

Initial stage of epitaxial growth at the high temperature of GaAs and AlGaAs on Si by metalorganic chemical vapor deposition

T. Soga, T. George,^{a)} T. Jimbo, and M. Umeno

Department of Electrical and Computer Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466, Japan

E. R. Weber

Department of Material Science, University of California, Berkeley, California 94720

(Received 1 November 1990; accepted for publication 11 December 1990)

GaAs and AlGaAs grown directly on Si were characterized by transmission electron microscopy. Both GaAs and AlGaAs grow three-dimensionally on Si at 750 °C. The spacing between GaAs islands is large, while the AlGaAs islands appear to be contiguous for a nominal thickness of 22.5 nm. There is a high density of dislocations, stacking faults, and microtwins in the thin GaAs layer, but drastic reduction of such defects was observed in the planar AlGaAs nucleation layer.

The heteroepitaxial growth of GaAs on Si has been an active research area in recent years and various devices have been fabricated on these layers.¹ However, the problems of high dislocation densities and stress in the GaAs/Si layer have not been solved yet. Usually, GaAs is grown on Si by the two-step growth method, where the first step is the growth of a low-temperature GaAs nucleation layer.² The role of the low-temperature GaAs layer is to ensure complete coverage of the Si substrate surface at the initial stage of growth. However, many structural defects exist in the low-temperature GaAs/Si layers, and defects such as dislocations or stacking faults propagate towards the upper GaAs layer. It was reported that the low-temperature GaAs nucleation layer grows on Si three-dimensionally.³ Once the GaAs islands are formed on the Si substrate at the first stage of growth, many defects such as dislocations and stacking faults could be produced during coalescence of the islands. On the other hand, if two-dimensional growth of GaAs on the Si substrate from the beginning of growth is realized, the dislocation density could be lowered considerably.

Atomic layer epitaxy of AlAs on Si has been reported⁴ to achieve the two-dimensional growth of compound semiconductors on Si. However, the conventional growth method is the preferred one for practical applications.

In previous papers,^{5,6} we reported that the growth mode of $\text{Al}_x\text{Ga}_{1-x}\text{P}$ changes from three-dimensional to two-dimensional with increasing x . The problem with using a structure such as GaAs/AlGaP/Si is that GaAs tends to grow on AlGaP three-dimensionally even if the AlGaP intermediate layer grows on Si two-dimensionally. Therefore an intermediate layer is required between GaAs and AlGaP in order to eliminate island-type growth. An alternative approach is attempting the two-dimensional growth of GaAs on Si by growth on an intermediate III-V compound semiconductor layer which is lattice matched to GaAs such as AlGaAs, since it is well known that GaAs

grows on AlGaAs two-dimensionally. This letter reports the initial stage of epitaxial direct growth of GaAs and AlGaAs on Si by metalorganic chemical vapor deposition (MOCVD).

Epitaxial layers were grown by a conventional MOCVD system consisting of an atmospheric pressure horizontal reactor with an rf-heated susceptor. The source materials were trimethylgallium, trimethylaluminum, and AsH_3 . Vicinal (100)Si substrates, misoriented 2° towards [011] were used. The substrate surface preparation procedures have been reported elsewhere.⁷ The growth temperature and V/III ratio were 750 °C and 40, respectively. The epitaxial layers were characterized by transmission electron microscopy (TEM) operating at 200 kV.

Figures 1(a) and 1(b) show the cross-sectional TEM micrographs of 22.5-nm-thick and 3- μm -thick GaAs grown directly on Si, respectively. It is observed that the GaAs layer forms separate islands at the initial stage of growth. The average island spacing is estimated to be about 600–700 nm from the TEM micrograph. A high density of defects such as stacking faults, microtwins, and dislocations are observed in the islands. The islands increase in size with increasing growth time. At a nominal thickness of 3 μm , the GaAs layer is almost polycrystalline and contains a high density of structural defects. The lack of a single epitaxial orientation and the high density of defects are presumed to have been formed during the growth and coalescence of the GaAs layer.

Conventional and high-resolution TEM micrographs of cross-sectional $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ grown on Si are shown in Figs. 2(a) and 2(b), respectively. The nominal thickness of the AlGaAs layer is 22.5 nm. Comparing Figs. 1(a) and 2(a), there is a large difference between the defect generation and growth behavior of GaAs and AlGaAs. Island-type growth is observed in both figures. However, the island density of AlGaAs on Si is higher than in the corresponding GaAs/Si direct growth [Fig. 1(a)]. The AlGaAs islands appear to be connected. These islands are highly defective with stacking faults and microtwins, but some microtwins are terminated during growth by mutual interactions. Figure 3 shows a cross-sectional TEM (200) dark

^{a)}On leave from University of California, Berkeley 04720. Present address: Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109.

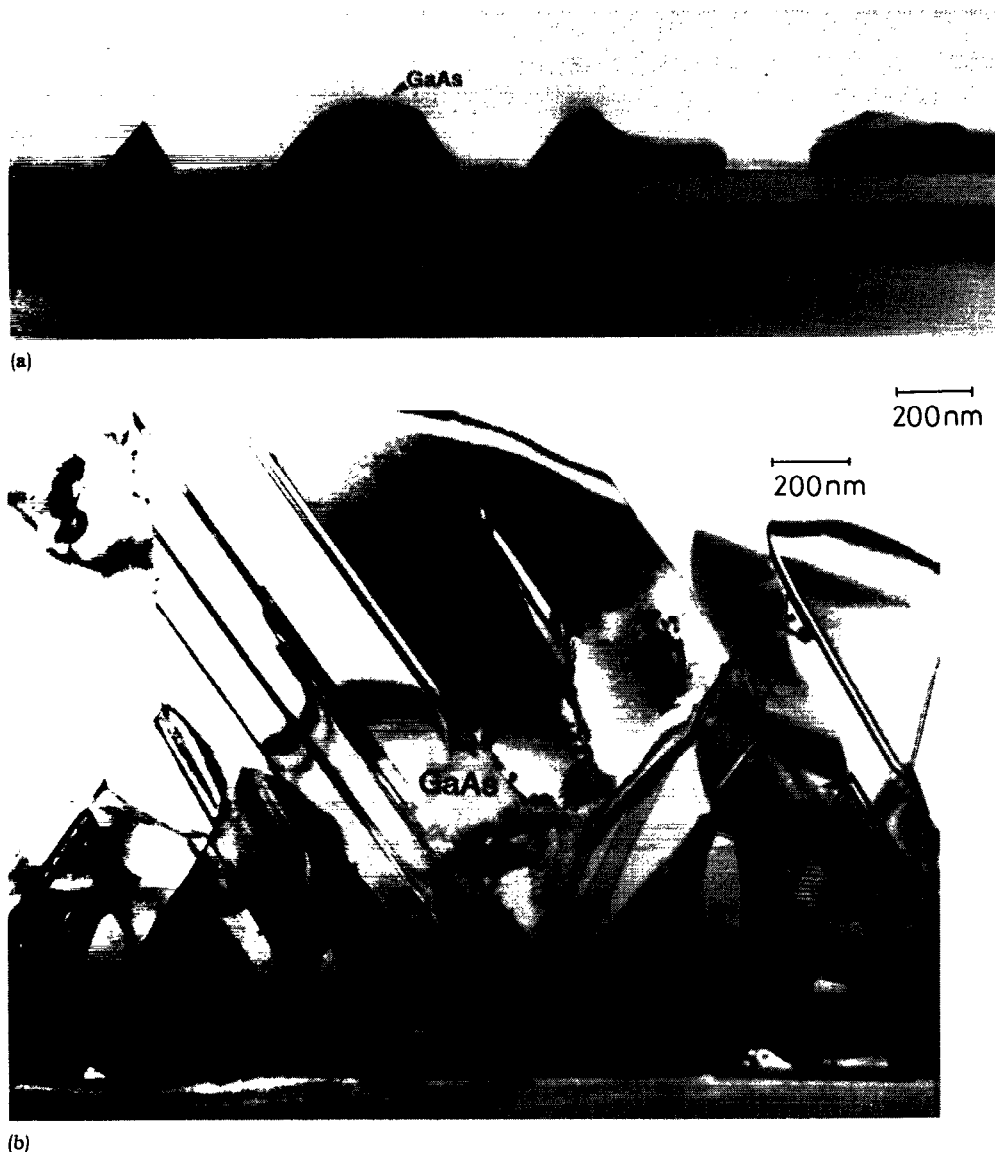


FIG. 1. Cross-sectional TEM micrographs of GaAs on Si grown at 750 °C. The GaAs layer thickness is (a) 22.5 nm and (b) 3 μ m.

field image of 3 μ m GaAs on Si with a 22.5-nm-thick $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ intermediate layer. Stacking faults observed in AlGaAs annihilated at the interface of GaAs and AlGaAs , and the defect density in the GaAs layer is very low. Comparing Figs. 1(b) and 3, drastic reduction of defects is observed through the use of the AlGaAs intermediate layer. Defect density is low in spite of the fact that traditional defect reduction methods such as strained layer superlattices, thermal cycle annealing, and low-temperature nucleation layers have not been used.

The growth of III-V/Si heteroepitaxial layers by MOCVD can be considered to take place by the diffusion of growth species through the boundary layer followed by surface migration to the nucleation sites. When one compares the nucleation modes for GaAs and AlGaAs on Si, the differences in the Si substrate coverage indicate a distinction between the surface migration behavior of the two materials. It was speculated earlier⁶ that the highly reactive nature of Al could contribute to increased “wetting” of the Si substrate by the AlGaAs layer, through the formation of

Al—Si bonds and also by means of surface reactions of the Al with residual oxide.

In the case of the GaAs layer on Si, surface migration is enhanced perhaps because the wetting of the Si substrate by Ga is weak. The migration process thus determines the nucleation density of the GaAs. When the nuclei cross the critical size, stable separated islands of GaAs are formed and further growth occurs by growth, both laterally and vertically of these islands. Additionally the lattice mismatch induced strain of the GaAs/Si layer could contribute to the lack of two-dimensional growth. By minimizing the interface contact area, the strain energy in the GaAs can be reduced.

The dissimilarity in the defect generation and propagation behavior in these layers is also of interest. The three-dimensional growth mode of the GaAs layer, consisting of widely separated islands, is probably responsible for the high defect densities observed in the fully coalesced layers.⁸ The GaAs islands are highly defective and since the island sizes are relatively large on coalescence, thermal annealing



FIG. 2. (a) Conventional and (b) high-resolution TEM micrographs of $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ on Si grown at 750°C . The AlGaAs thickness is 22.5 nm.

of the structural defects, as in the case of the two-step grown layers, is less likely.⁸ Thus the $3\ \mu\text{m}$ GaAs layers are highly defective and almost polycrystalline in nature.

The AlGaAs nucleation layer does exhibit the presence of structural defects. However the quasi-two-dimensional growth mode with an attendant high coverage of the Si substrate probably is responsible for the defect reduction by annihilation and for a single epitaxial orientation being preserved. Hence the defect density of the GaAs layer, which is then grown above the lattice-matched AlGaAs layer, is considerably reduced and rivals the state-of-the-art two-step grown material. Therefore this promising growth scheme, which is carried out entirely at a single growth

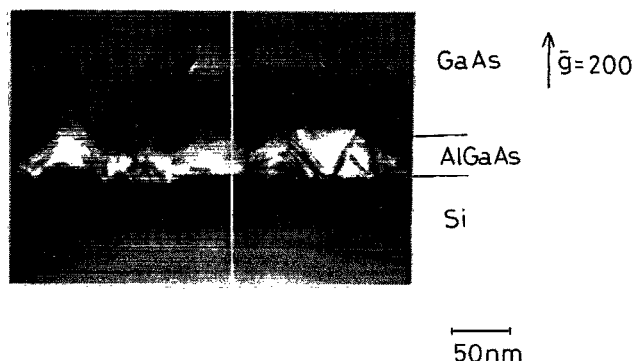


FIG. 3. Cross-sectional TEM (200) dark field image of GaAs on Si with $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ intermediate layer.

temperature, bears further investigation and optimization of the growth conditions.

In summary, the initial stage of epitaxial growth of GaAs and AlGaAs on Si was investigated by TEM. Both GaAs and AlGaAs grow on Si three-dimensionally at the first stage of growth. Separated GaAs islands were formed on Si, but AlGaAs islands were almost connected. Defect reduction of GaAs on Si was observed by using the AlGaAs intermediate layer.

The authors would like to thank Z. K. Jiang for the TEM sample preparation.

¹T. Egawa, H. Tada, Y. Kobayashi, T. Soga, T. Jimbo, and M. Umeno, *Appl. Phys. Lett.* **57**, 1179 (1990).

²M. Akiyama, Y. Kawarada, and K. Kaminishi, *Jpn. J. Appl. Phys.* **23**, L843 (1984).

³H. Takasugi, M. Kawabe, and Y. Bando, *Jpn. J. Appl. Phys.* **26**, L584 (1987).

⁴N. Ohtsuka, K. Kitahara, M. Ozeki, and K. Kodama, *J. Cryst. Growth* **99**, 346 (1990).

⁵N. Noto, S. Nozaki, T. Egawa, T. Soga, T. Jimbo, and M. Umeno, *Mater. Res. Soc. Symp. Proc.* **148**, 247 (1989).

⁶T. George, E. R. Weber, S. Nozaki, A. T. Wu, N. Noto, and M. Umeno, *J. Appl. Phys.* **67**, 2441 (1990).

⁷T. Soga, S. Nozaki, N. Noto, H. Nishikawa, T. Jimbo, and M. Umeno, *Jpn. J. Appl. Phys.* **28**, 2441 (1989).

⁸T. George, S. Nozaki, E. R. Weber, and M. Umeno (to be published in *Mater. Res. Soc. Symp. Proc.*, 1990).