrent for identical chips from the same wafer are factors of 1.5. Third, since the GaAs:As

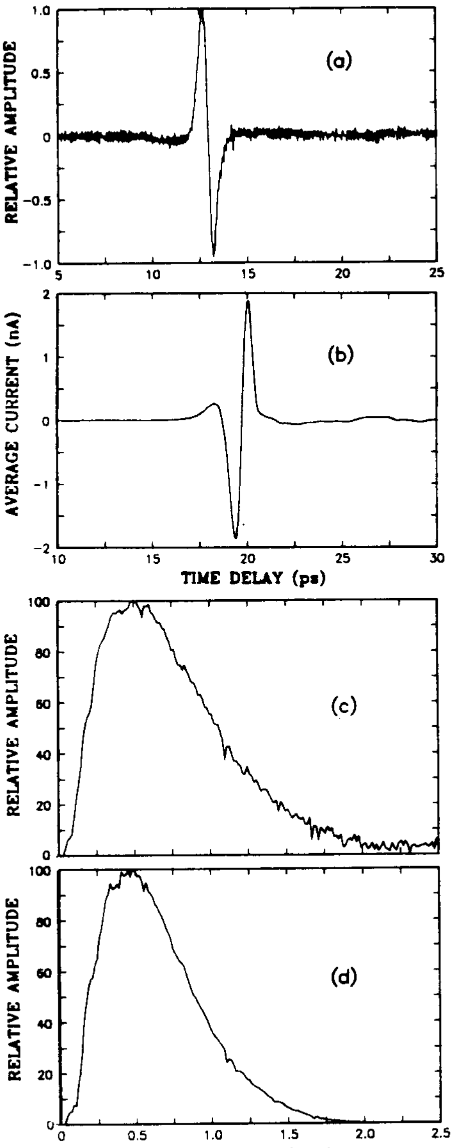

FIG. 2. Direct comparison between GaAs:As and SOS receivers, using a GaAs:As transmitter (the difference in time delay is arbitrary): (a) Numerical derivative of the measured GaAs:As receiver pulse shown in Fig. 1(b); (b) measured SOS receiver pulse; (c) amplitude spectrum of derivative pulse in (a) (GaAs:As); (d) amplitude spectrum of pulse in (b) (SOS).

receiver operates in an integrating mode, in contrast to SOS operation in a sampling mode, a more direct pulse width comparison was made by using a GaAs:As transmitter with both receivers, but differentiating the GaAs:As receiver results. Figures 2(a) and 2(b) show these signals for GaAs:As and SOS, respectively, yielding minimum-maximum differences of 0.58 ps for the numerical derivative of the GaAs:As receiver signal and 0.67 ps for the SOS. The derivative signal has the opposite polarity compared to the SOS signal, because the original GaAs:As signal is proportional to the negative integral. It should also be noted that the measured pulse width is extremely sensitive to precise alignment of the silicon lens, which we optimized for each antenna. Figures 2(c) and 2(d) show the amplitude spectra for 2(a) and 2(b), respectively, illustrating a slight advantage in bandwidth for the GaAs:As signal after differentiation. Lastly, by comparing noise levels in the GaAs:As and SOS receivers, it is estimated that the photoexcitation decay in the GaAs:As is on the order of 2 ps, which is consistent with mediation by sparse As clusters rather than a high density of bulk defects (as in SOS or LT GaAs). Because of the indirect nature of this pulse shape inference it would be dubious to attempt a rigorous direct comparison with earlier LT GaAs work.[9] Nevertheless, the above results and corroborating DLTS measurements[14] suggest a quality now approaching that of intrinsic GaAs.

In conclusion, we have demonstrated an optoelectronic THz beam transceiver system, which uses GaAs:As as the photoconductive material in the laser driven Auston switches. The system generates relatively powerful subpicosecond pulses of THz radiation. Our measured integrated pulse widths of 0.71 ps indicate that the GaAs:As photoconductive material has the desired combination of an ultrafast, subpicosecond turn-on time, due to the excellent mobility in the high-quality, epitaxial material, together with a reasonably short carrier lifetime of several picoseconds due to the high density of As clusters acting as recombination centers.

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[13] In terms of the time delay τ between the incoming THz pulse and the "step function," the measured integral $I(\tau)$ is taken from τ to ∞. Because we are measuring a freely propagating pulse, the complete integral from $-\infty$ to $+\infty$ is zero. Thus, the integral from $-\infty$ to τ is equal to $-I(\tau)$.

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