Subpicosecond photoresponse of carriers in low-temperature molecular beam epitaxial $In_{0.52}Al_{0.48}As/InP$

S. Gupta, P. K. Bhattacharya, J. Pamulapati, and G. Mourou
Ultrafast Science Laboratory and Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

(Received 20 April 1990; accepted for publication 23 July 1990)

Femtosecond time-resolved reflectivity and photoconductive switching measurements have been made of $In_{0.52}Al_{0.48}As$ grown by molecular beam epitaxy on (100) InP substrates at growth temperatures ranging from 150 to 480 °C. A response/switching time of ~ 400 fs is measured in the sample grown at 150 °C. Temperature-dependent measurements shed light on the nature of the material producing the ultrafast response.

$In_{0.52}Al_{0.48}As$ lattice matched to InP is an important material (band gap 1.45 eV at room temperature) for the development of $In_{0.53}Al_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure devices.[1-4] Under normal molecular beam epitaxial (MBE) growth temperatures (~ 520 °C) the material is of high resistivity ($\rho > 10^4$ Ω cm) and more so when the growth temperature is lowered. In fact, it has recently been demonstrated that buffer layers of InAlAs grown at temperatures well below 500 °C improve the performance characteristics of modulation doped field-effect transistors.[5] It is important to know if the high resistivity of InAlAs can be useful for high-speed switching applications.[6] In particular, it is known that the carrier lifetime in most semiconductors can be lowered by impurity and deep level defects. Very high-speed photoconductive response has been observed in MBE GaAs grown at low temperatures.[7] With this in mind we have studied the properties of low-temperature MBE-grown InAlAs by time-resolved reflectivity and photoconductive switching using femtosecond optical pulses.

A series of 1-μm-thick $In_{0.52}Al_{0.48}As$ layers was grown on Fe-doped semi-insulating (100) InP substrates by MBE at substrate temperatures ranging from 150 to 480 °C at a growth rate of 0.6 μm/h. The substrates were prepared for growth by standard degreasing and etching in 0.5% bromine methanol and 5 H_2SO_4:1 H_2O: 1 H_2O_2, respectively. The V/III flux ratio was maintained at 45. Growth was done on As-stabilized (2×4) reconstructed surface as observed in the *in situ* reflection high-energy electron diffraction (RHEED) pattern before and after the growth. One sample grown at 150 °C was annealed *in situ* under an arsenic overpressure by raising the substrate temperature to 500 °C for 10 min after the growth was completed. Another sample grown at 150 °C was externally annealed in a baking oven at 300 °C for 10 min, without encapsulation, after removal from the growth system. Standard photolithography was used to define a gap (15 μm) photoconductive switch[6] embedded in a coplanar strip structure, with 500 Å Ti/3500 Å Au metallization in the unannealed, externally annealed, and *in situ* annealed material grown at 150 °C. The morphology of the samples was characterized by increased roughness with lowering of growth temperature. High-resistivity behavior was observed in all the InAlAs layers. For the material grown at 150 °C, the resistivity increased approximately by an order of magnitude after external anneal and after *in situ* anneal. The crystal quality of the epitaxial layers is good as evidenced by single-crystal x-ray diffraction. A slight broadening and mismatch (0.12%) was observed for the layers grown at 150 and 200 °C.

To investigate carrier lifetimes in these materials, the evolution of photogenerated carriers from a short optical pulse was studied by measuring the time-resolved reflectivity signal from the surface. A balanced colliding-pulse mode-locked (CPM) ring dye (gain/absorber Rh6G/DODCI) laser producing 100 fs pulses at $\lambda = 620$ nm was used for intrinsic excitation at a repetition rate of 100 MHz. One beam passing through a computer-controlled optical delay line was used as an excitation beam with an average attenuated power of ~ 5 mW and focused spot size of about 20 μm. Another beam attenuated to 0.5 mW and focused to a 10 μm spot was used as the probe beam at near-normal incidence. The polarization of both beams was crossed to avoid unwanted interference effects. The sample whose surface transient reflectivity $[\Delta R(t)/R]$ is to be measured was mounted in a liquid-He flow cold-finger cryostat with optical windows. The bulk temperature of the sample could be varied between 8 and 300 K, thus enabling a study of the temperature dependence of carrier lifetimes. With the use of acousto-optic modulation of the excitation beam at 1–3 MHz and using mixing and lock-in techniques, a sensitivity of $\Delta R/R$ of about 10^{-6} could be easily achieved. Typical peak signals lie in the 10^{-3}–10^{-4} range. The same laser source was also used to generate an electrical transient in the gap photoconductive switches. A dc bias of 10–20 V was used. To detect the electrical transient, external electro-optic sampling[8] technique with a $LiTaO_3$ probe tip was employed.

The transient reflectivity of a weak probe pulse from the surface of the InAlAs samples is shown in Fig. 1 (a), the data being taken at room temperature. Five samples grown at 150, 200, 300, 400, and 480 °C were tested. A gradual reduction of the initial fall time from ~ 12 to ~ 3 ps is observed as the growth temperature is lowered to 200 °C. For the sample grown at 150 °C, a drastic reduction in the fall time to ~ 400 fs is observed. Note also that the reflectivity signal from this sample is inverted and crosses the zero axis, as opposed to the signal from other samples. The

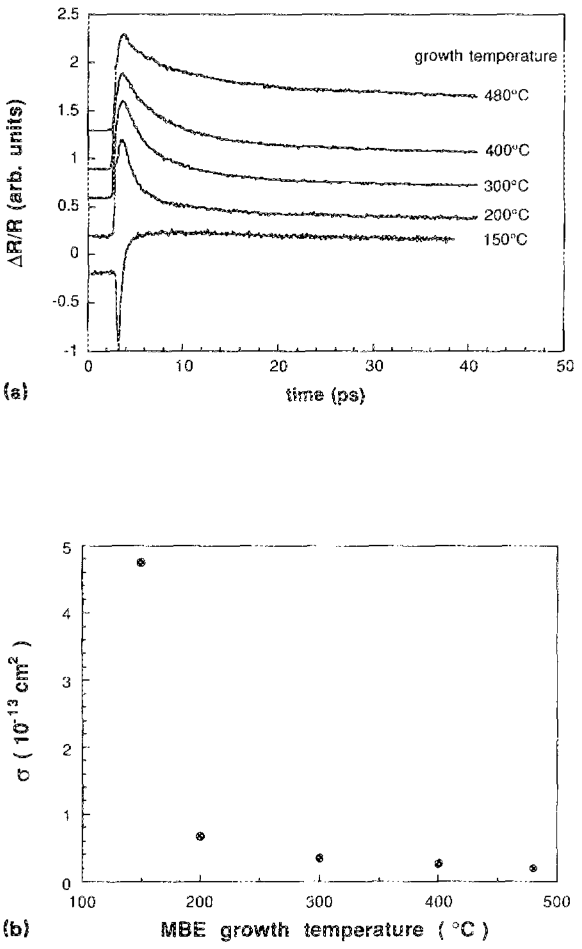

FIG. 1. (a) Time-resolved reflectivity of low-temperature MBE-grown $In_{0.52}Al_{0.48}As$ layers, showing evolution of photogenerated carriers; (b) estimated capture cross sections in $In_{0.52}Al_{0.48}As$ for different MBE growth temperatures.

transient reflectivity was also studied as a function of the measurement temperature in the range of 11–300 K in the samples grown at 150, 300, and 480 °C. In these samples, there is a decrease in the decay time between 300 and 200 K, below which there is no noticeable change. This is shown in Fig. 2.

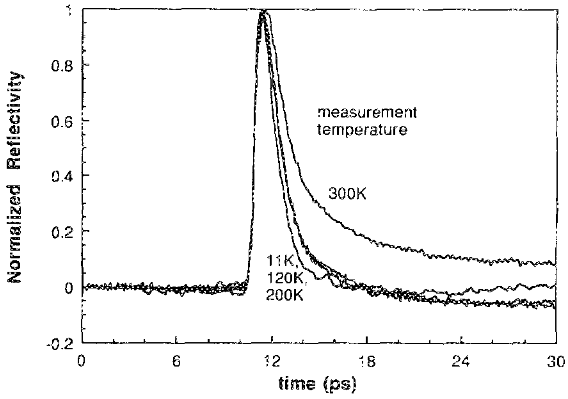

FIG. 2. Time-resolved reflectivity as a function of measurement temperature from 11 to 300 K, for the 300 °C MBE-grown $In_{0.52}Al_{0.48}As$ layer.

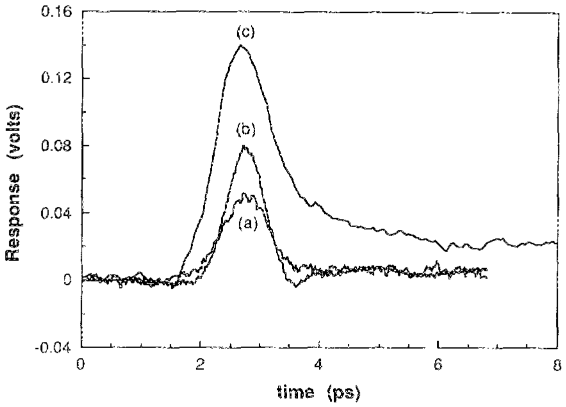

FIG. 3. Photoconductive response of 15 μm gap switches on 150 °C MBE-grown $In_{0.52}Al_{0.48}As$, measured by external electro-optic sampling for (a) unannealed, (b) external annealed (at 300 °C for 10 min), and (c) *in situ* annealed (at 500 °C for 10 min) materials.

The photoconductive switch response measured by external electro-optic sampling is shown in Fig. 3 for the sample grown at 150 °C. Three cases are shown: unannealed, external annealed, and *in situ* annealed. It is seen that in the former two cases, the subpicosecond $1/e$ fall time of $\sim$0.5 ps (partly system response limited[8]) is maintained which matches very well with the fall time of $\sim$0.4 ps as obtained from the time-resolved reflectivity data. However, with *in situ* anneal, the switching response slows down to about 1.2 ps as is also indicated by the decay time from the transient reflectivity data. The *in situ* annealed material also exhibits a fairly long decay component ($\sim$10 ps) in the photoconductive response. The responsivity is seen to improve marginally with external anneal and moderately with *in situ* anneal. The best responsivity translates into an approximate mobility[9] value of $\sim$ 5 cm²/V s , for the photoconductive switch response.

Assuming that the measured transient response time of reflectivity or photoconductivity is related to a single recombination center, an average capture cross section of these centers can be estimated by fitting the data to a recombination decay of hyperbolic nature.[10] This kind of decay is expected as the initial photoinjected carrier density of $\sim 4\times10^{17}/\text{cm}^3$ is very large to satisfy minority-carrier injection in this nominally undoped material. These capture cross sections are plotted in Fig. 1(b) as a function of the growth temperature. It is clear that for growth temperatures down to 200 °C , $\sigma \sim (2–6)\times10^{-14}$ cm², but increases by almost an order of magnitude for the sample grown at 150 °C. These values of capture cross section are certainly of the right order of magnitude expected for deep level recombination centers in III-V materials. Hence picosecond lifetimes[6] are possible if the concentration of these deep levels is $\gtrsim 10^{18}/\text{cm}^3$.

It is important to try to understand the nature of these materials in which high resistivity and short switching times are observed. For this it is useful to consider the temperature-dependent transient reflectance measurement. It is observed that the decay time progressively decreases from 300 to 200 K and then remains fairly constant. This decay consists of an initial capture by traps and a subsequent reemission. Similar behavior has been observed in amorphous silicon,[6] where the reemission from traps decreases with lowering of measurement temperature. This is interpreted to be due to a reduction in the thermal emission rate of captured carriers in localized states back to extended states.[6] We believe that similar behavior in InAlAs is due to presence of shallow localized states from which reemission can occur followed by recombination at a deep level.

Another fact which is quite evident from the data is that the nature of the material grown at 150 °C is remarkably different from those grown at higher temperatures. This is evident from the data of Fig. 1. In particular, the sign of the reflectivity is reversed for the sample grown at 150 °C, which suggests that the nature of the material, and the traps therein are different. The reversal in the sign of the transient suggests a fast carrier depletion effect upon photoexcitation. This may occur due to the involvement of bound states.

In conclusion, we have investigated time-resolved reflectivity and photoconductivity behavior in $In_{0.52}Al_{0.48}As$ grown on InP substrates by MBE at temperatures ranging from 150 to 480 °C. Recombination times (τ_R) are reduced with lowering the growth temperature, with $\tau_R \sim 400$ fs for growth at 150 °C. Field-effect transistors having improved performance with the low-temperature layer as a buffer layer have been demonstrated.[5] The material therefore shows promise for the realization of integrated subpicosecond optoelectronic switches for high-speed testing and other applications. The photocarrier response exhibits more complicated behavior than is expected from a simple trapping/recombination event.

The authors acknowledge helpful discussions with Professor J. Singh. One of us (S.G.) acknowledges the help of M. Frankel and J. Chwalek for some of the measurements. This work was supported by the Air Force Office of Scientific Research, University Research Initiative under contract number F49620-87-C-0016 and the Army Research Office (URI program) under contract DAAL03-87-K-0007.

[1] H. Ohno, C. E. C. Wood, L. Rathburn, D. V. Morgan, G. W. Wicks, and L. F. Eastman, J. Appl. Phys. **52**, 4033 (1981).

[2] G. J. Davies, T. Kerr, C. G. Tuppen, B. Wakefield, and D. A. Andrews, J. Vac. Sci. Technol. B **2**, 219 (1984).

[3] A. S. Brown, J. A. Henige, and M. J. Delaney, Appl. Phys. Lett. **52**, 1142 (1988).

[4] W. P. Hong, J. Singh, and P. Bhattacharya, IEEE Electron Device Lett. **EDL-7**, 480 (1986).

[5] A. S. Brown, U. K. Mishra, C. S. Chou, C. E. Hooper, M. A. Melendes, M. Thompson, L. E. Larson, S. E. Rosenbaum, and M. J. Delaney, IEEE Electron Device Lett. **EDL-10**, 565 (1989).

[6] D. H. Auston, "Picosecond Photoconductors: Physical Properties and Applications," in *Picosecond Optoelectronic Devices* (Academic, Orlando, 1984), pp. 73–117.

[7] F. W. Smith, S. Gupta, H. Q. Le, M. Frankel, V. Diadiuk, D. R. Dykaar, M. A. Hollis, G. Mourou, A. R. Calawa, and T. Y. Hsiang, Appl. Phys. Lett. **54**, 890 (1989).

[8] J. A. Valdmanis, Electron. Lett. **23**, 1308 (1987).

[9] D. H. Auston, P. Lavallard, N. Sol, and D. Kaplan, Appl. Phys. **36**, 66 (1980).

[10] V. K. Mathur, P. S. Mak, and C. H. Lee, J. Appl. Phys. **51**, 4889 (1980).