Reflection high-energy electron diffraction studies of the growth of strained $In_xGa_{1-x}As$ on GaAs substrate by migration-enhanced epitaxy

Y. C. Chen, P. K. Bhattacharya, and J. Singh
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

(Received 20 December 1989; accepted for publication 2 June 1990)

Reflection high-energy electron diffraction oscillations have been studied during the growth of strained $In_xGa_{1-x}As$ on GaAs by molecular beam epitaxy and migration-enhanced epitaxy. The oscillations decay rapidly for $x > 0.2$ during molecular beam epitaxy, while they persist for a long while during migration-enhanced epitaxy. We believe that the altered surface reconstruction pattern in the latter case changes the growth mode from three-dimensional to a near perfect two-dimensional mode for high strain values. Using migration-enhanced epitaxy, we demonstrate improved channel mobility and performance of GaAs-based modulation-doped field-effect transistors and narrower linewidths in the low-temperature excitonic photoluminescence of $In_{0.1}Ga_{0.9}As/Al_{0.3}Ga_{0.7}As$ quantum wells.

Strained $In_xGa_{1-x}As$ layers have recently been used intensively as active regions of high-frequency and high-speed modulation-doped field-effect transistors (MODFETs) as well as optical devices.[1,2] To fully utilize the advantages provided by strained layers, one must be able to deposit the pseudomorphic heterostructure with very high quality and obtain atomically smooth interfaces. In molecular beam epitaxy (MBE), a smooth growth front can be achieved if the growth is in a layer-by-layer two-dimensional mode. This requires the randomly arriving atoms/molecules be able to migrate a large distance so that they are incorporated at step sites.[3,4] This picture describes MBE of lattice-matched systems very well since in these systems the free-energy minimum for the growth front favors an atomically smooth surface. However, it has been observed that, for pseudomorphically strained $In_xGa_{1-x}As$ grown on a GaAs substrate by MBE at the standard growth temperature (520 °C), the compressive strain induced by excess indium tends to make the growth front roughen. The argument used to explain this observation is that the minimum free energy for a strained system may favor a three-dimensional (3D) surface.[5] If this is the case, then the growth of strained systems cannot be improved simply by enhancing the surface migration rate of atoms.

One expects the free energy to depend upon the surface reconstruction during growth. In MBE the surface is anion stabilized with *a* (2×4) or *c* (2×8) reconstruction. It is therefore important to examine other possible surface reconstructions which might change the surface chemical energy. Since MBE of III-V semiconductors cannot be carried out under a cation-rich condition because the excess cation causes nonstoichiometric growth, we examine here the migration-enhanced epitaxy (MEE) approach (Fig. 1),[6-9] where a few monolayers (up to four) of cations and a monolayer of the anion are alternately deposited by shutter control. The surface reconstruction thus alternates between cation and anion stabilized. In this letter we report the *in situ* refraction high-energy electron diffraction (RHEED) observations on the growth of $In_xGa_{1-x}As$ on GaAs by both MEE and normal MBE with different growth parameters. Properties of $In_xGa_{1-x}As$/AlGaAs MODFETs and quantum well structures grown by the two techniques are also compared.

RHEED oscillations were observed for growth of $In_xGa_{1-x}As$ on (001) GaAs substrates in a Varian GEN-II MBE system. The RHEED system consists of a commercial 10 keV electron gun focused onto a phosphor-coated screen. Light from the specular spot in the pattern was collected by a lens and focused onto a photomultiplier tube. Prior to RHEED observations, growth was interrupted under As_4 overpressure for about 10 min to allow a smoothening of the surface. Strained $In_xGa_{1-x}As$ layers with different indium mole fractions were then grown on the buffer by both MBE and MEE techniques. The growth rate was ~0.6 μm/h. Substrate temperatures ranging from 520 up to 600 °C were used to reveal their effects on the growth modes for normal MBE. It may be noted that in growing $In_xGa_{1-x}As$ at high substrate temperatures, significant reevaporation of indium may occur.[10] In our system, however, approximately constant indium incorporation rates were maintained as judged from the period of the RHEED oscillations and post-growth x-ray diffraction measurements.

We note that during the growth of $In_xGa_{1-x}As$ by MBE with low V/III pressure and very high substrate tem-

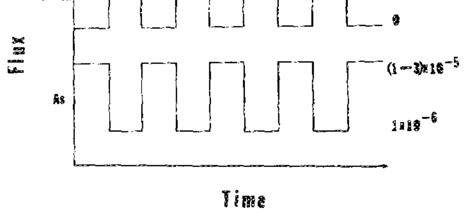

FIG. 1. Temporal variation of group III and V fluxes for migration-enhanced epitaxy.

0003-6951/90/330692-03$02.00

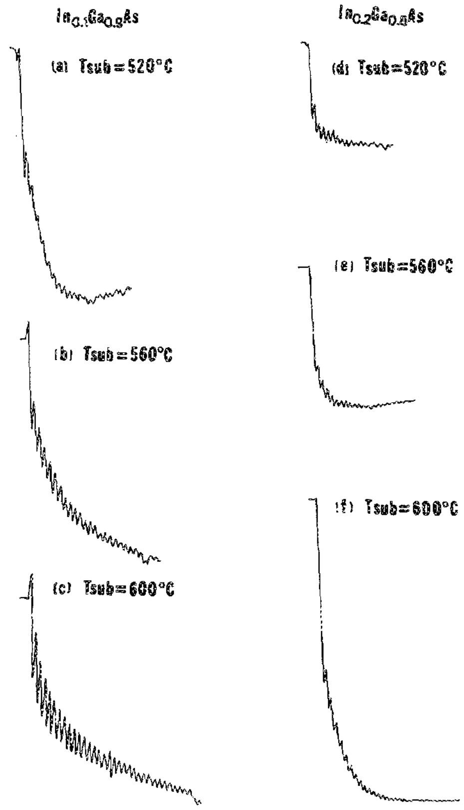

FIG. 2. RHEED intensity oscillations observed during MBE growth of $In_xGa_{1-x}As$ at different substrate temperatures: (a), (b), (c) $P_{Ga}=5.2\times10^{-7}$ Torr, $P_{As}=3\times10^{-5}$ Torr, $P_{In}=1.14\times10^{-7}$ Torr (d), (e) $P_{In}=2.28\times10^{-7}$ Torr.

peratures, RHEED oscillations may terminate abruptly after a few monolayers are deposited. This is because at very high temperatures the growth front changes from the arsenic-stabilized phase into a cation-stabilized phase, resulting in the formation of droplets of cation atoms. This should not be confused with the effects of strain. The abrupt termination of RHEED oscillations can be prevented even at very high temperatures provided the arsenic flux is high enough to maintain an anion-stabilized growth front. Figure 2 illustrates the measured RHEED oscillations for $P_{Ga}=5.2\times10^{-7}$ Torr, $P_{As}=3\times10^{-5}$ Torr, $P_{In}=1.14\times10^{-7}$ Torr [(a)–(c)], and $P_{In}=2.28\times10^{-7}$ Torr [(e)–(f)]. One can see that with this V/III flux ratio, instead of an abrupt termination, the oscillations exhibit a gradual decay even at 600 °C. Though the oscillations are slightly improved at high temperatures, they are by no means comparable to those obtained in lattice-matched growth. These results verify the argument that strained-layer MBE at high misfit values favors a 3D growth mode.

Next we discuss the RHEED oscillations observed during MEE of strained layers. Shown in Figs. 3(a)–3(c) are the oscillations observed under the MEE condition. During MEE growth the surface changes from cation to anion stabilized phase alternatively, corresponding to the opening of the source shutters. This makes the structure of the oscillations very different from those of the anion-stabilized MBE case. If the shutter opening time is adjusted such that approximately a monolayer of atoms are deposited in each shutter opening, near-perfect 2D growth is possible, with long-lasting oscillations. Differences in

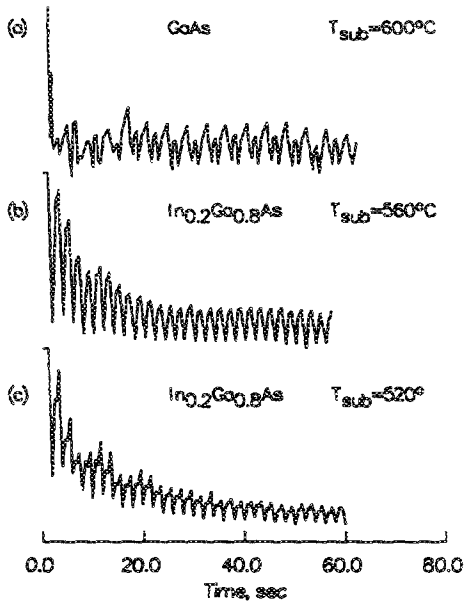

FIG. 3. RHEED intensity oscillations observed during growth of $In_xGa_{1-x}As$ by MEE: (a) $P_{Ga}=4.65\times10^{-7}$ Torr, $P_{As}=1.5\times10^{-5}$ Torr, (b), (c) $P_{In}=2.05\times10^{-7}$ Torr.

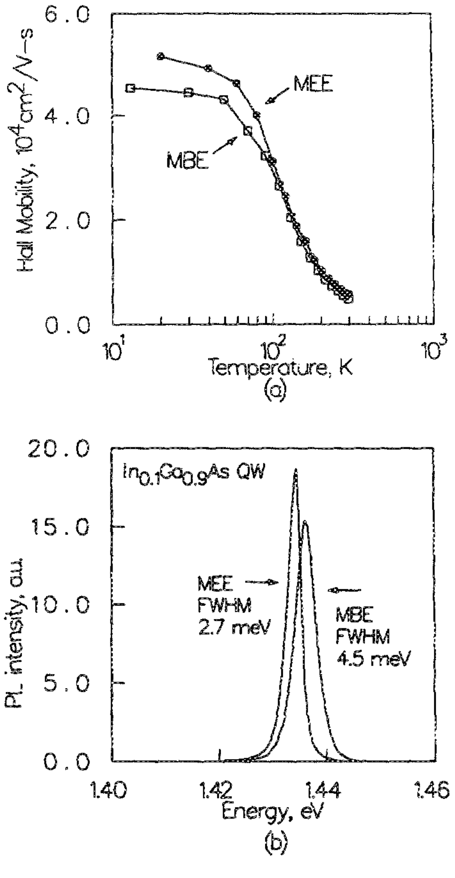

FIG. 4. (a) Hall mobility as a function of temperature in $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ MODFET structures and low-temperature PL data for $Al_{0.3}Ga_{0.7}As/In_{0.1}Ga_{0.9}As$ quantum well structures with 150 Å well size.

RHEED patterns between MBE and MEE are also observed for $In_xGa_{1-x}As$ with $x = 0.3$. In MBE growth, the RHEED pattern becomes spotty after a few monolayers are deposited. In MEE, the pattern remains streaked even after 20 monolayers.

The long-lasting RHEED oscillations in strained-layer MEE indicate that the growth is perfectly 2D. We also emphasize that strained-layer anion-stabilized MBE favors 3D growth. This suggests that due to strong surface reconstruction differences between the two techniques the free-energy minimum configuration may be different. Further studies are required to verify this interesting and important observation.

To verify the advantages of MEE over MBE, we have compared the properties of GaAs-based $Al_{0.3}Ga_{0.7}As/In_{0.2}Ga_{0.8}As$ MODFETs with 100 Å $In_{0.2}Ga_{0.8}As$ channels. In one set the entire structure is grown by MBE at 560 °C while in the other the last five monolayers of the $In_{0.2}Ga_{0.8}As$ channel are grown by MEE. The latter exhibits improved mobilities at temperatures ranging from 13 to 300 K [Fig. 4(a)]. The channel electron density in the two structures is $\sim 1.5\times10^{12}$ cm^{-2}. 1 μm gate MODFETs made of the MEE samples also show improved dc transconductance and microwave performance. For example, at room temperature $g_m = 108$ and 59 mS/mm in the devices grown by MEE and MBE, respectively. Note that the low g_m values are partly due to the low electron densities. Low-temperature photoluminescence (PL) measurements were also made on $Al_{0.3}Ga_{0.7}As/In_{0.1}Ga_{0.9}As$ quantum well structures with 150 Å well size. In one set the whole structure is grown by MBE while in the other the $In_{0.1}Ga_{0.9}As$ well is grown by MEE. The latter shows narrower PL linewidth [Fig. 4(b)]. These results suggest that MEE is superior to MBE for highly strained-layer growth, and should emerge as a viable technique for the realization of high-performance devices.

The authors acknowledge the help and comment provided by P. R. Berger. This work was supported by the Office of Naval Research under grant no. N00019-89-J1519.

[1] T. Henderson, M. Aksun, C. Peng, H. Morkoç, P. Chao, P. Smith, K. Duh, and L. Larson, 1986 International Electron Devices Meeting Technical Digest, p. 464.

[2] G. C. Osbourn, B **1**, 379 (1983).

[3] J. Singh and K. K. Bajaj, Superlatt. Microstruct. **2**, 185 (1986).

[4] J. H. Neave, P. J. Dobson, B. A. Joyce, and J. Zhang, Appl. Phys. Lett. **47**, 100 (1985).

[5] P. R. Berger, K. Chang, P. Bhattacharya, and J. Singh, Appl. Phys. Lett. **53**, 684 (1988).

[6] J. M. Gerard and J. Y. Marzin, Appl. Phys. Lett. **53**, 568 (1988).

[7] R. Katsumi, H. Ohno, H. Ishii, K. Matsuzaki, Y. Akatsu, and H. Hasegawa, J. Vac. Sci. Technol. B **6**, 593 (1988).

[8] J. M. Gerard, J. Y. Marzin, B. Jusserand, F. Glas, and J. Primot, Appl. Phys. Lett. **54**, 30 (1989).

[9] F. Briones, L. Gonzalez, and A. Ruiz, Appl. Phys. A **49**, 729 (1989).

[10] E. G. Scott, D.A. Andrews, and G. J. Davies, J. Vac. Sci. Technol. B **4**, 534 (1986).