Characterization of Planar Antennas Fabricated on GaAs Epilayers Containing As Clusters for Picosecond Short-Pulse Applications

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***Abstract*— Coplanar-strip horn antennas are fabricated on GaAs grown by molecular beam epitaxy at substrate temperatures of 220, 250, and 270° C. These antennas are switched photoconductively using a picosecond laser to generate and detect freely propagating bursts of electromagnetic radiation. The dependence of the antenna performance on substrate growth temperature is assessed and is also compared with the performance of like antennas fabricated on oxygen-bombarded silicon on sapphire. It is shown that in our picosecond measurements the radiated pulse duration is not very sensitive to substrate growth temperature but the radiated intensity is highly sensitive to this parameter.**

OVER the last several years planar antenna technology has been combined with advances in picosecond and femtosecond lasers to photoconductively generate and detect ultra-short bursts of freely propagating electromagnetic radiation [1]–[4]. These pulses have found application in material characterization [5]–[7] as well as in electromagnetic scattering measurements [8]–[10]. An important aspect in the performance of these antennas is the characteristics of the photoconductor on which the antenna is fabricated. Oxygen-bombarded silicon on sapphire (SOS) [11] has been among the most widely used photoconductors for picosecond and subpicosecond applications. Recently, however, there has been much interest in materials grown at relatively low substrate temperatures (150–300° C) via molecular beam epitaxy (MBE) [12]–[15].

When one grows GaAs using normal MBE conditions except at low substrate temperatures, excess As can be incorporated into the epilayer. The amount of excess As is strongly dependent on the substrate temperature during MBE [16]. Upon annealing these epilayers at temperatures of 600° C or higher, the excess As precipitates [17]. The final As cluster density and average diameter is a function of the time and duration of this anneal [18]. We will designate this composite material consisting of As clusters in a GaAs matrix as GaAs:As. In this letter, we present experimental results which assess the performance of antennas that are fabricated on GaAs:As and are switched photoconductively. We concentrate on measurements involving picosecond lasers and show that for such applications the optimal GaAs:As can be significantly different than what has been used previously for femtosecond applications [19]. Moreover, we show that the sensitivity of the GaAs:As photoconductors greatly improves the antenna-system efficiency when compared to like antennas which use conventional oxygen-bombarded SOS photoconductors.

Manuscript received June 8, 1993. This work was supported by the National Science Foundation under Grant ECS-9211353 and by the Air Force of Scientific Research under Grant F49620-93-1-0031.

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IEEE Log Number 9211886.

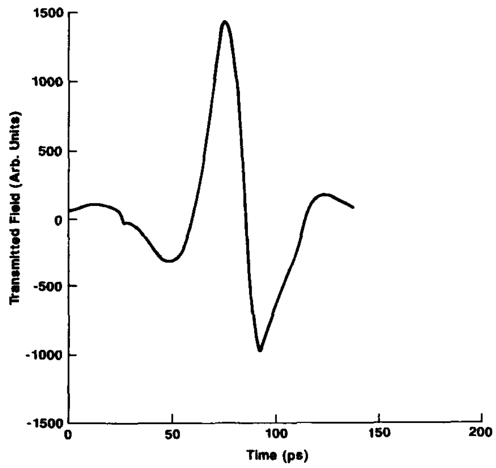

Fig. 1. Received signal on a coplanar-strip horn antenna fabricated on a GaAs:As epilayer grown at 250° C with a 45 minute post anneal at 600° C. The radiation was produced by a similar antenna fabricated on oxygen-bombarded SOS.

We use a mode-locked Nd–YLF laser and the infrared pulses it generates are pulse compressed and frequency doubled to produce green (527 nm) pulses of approximately 5 ps duration and 200 mW average power at a 76 MHz repetition rate. These pulses are used to switch coplanar-strip horn antennas photoconductively (this antenna is described in detail elsewhere [3]). The antennas were fabricated using AuGeNi lines in an oil diffusion pumped system. We considered several different GaAs:As epilayers. The epilayers were grown in a Varian GEN II MBE system on two-inch diameter semi-insulating GaAs substrates using an As_2 to Ga beam equivalent pressure ratio of 20. Three film structures were grown. Each began with a GaAs buffer layer grown at 600°C,

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then while continuing to grow GaAs, the substrate temperature was lowered to the growth temperature for the epilayer with excess As. The final substrate growth temperatures used were 220, 250, and 270° C, with respective epilayer thickness of 0.4 μm, 0.5 μm, and .09 μm, and respective post-growth anneals of 600° C under the As_2 flux of 20, 45, and 50 minutes.

The transmitting antennas was dc biased at 40 V and the receiving antenna was connected to a current preamplifer and then to a lockin amplifer. The pump (used to switch the transmitter) and probe (used to switch the receiver) optical pulses were split equally such that approximately 100 mW average-power pulses switched each antenna and the pump pulse was chopped at 1 KHz. The antennas were arranged in transmission and separated by 10 cm; fused silica hemispherical lenses were placed in front of each antenna. In all measurements, GaAs:As grown at 250° C with a 45 minute post-growth anneal at 600° C was used as the substrate for the receiving antenna. For comparison, we first considered a transmitting antenna fabricated on silicon-on-sapphire (SOS) which was bombarded with 180 KeV oxygen ions with dosages of $10^{15}/\text{cm}^2$. Aluminum lines were used for the antennas fabricated on SOS. The results for the SOS transmitter are shown in Fig. 1. These results are also typical of what we measure when both the transmitter and receiver are fabricated on oxygen-bombarded SOS.

We next considered transmitting antennas which were fabricated on GaAs:As. The results for the 220, 250, and 270° C epilayers are shown in Fig. 2(a)–(c), respectively. We see from these results that the detected pulse duration for our picosecond applications is not very susceptible to the substrate growth temperature. Although the pulse shapes are different for the transmitting antennas grown at different temperatures, the pulse duration of each waveform is essentially the same. Moreover, a numerical Fourier transform of each waveform shows that each contains significant frequency components over approximately the same bandwidth (10–80 GHz). The most noticeable difference between the waveforms received from the three different epilayers is found in the peak radiated amplitude. The transmitting antenna on GaAs:As grown at 220° C produces lower peak signals than that of the antennas grown on oxygen bombarded SOS. The antennas fabricated on GaAs:As grown at 250 and 270° C produce waveforms with amplitudes that exceed that produced by the antennas on SOS (the antenna on GaAs:As grown at 270° C produces a waveform with peak amplitude twice that on the SOS substrate). We see from these measurements that the loss in carrier mobility caused by GaAs:As growth at temperature levels below 270° C does not reduce the radiated pulse duration significantly but causes a dramatic reduction in the radiated signal amplitude.

Measurements were also performed in which the receiving antenna was fabricated on GaAs:As grown at 220° C and we did not witness any significant reduction in the duration of the received waveform (using again transmitting antennas fabricated on GaAs:As grown at the three different substrate temperatures). Femtosecond studies have indicated that

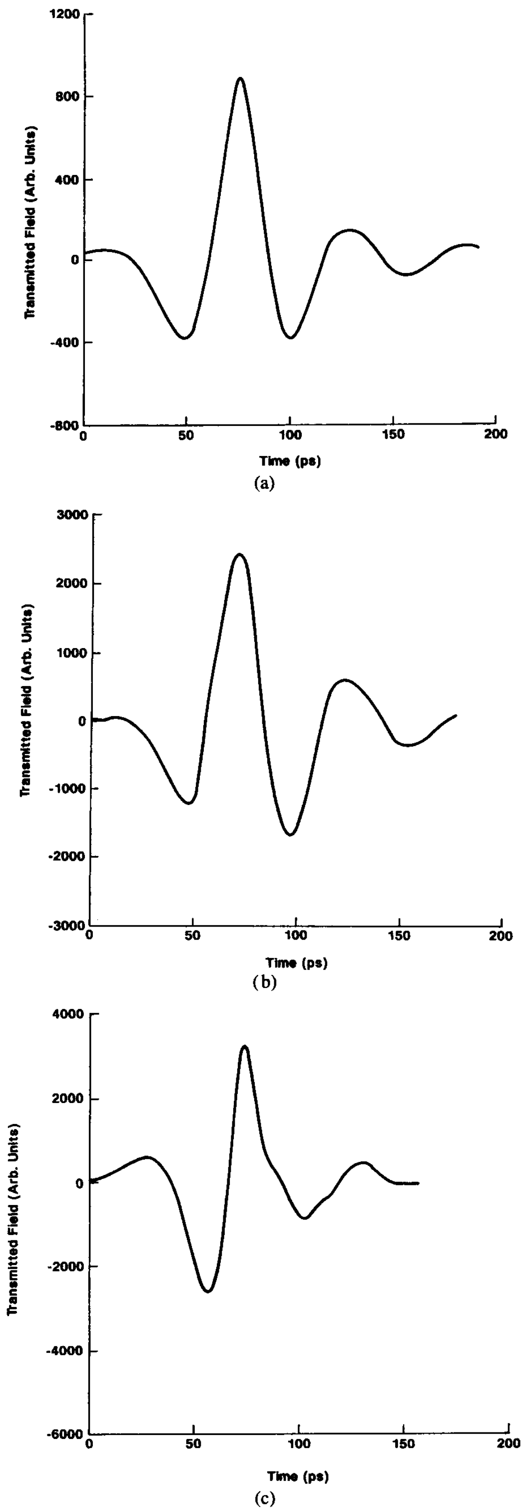

Fig. 2. Received signals on a coplanar-strip horn antenna fabricated on a GaAs:As epilayer grown at 250° C with a 45 minute post-growth anneal at 600° C. In all cases, the transmitting antenna was fabricated on a GaAs:As epilayer with a post-growth anneal at 600° C. In (a)–(c), the epilayer was grown at 220, 250, and 270° C, respectively, with respective post-growth anneals of 20, 45, and 50 minutes.

GaAs:As grown at 220° C has a faster relaxation time [14] than similar epilayers grown at 250° C. We, therefore, conclude that in our measurements involving picosecond optical pulses the temporal resolution is limted by the optical pulse duration and the bandwidth of the antenna and not by the response time of the epilayer. This has important implications for many of the applications involving picosecond systems since the growth temperature proscribed by previous studies, which have dealt primarily with femtosecond optical pulses [19], may lead to the design of antenna substrates which are not optimized for picosecond applications. These same considerations may apply to oxygen bombarded SOS, for which the ion-implanation dosage may warrant reconsideration for picosecond applications.

Of interest are results we obtained when both the transmitting and receiving antenna were fabricated on GaAs:As grown at 270° C. In those experiments we measured waveforms with peak amplitudes 5 times greater than the results in Fig. 1. We attribute this to the sensitvity of the receiver afforded by the relatively strong photoconductive responses of GaAs:As grown at 270° C. Unfortunately, these antennas, which have important applications for the generation of high-power picosecond waveforms, has a relatively short lifetime in this configuration. After a few hours of continuous operation, the receiving antenna failed to work. From dc-current measurements, we found that the resistance between the coplanar strips reduced from an initial resistance of on the order of megaohms before antenna use to almost a perfect short after it was destroyed. It is not clear what caused this, however, similar effects have been reported by other researchers concerning the operation of GaAs:As at or near breakdown fields [20]. We only experienced such breakdown when both the transmitting and receiving antennas were fabricated on GaAs:As grown at 270° C and the short usually occurred on the receiving antenna. This is interesting because it appears to be a transient effect since the fields on the receiving antenna are certainly much smaller than the fields associated with the 40-V dc source on the transmitting antenna.

In summary, we have investigated experimentally the performance of coplanar-strip horn antennas fabricated on GaAs:As for picosecond applications. We considered MBE at substrate temperatures of 220, 250, and 270° C, and have concluded that there is not a significant variation in the radiated pulse duration for these growth temperatures using our 4 ps optical excitation pulse. However, we have found that the peak radiated signal is strongly dependent on the growth temperature, increasing with increasing growth temperature. Additionally, we found that when both the transmitting and receiving antenna were fabricated on GaAs:As grown at 270° C, a radiated waveform was measured with an amplitude five times that found when both the antennas were grown on oxygen bombarded SOS at "typical" ion-implanation dosages. In this cases, however, the antennas has a relatively short lifetime (hours).

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