Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 124-126

Subpicosecond Carrier Lifetime in Low-Temperature-Grown GaAs Layer on (311)-Oriented Substrate

T. M. Cheng, C. Y. Chang[1], G. R. Lin, F. Ganikhanov, C. L. Pan[2], and J. H. Huang[3]

Institute of Electronics[1], National Chiao-Tung University, Hsinchu, 300, Taiwan, Republic of China
Institute of Electro-Optical Engineering[2], National Chiao-Tung University, Hsinchu, 300, Taiwan, Republic of China
Materials of Science Center[3], National Tsing-Hua University, Hsinchu, Taiwan, Republic of China

Femtosecond time-resolved reflectivity measurement has been used to study the carrier lifetime in GaAs layer grown on (311)-oriented substrate by molecular beam epitaxy at low substrate temperature. In both the as-grown and post-growth-annealing states, the carrier lifetime is shorter for the (311) sample than that in the (100) sample. The shorter carrier lifetime together with the high crystalline quality and high concentration of As precipitates make annealed low-temperature GaAs layer grown on (311)-oriented substrate as an interesting alternative for ultrafast photoelectronic device application than annealed (100) sample.

1. TEXT

High-speed photoconductive optoelectronic detectors have attracted much attentions due to their possible applications as subpicosecond optoelectronic switches and sampling gates.[1] To achieve ultrafast optoelectronic performance, materials with properties such as short carrier lifetime, high carrier mobility, high dark resistivity, and high dielectric breakdown are desired. Techniques such as ion implantation,[2] or growth of polycrystalline or amorphous layers[3] have been used to shorten the carrier lifetime. However, devices fabricated from these materials typically are less desirable owing to low mobility and low resistivity. Recently, layers of GaAs and other III-V semiconductor grown by molecular beam epitaxy (MBE) at low substrate temperatures[4,5] (LT-GaAs) have been demonstrated to exhibit superior characteristics than any other photoconductors.

When grown at a temperature of about 200 °C, the GaAs layer contains about 1 at. % excess arsenic,[6] The excess arsenic results in an expansion of lattice constant and a high concentration of antisite defect[7] ($\sim 10^{19}$ cm^{-3}) with a deep-level donorlike character. The as-grown LT-GaAs layer is known to have a relatively low resistivity[7] (~10 W-cm) and a low mobility, therefore even though it possesses a fast carrier response, it is not an ideal photoconductor. Upon post-growth annealing at high temperatures (600-900 °C), the excess arsenic precipitate into clusters,[8,9] which change the layer's resistance into an extremely high resistivity state ($\geq 10^7$ W-cm). The improved resistivity and mobility make the annealed LT-GaAs layer more suitable for photoconductive device application, in spite of a little longer carrier lifetime due to the reduction of defect concentration. In this work, we use femtosecond time-resolved reflectance measurements to study the carrier lifetime in the LT-GaAs layers grown on (311)-oriented GaAs substrate. These experiment data are demonstrated for the first time to our knowledge, that carrier lifetime as short as 200 fs is observed from the as-grown layer on (311)B-oriented substrate. This value is shorter than that (330 fs) on the (100) sample. The shorter carrier lifetime together with high crystal quality, as confirmed from the transmission electron microscopy study, make LT-GaAs layer on (311) substrate become an interesting material for ultrafast photoelectronic applications.

The epilayers used in this work were grown in a Varian GEN II MBE system using element solid source effusion cells and uncracked As_4. Semi-insulating (SI) GaAs substrates with (100) and (311)B orientations were mounted simultaneously on the same Mo block by In solder. The growth procedure has been reported earlier.[10] After native oxide desorpted at 600 °C, a 0.3 mm GaAs buffer layer was first deposited to provide a oxide-free smooth surface. Following the substrate temperature stabilized at 215 °C, a LT-GaAs layer of 0.5 mm was deposited with 1.0 mm/h growth rate and As_4/Ga ratio (beam equivalent pressure ratio) of 24. After growth, the samples were cleaved into pieces and annealed in a furnace at 600 °C for 10 min. with a GaAs wafer encapsulant. The crystal quality was characterized by double crystal x-ray diffraction (DXRD) and transmission electron microscope (TEM).

Ultrafast photoresponses were measured in femtosecond pump and probe experiments where transient reflectivity of the samples were detected. The pump-probe experimental setup is standard. The light source was a home-made passively mode-locked Ti:sapphire/HITCI+IR140 laser generating 90 fs pulses at repetition rate of 85 MHz. For this experiment, the laser wavelength was tuned to about 857 nm (~1.45 eV). The laser beam was divided into excitation and probe with a 20/1 ratio. The polarization directions of the beams were set exactly perpendicular to minimize the contribution of

the coherent artifact. Noncollinear geometry of excitation and probe beams was employed. The average power of the intensity-modulated beam at 2.5 kHz was 50 mW. This correspond to an optical pulse energy of 1.2 nJ per pulse. The intensity changes in the reflected probe beam were detected by large area Si photodiodes and fed to a lock-in amplifier. We estimated that excess carrier density generated by the pump pulse at our focusing conditions and excitation wavelength were in the range of $5x10^{17}$ - $2x10^{18}$ cm^{-3}. The time resolution of our pump-probe apparatus is 145 fs as characterized by the measurement of the cross-correlation between the pump and probe pulses in a 0.2 mm thick KDP crystal. To obtain the carrier lifetimes the experimental pump-probe (differential reflection) signal ($\Delta R/R$) was fitted by a single exponential decay function with the starting point (in most cases typically 100 fs from the peak) and varying the parameter until the best fit was obtained.

Figure 1 shows the time evolution plot of the normalized reflectivity change ($\Delta R/R$) after a photoexcitation on the as-grown LT-GaAs layers grown on (100) and (311)B substrates. The data in Fig. 1 show a fast rise followed by a rapid recovery back toward normal reflectivity. The peak change in ΔR is approximately 2×10^{-4}. For (100) sample, the curve exhibits a single-exponential decay with a time constant of about 330 fs. Significantly different behaviors are observed for samples grown on the (311)B-oriented surfaces. After laser pulse excitation, the change of reflectivity drops much more rapidly than that in (100) sample, and the carrier lifetimes is estimated to be 200 fs. For the 600 ^{o}C annealed samples, as shown in Fig. 2, the carrier lifetimes increase to 3.3 and 2.2 ps for (100) and (311)B samples, respectively.

In the as-grown state, trapping centers arising from the excess As or other point or structure defects are suggested [11,12] to be responsible for the fast response. In the annealed state, the short carrier lifetime has been ascribed to the As precipitates.[5,13] In this work, the shorter carrier lifetime in (311)B sample, as compared to (100) sample, can be explained reasonably from the DXRD and TEM results. From the DXRD data,[10] the lattice mismatches of the as-grown samples are estimated to be 0.16 % and 0.14 % for (311)B and (100) samples, respectively. The higher excess As concentration and the corresponding higher As-antisite related defects are believed to exist in the (311)B sample. This should lead to the shorter carrier lifetime in the as-grown state, as compared to the (100) sample. From the TEM result, as shown in Fig. 3, high concentration of As precipitates with diameter of about 6 nm distributes uniformly inside the LT-grown region of (100) sample and no obvious structure defects are observed. For the (311)B sample, the average diameter (4 nm) of As precipitate is smaller and the cluster concentration is higher than that in (100) samples. This also should lead to the shorter carrier lifetime in the annealed state, as compared to the (100) sample. From the DXRD and TEM results, the (311)B sample shows high structure perfection (implying high mobility) and contains high concentration of As precipitates (implying high resistivity). Combining these properties with shorter carrier lifetime, LT-GaAs layer on (311)B substrate has been demonstrated to be more suitable for ultrafast photoelectronic device application than (100) sample.

In summary, we have demonstrate the substrate orientation effect on the carrier lifetime of the LT-GaAs layer grown by molecular beam epitaxy at low substrate temperature (215 ^{o}C). The carrier lifetime is shorter for the (311)B than that for the (100) sample in both the as-grown and annealed states. The short carrier lifetime together with the high crystalline quality and high concentration of As precipitates make annealed (311)B-oriented substrate as an interesting alternative for ultrafast photoelectronic device applications than annealed (100) sample.

This work has been supported by the National Science Council of Taiwan, Republic of China, under Contract No. NSC-83-0417-E009-016 and 84-2215-E009-032.

2. FIGURES

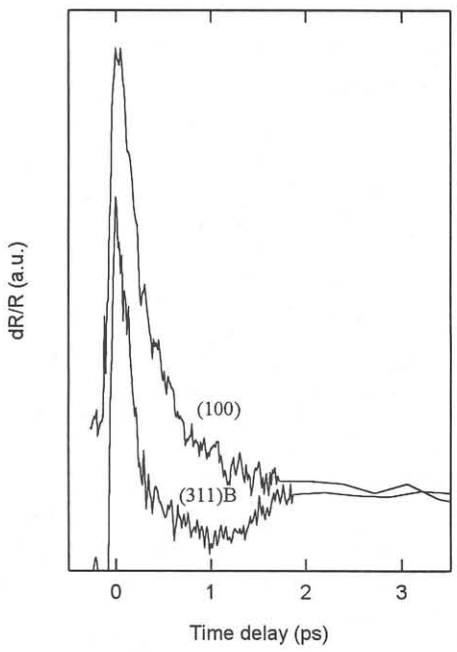


Fig. 1 Transient reflectivity of as-grown LT-GaAs layer grown on (100) and (311)B GaAs substrates.

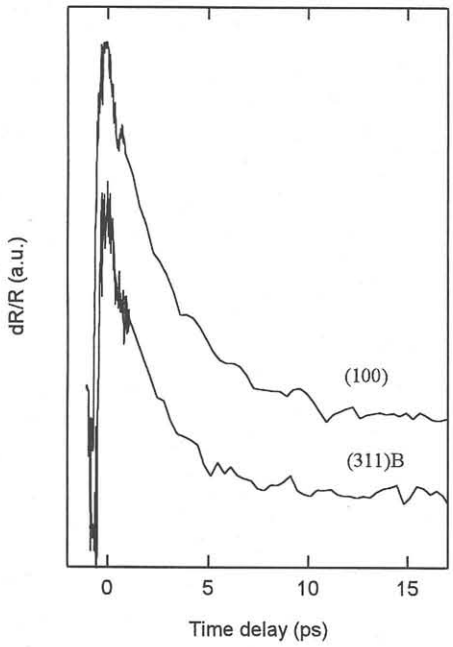
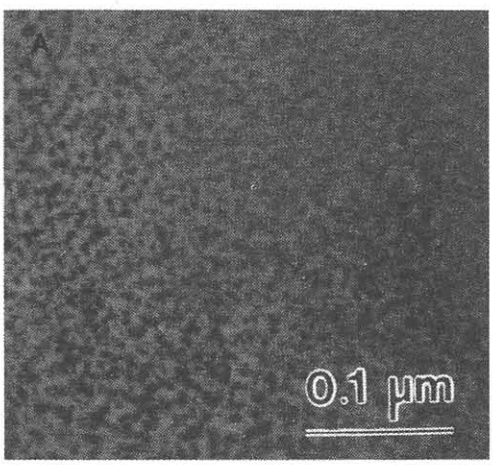


Fig. 2 Transient reflectivity of 600 °C annealed LT-GaAs layer grown on (100) and (311)B GaAs substrates.



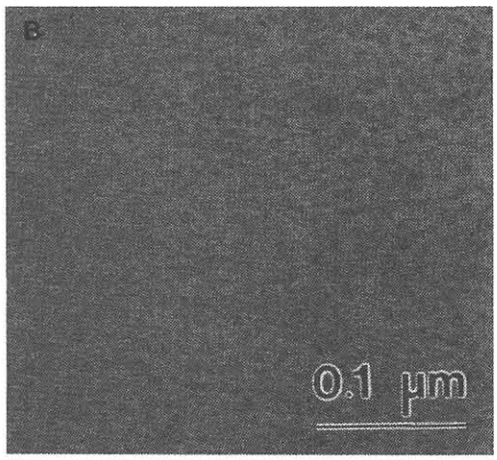


Fig. 3 Bright-field TEM image of 600 °C annealed LT-GaAs layer grown on (a) (100) and (b) (311)B substrate.

3. REFERENCES

1) D. H. Auston, in Picosecond Optoelectronic Device, edited by C. H. Lee (Academic, Orlando, 1984) 73.
2) F. E. Deaany, D. Grischkowsky, and C. C. Chi, Appl. Phys. Lett. 50 (1987) 460.
3) D. H. Auston, P. Lavallard, N. Sol, and D. Kaaplan, Appl. Phys. Lett. 36 (1980) 66.
4) F. W. Smith, H. Q. Le, V. Diadink, M. A. Hollis, A. R. Calawa, S. Gupta, M. Frankel, D. R. Dykaar, G. A. Mouron, and T. Y. Hsiang, Appl. Phys. Lett. 54 (1989) 890.
5) A. C. Warren, N. Katzenellenbogan, D. Grischkowsky, J. M. Woodall, M. R. Melloch, and N. Ostuka, Appl. Phys. Lett. 58 (1991) 1512.
6) M. Kaminska, Z. Liliental-Weber, E. R. Weber, T. George, and J. B. kortright, Appl. Phys. Lett. 54 (1989) 1881.
7) D. C. Look, D. C. Walters, M. O. Manasreh, J. R. Sizelove, C. E. Stutz, and K. R. Erans, Phys. Rev. B 42 (1990) 3578.
8) M. R. Melloch, N. Otsuka, j. M. Woodall, A. C. Warren, and J. L. Freeout, Appl. Phys. Lett. 57 (1990) 1531.
9) T. M. Cheng, C. Y. Chang, and J. H. Huang, Appl. Phys. Lett. 64 (1994) 3626.
10) T. M. Cheng, C. Y. Chang, and J. H. Huang, Appl. Phys. Lett. 66 (1995) 55.
11) S. Gupta, M. Y. Frankel, J. A. Valdmanis, J. F. Whitaker, G. A. Mourou, F. W. Smith, and A. R. Calawa, Appl. Phys. Lett. 59 (1991) 3276.
12) Z. Lilental-Weber, J. J. Cheng, S. Gupta, J. Whitaker, K. Nichols, and F. W. Smith, J. Electron. Mat. 22 (1993) 1465.
13) E. S. harmon, M. R. Melloch, J. M. Woodall, D. D. Notte, N. Otsuka, and C. L. Chang, Appl. Phys. Lett. 63 (1993) 2248.