GaAs–InP heteroepitaxy and GaAs–InP MESFET fabrication by MOVPE

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Abstract

Lattice-mismatched heteroepitaxy has attracted considerable attention in recent years. A great interest of these systems is the possibility of integrating devices from different materials on a single substrate. 1.3 and 1.5 μm InGaAs(P)/InP laser diodes are essential for optical communication, whereas InP field effect transistor technology is less developed than that of GaAs MESFET. The performances of laser diodes are much more sensitive to a high density of dislocations, so it would be interesting to grow GaAs MESFET on InP for integration with 1.3 and 1.5 μm lasers. Due to the large difference of the thermal expansion coefficient and lattice parameter between GaAs and InP, it is very difficult to grow GaAs epilayers of high quality on InP substrates due to the large difference of the thermal expansion coefficient and lattice parameter between GaAs and InP. A new method, metalorganic source modulation epitaxy (MOSME), which improves the crystal quality of GaAs epilayers on InP substrates by MOVPE, has been adopted in our laboratory. The lowest full width at half maximum (FWHM) of the double crystal X-ray (DCX) diffraction spectra reaches as low as 120 arcsec for a 5 μm thick layer. Structural properties (misorientation, lattice parameters and crystal quality) of 1.0–5.0 μm thick GaAs layers grown on InP have been measured by DCX diffraction. On GaAs MESFETs grown on InP, we have measured $g_m = 100$ ms/mm. For these transitions, the current gain cut-off frequency ($f_t$) is around 12 GHz and the maximum frequency of oscillation ($f_{max}$) is higher than 30 GHz.

1. Introduction

Non-lattice-matched heteroepitaxy has attracted considerable attention in recent years. A great interest of these systems is the possibility of integration on the same wafer devices grown from different materials, for instance devices based on GaAs and InP. 1.3 μm and 1.5 μm laser diodes are InGaAs(P)/InP heterostructures, whereas InP field effect transistor technology is less developed than that of GaAs MESFET. The performances of laser diodes are much more sensitive to a high density of dislocations, so it would be interesting to grow GaAs MESFET on InP for integration with 1.3 and 1.5 μm lasers.

In this work, we have investigated the structural properties of these layers. We have grown GaAs MESFET on InP with $g_m = 100$ ms/mm by MOVPE.

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2. Growth conditions

Undoped GaAs layers were grown by low-pressure metalorganic vapor phase epitaxy (MOVPE) on (100)-oriented Fe-doped InP substrates, at a pressure of 76 mbar. The horizontal reactor cell had a rectangular cross section. The growth system was designed for rapid gas switching having a compact vent-run manifold. As starting compounds, trimethylgallium (TMGa), trimethylindium (TMIn), phosphine (PH₃) and arsine (AsH₃) were used with Pd-purified hydrogen as the carrier gas. The total flow rate was about 5000 cm³/min. During the heat up to a 650°C state, PH₃ was used to protect the substrate surface. This was cooled down to 425°C to grow the first GaAs buffer layer (~10 nm) using 4.4 sccm of TMGa and 14.5 sccm AsH₃. After that the substrate was heated up to 630°C again in AsH₃ ambient. The flow rate of the TMGa sources was modulated while keeping AsH₃ at 14.5 sccm during the growth of the second GaAs buffer layer (~10 nm). Finally the top GaAs layer was grown with an As:Ga ratio of 60. The thickness of the GaAs layers examined were between 1.0 and 5.0 µm including about 200 µm thick buffer layers.

3. Structural properties

The structural properties of the layers were investigated by double crystal X-ray diffraction. We have studied the dislocation densities and misorientation of the GaAs-on-InP layers.

3.1. Dislocation densities

Epitaxial layers grown on a rigid substrate are under an elastic strain because of a lattice mismatch and/or a difference in thermal expansion coefficients. If the interfacial energy of the epitaxial layer exceeds a critical value, the strain is released by the formation of misfit dislocations and misorientation of the epitaxial layer. In the case of GaAs–InP, the critical thickness is about 1.6 nm [1]. Therefore, the large mismatch between GaAs and InP ensures that there will be virtually no elastic coupling between the two materials in films thicker than a few thousand nanometers. This fact can lead to broadening of the full width at half maximum (FWHM) of the X-ray rocking curve.

Fig. 1 illustrates a typical 400 rocking curve that is obtained from a 5 µm thick GaAs epilayer. The curve has a FWHM of 120 arcsec. Under the assumption that the epitaxial layer can be described as a uniform mosaic structure with simple low-angle boundaries, the dislocation densities can be calculated from the relation [2]

\[ D = \frac{\alpha^2}{9b^2}, \]  

where \( \alpha \) is FWHM in radians after correction for the
instrumental broadening \((\alpha^2 = \alpha_{\text{meas}}^2 - \alpha_{\text{instr}}^2)\) and \(b\) is the length of the Burgers vector for the principal dislocations in the structure. Using the value \(b = \sqrt{a}\) for 60° dislocation, \(a = 0.5653\) nm is the lattice parameter of GaAs, we obtain \(D = 1.3 \times 10^7\) cm\(^{-2}\) for the FWHM of 120 arcsec. It represents the density averaged over the entire epitaxial layer. It may be significantly higher than the dislocation density at the surface [3]. According to the results above, we believe that the two buffer layers with MOSME can improve the epilayer quality especially for lattice-mismatched epitaxy.

Fig. 2 shows the results of photoluminescence measurements on a high-quality GaAs/InP sample. Pump laser power is 10 mW. Its peak energy is around 1.525 to 1.528 eV, which is 0.15 meV larger than that of GaAs. Peak A may be due to a combined contribution of three kinds of binding excitons [4], i.e. that of the neutral donor and neutral acceptor, that of the ionized donors, and that of the defects. Exciton energy of peak B is at 1.497 eV after a subtraction of 15 meV. It must come from the recombination of free electrons with holes of carbon acceptors. From the experimental data of this sample, the pollution of C seems small. The peak of the carbon acceptor is only about one tenth of the main peak and its FWHM is 8.4 meV, which shows that the purity and quality of the sample is good.

3.2. Misorientation and lattice parameters

The misorientation of the GaAs layer with respect to the InP substrate is determined by measuring the dependence of 400 reflections on the rotation of the sample around the [100] direction. In Fig. 3 the two extreme cases of the angular separation \(\Delta \Theta\) for the 400 reflection of GaAs-on-InP are shown. The shift in the GaAs(400) peak position relative to that from the InP substrate during azimuthal rotation is indicative of the misorientation between the substrate and the epitaxial layer. If \(\Delta \Theta\) is the difference in the angular settings for a particular set of planes in the substrate and the epilayer \((\Delta \Theta = \Delta \Theta_{\text{GaAs}} - \Delta \Theta_{\text{InP}})\), then it is possible to separate the effects of lattice distortion from those arising from misorientations. When \(\Delta \Theta_{\text{max}}\) and \(\Delta \Theta_{\text{min}}\) are, respectively, the maximum and minimum angular differences, the misorientation \(\beta\) between the GaAs and InP layers is given by

\[
\beta = \frac{1}{2} (\Delta \Theta_{\text{max}} - \Delta \Theta_{\text{min}}) .
\]
Table 1
Structural parameters of GaAs-on-InP grown by MOVPE

| Sample | Thickness (μm) | a⊥ (nm) | a|| (nm) | β     | FWHM (arcsec) | D (cm⁻²) |
|--------|---------------|---------|---------|-------|---------------|----------|
| 1      | 1.0           | 0.5647  | 0.5664  | 0.05° | 250           | 2.5×10⁷  |
| 2      | 2.0           | 0.5646  | 0.5657  | 0.05° | 200           | 2×10⁷    |
| 3      | 3.0           | 0.5647  | 0.5654  | 0.07° | 120           | 6.2×10⁶  |

While the lattice parameter of GaAs perpendicular to the (400) diffracting planes is calculated from

\[ a_{\perp} = a_{\text{InP}} \left[ \sin(\Theta_{\text{InP}}) / \sin(\Theta_{\text{InP}} + \Delta \Theta) \right], \]

where

\[ \Delta \Theta = \frac{1}{2} (\Delta \Theta_{\text{max}} + \Delta \Theta_{\text{min}}). \]

The lattice constant ratio \(a_{\parallel}/a_{\perp}\) is calculated from

\[ a_{\parallel} = \frac{1 - \nu (k^2 + l^2)^{1/2}}{h \cosec \left[ \arctan \left( k^2 + l^2 \right)^{1/2} / h \right]} \]

\[ = 1 - 1.381 \nu, \]

where \(\nu = \frac{1}{2}(\Delta \Theta_{\parallel} - \Delta \Theta_{\perp})\), \(\Delta \Theta_{\parallel}\) and \(\Delta \Theta_{\perp}\) are the angular separations between the InP and GaAs reflections from the (511) and (311) planes, respectively (as shown in Fig. 4), and \(h = 5, k = 1, l = 1\) the relevant reflection plane indices.

The experimental values of \(a_{\parallel}, a_{\perp}\) and \(\beta\) were calculated from Eq. (2) through Eq. (6) and summarized in Table 1. The value of \(a_{\parallel}\) is larger than \(a_{\perp}\) due to the difference in the thermal expansion coefficients between GaAs and InP. On the other hand, the value of \(a_{\parallel}\) depends on the film thickness, this result may be brought about by the stacking faults of the sample in addition to the dislocations at the interface and affect the measured value of \(a_{\parallel}\).

### 4. GaAs MESFET

Schottky gate field effect transistors were fabricated on GaAs/InP epitaxial layers using a conventional recessed technology. The device structure consists of a 3 μm undoped GaAs buffer layer, a 0.2 μm S-doped channel \((1 × 10^{17} \text{ cm}^{-3})\) and a 0.01 μm contact layer doped to \(3 × 10^{18} \text{ cm}^{-3}\). Mesa etching or implantation were used for device insulation. AuGeNi source and drain ohmic contacts were fabricated by E-beam evaporation. Al gates, 0.6 μm long with widths of 80 μm, were deposited by E-beam evaporation. Pinch-off at 3.0 V and low output conductance were observed and indicate the good quality of the GaAs buffer layers. Electrical characteristics were insensitive to light illumination and the lack of hysteresis in the drain current–voltage sources indicates an absence of deep levels at the channel–buffer or channel–Schottky gate interfaces. Extrinsic transconductance as high as 100 ms/mm was measured. For these transitions, the current gain cut-off frequency \((f_T)\) is around 12 GHz and the maximum frequency of oscillation \((f_{max})\) is higher than 30 GHz (Fig. 5).

### 5. Conclusion

We have studied the growth method of GaAs-on-InP by MOVPE. On a 5 μm thick layer the FWHM of the (400) reflection curve of the DCX diffraction is 120 arcsec, which is the lowest value reported up to date. The measured lattice constants normal \((a_{\perp})\) and parallel \((a_{||})\) to the interface are 0.5647 nm and 0.5664–0.5654 nm, respectively; \(a_{\perp}\) does not depend on the layer thickness, but \(a_{||}\) depends on the layer thickness in the range 1.0–5.0 μm. The magnitude of the relative tilt between the GaAs and InP in
the [100] direction is about 0.05. For GaAs MESFETs grown on InP substrates, we have measured $g_m = 100$ ms/mm. For these transitions, the current gain cut-off frequency ($f_t$) is around 12 GHz and the maximum frequency of oscillation ($f_{max}$) is higher than 30 GHz.

References