Active and Passive Elec. Comp., 2003, Vol. 26(2), pp. 71–79

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DIRECT GROWTH OF HIGH-QUALITY InP LAYERS ON GaAs SUBSTRATES BY MOCVD

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(Received 7 November 2002; In final form 17 November 2002)

In this report, we have overcome the drawback of surface roughness of metamorphic buffer layer by LP-MOCVD technique and have grown InP metamorphic buffer layers with various thickness on misoriented GaAs (1 0 0) substrates with 10 degree towards (1 1 1)A. The grown films are characterized by optical microscopy, atomic force microscopy, secondary ion mass spectrometry, transmission electron microscopy and double-crystal X-ray diffraction. We also analyze the surface morphology, which is dependent on growth temperature, group III and group V partial pressure, growth rate and V/III ratios. A mirror-like, uniform surface and high crystal quality of the metamorphic buffer layer directly grown on a GaAs substrate can be achieved. Finally, to investigate the performance of the metamorphic microwave devices, we also fabricate the InAlAs/InGaAs metamorphic HEMT on GaAs substrates.

Keywords: Metamorphic buffer layer; LP-MOCVD; HEMT

1 INTRODUCTION

The InP-based material has shown great potential for long-distance communications (lasers, light-emitting diodes or detectors) [1,2], high frequency electronic devices (*e.g.* heterojunction bipolar transistors and modulation doped field effect transistors [3]), and opto-electronic intergrated circuits (OEIC) [4], etc. Some feature of the InP substrates such as the limitation of wafer size, high cost and frailness limits the possibility of commercial application. The technology of growing the InP layer on GaAs substrates has become more and more important due to its ability to eliminate the disadvantages of the InP substrates.

In this work, we overcome the difficulty of large mismatch between InP and GaAs layers by LP-MOCVD technique and directly grow InP layer, instead of using graded or inverse-step method, deposited on GaAs substrate. We discuss a new method to directly grow InP layers, instead of using graded buffer layers, on GaAs while maintaining low interface dislocations, high crystal quality, and uniform and mirror-like surfaces of the layers grown by LP-MOCVD. The large lattice defects existing between InP and GaAs layers which lead to numerous interface dislocations and rough surface areas have been suppressed

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ISSN 0882-7516 print; ISSN 1563-5031 online
DOI: 10.1080/0882751031000073797

successfully by accurate control of growth temperature, growth rate, and the group III and V partial pressure with total InP thickness only 400 nm. The surface roughness is measured by atomic force microscopy (AFM). Lower interface dislocations can be observed by transmission electron microscopy (TEM). High crystal quality compared with that in previous studies is measured by an X-ray diffractometer (XRD). Optical microscopy is used to characterize the mirror-like surface.

2 EXPERIMENTAL

In this work, we carry out the direct growth of InP layers on misoriented GaAs substrates in a commercial LP-MOCVD system with an AIXTRON 2400 planetary (vertical) reactor. It is a more practical growth tool for obtaining thick epitaxial layers and the total system is illustrated in Figure 1.

Because the planetary (vertical) reactor can eliminate the side wall effects, we ensure that excellent growth uniformity and high precursor utilization efficiency would be achieved. The top wall of the planetary (vertical) reactor would be the most important factor to influence the growth uniformity, so the ceiling temperature can be controlled to make the ceiling passive. For these reasons, the high quality, excellent uniformity and mirror-like InP surfaces on GaAs substrates can be expected.

The susceptor temperature we chose to grow and analyze was from 400 to 650 °C, and graphite susceptor was heated by six pairs of infrared lamps. The total pressure in reactor, P_{tot}, was 100 mbar and total hydrogen flow rate, Q_{tot}, was 15,000 sccm. We set the ceiling temperature at 170 °C and controlled it by adjusting the H_2/N_2 flow ratio between ceiling and reactor lid. During the growth of the InP layer on GaAs substrate, the gas phase partial pressures of TMIn were set to 2 Pa. The PH_3 partial pressure was changed from 340 to 200, 460 and 600 Pa when the different results were observed by changing the V/III ratio.

As the InP layer was grown, the measured optical properties of the InP layer had been investigated by photoluminescence (PL) performed with Ar^+ laser at room temperature. The interface dislocations and film defects could be observed by transmission electron microscopy (TEM). The surface morphology and roughness of InP layers were observed by optical microscopy and atomic force microscopy (AFM). On the other hand, a typical InAlAs/InGaAs modulation doped structure is shown in Figure 2.

The 500 nm AlInAs is grown on undoped 400 nm-thick InP buffer layer. The active channel is grown next. The thickness of the channel layer is 400 Å. Next, a spacer layer is grown, followed by the electron supplying layer. The doping level of the donor layer is

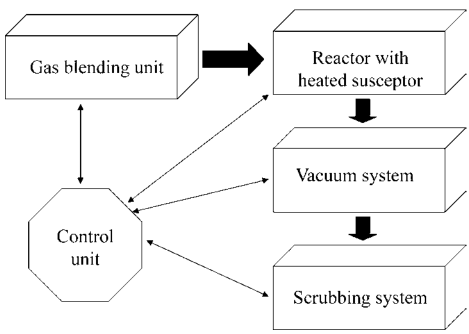

FIGURE 1 Components of a low pressure MOCVD system.

GaInAs	Contact Layer	n=2×10^{18}	(5nm)
AlInAs	Undoped Barrier Layer		(20nm)
AlInAs	Donor Layer	n=4×10^{18}	(12.5nm)
AlInAs	Undoped Spacer Layer		(2nm)
GaInAs	Undoped Channel		(40nm)
AlInAs	Undoped Layer		(500nm)
InP	Metamorphic Layer		(400nm)
GaAs	Semi-insulated Substrate		

FIGURE 2 A typical InAlAs/InGaAs modulation doped structure.

$3 \times 10^{18}\,cm^{-3}$. The low barrier of undoped AlInAs is grown on top of the electron supply layer to reduce gate leakage. Finally a $2 \times 10^{18}\,cm^{-3}$ doped cap layer with 50 Å thickness is grown to facilitate ohmic contact formation.

3 RESULTS AND DISCUSSION

We investigate the effects of crystal quality and surface morphology with different temperatures from 400 °C to 650 °C by direct growing InP layer on GaAs substrate. The thickness of MOCVD-grown InP layer is set to 400 nm. We measure the material wavelength and crystal quality of growth films by PL. The measured PL results with the temperature from 400 °C to

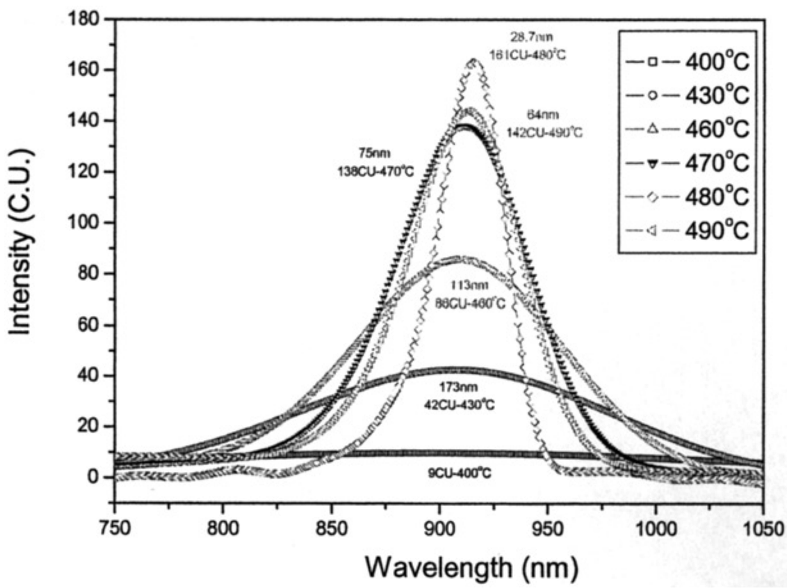

FIGURE 3 The measured PL results at room temperature for the samples of direct growing InP on GaAs substrate using a constant growth rate of 25 nm/min and a thickness of 400 nm. The growth temperature is from 400 to 490 °C.

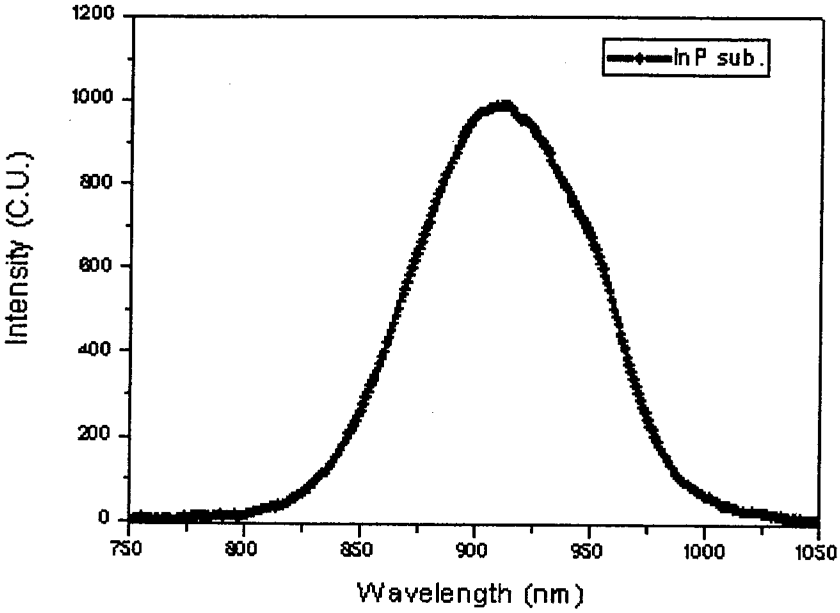

FIGURE 4 The measured PL results at room temperature for 350 μm-thick semi-insulating InP (1 0 0) substrate.

650 °C are shown in Figures 3 and 4. When the growth temperature is 400 °C, the growth film has poor surface morphology, like mist and grain shape, and the PL curve is almost flat and no intensity signal appeared. However, when we increase the growth temperature to 430 °C, the PL intensity rises to 42 CU (Calibration Unit means the value has been normalized) and the FWHM is 173 nm, which stands for crystal quality. From Figure 3, we can find that intensity becomes stronger and the FWHM is narrower when the temperature is increased from 400 °C. However, it is not certain that it can get higher crystal quality and mirror-like surface morphology by increasing the growth temperature unlimitedly. The optimum results of this work are growing the film at 480 °C. The narrowest FWHM and strongest peak value measured by PL can be obtained and are shown in Figure 3. The FWHM value is 28.7 nm and the peak intensity is 161 CU with the mirror-like surface while the growth temperature is 480 °C. On the other hand, the curve of 350 nm-thick semi-insulating InP (1 0 0) substrate measured by PL is shown in Figure 4. The FWHM of 95 nm is worse than the value which we grow at 480 °C (Fig. 3). Nevertheless, the crystal quality becomes worse when the growth temperature is higher than 480 °C. The wider FWHM value and weaker peak intensity will be realized and shown in Figure 5. From Figure 5, we can see that when the temperature is higher than 500 °C, the PL peak intensity is decreased and FWHM value is increased. The surface morphology also becomes worse (the mist surface becomes more and more significant and has something like grain). When the growth temperature is up to 650 °C, the peak intensity of 58 CU and FWHM of 112 nm are obtained. Because the value of V/III ratio is also a key point to grow a high quality InP buffer layer on GaAs substrate, we also investigate how the V/III ratio influences the crystal quality. The PL data shown in Figures 3 and 4 are all set the same V/III ratio of 170. Figure 6 shows the optimum result of the PL data with FWHM of 28.7 nm, peak intensity of 161 C.U., growth temperature of 480 °C and V/III ratio of 170. We choose the best growth condition to compare with different growth results by changing the V/III ratios and fixing other growth conditions. When the V/III ratio is increased from 170 to 230, the peak intensity is decreased slightly but the FWHM is raised to 55 nm. When the V/III ratio is increased

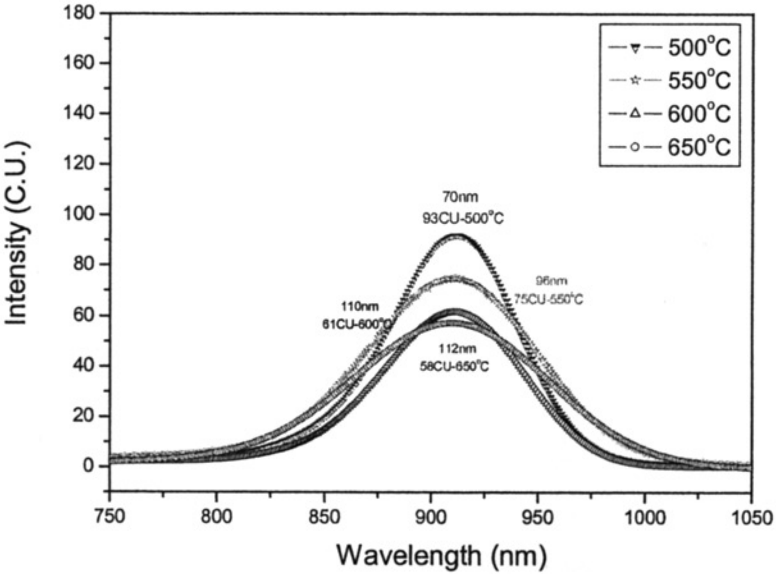

FIGURE 5 The measured PL results at room temperature for the samples of direct growth InP on GaAs substrate using a constant growth rate of 25 nm/min and a thickness of 400 nm. The growth temperature is from 500 to 650 °C.

to 300, the peak intensity is down to 126 CU and the FWHM is up to 89 nm. Therefore, the higher V/III ratio cannot ensure better crystal quality. When the V/III ratio is decreased from 170 to 100, the peak intensity is also decreased to 132 CU but the FWHM is raised to 78 nm. Therefore, worse crystal quality will result if the V/III ratio is too low or too high. From our experimental experience, the range of V/III ratio from 130 to 220 is the suitable region to

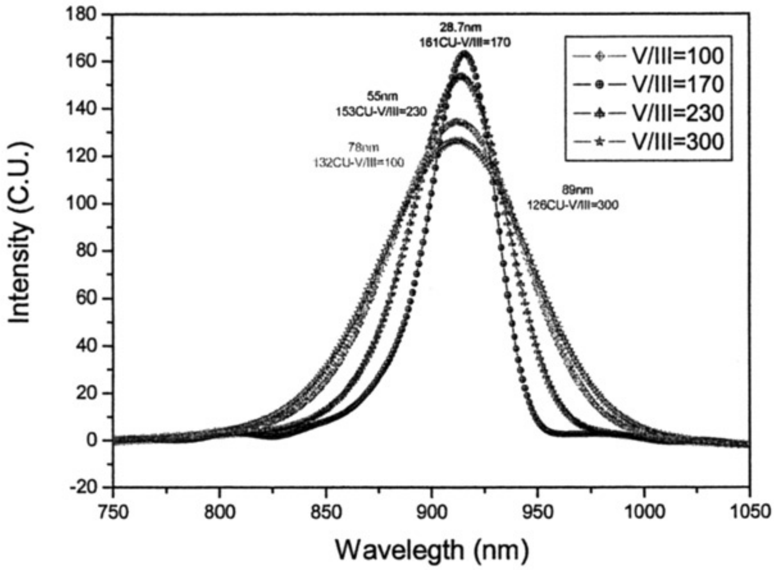

FIGURE 6 The different measured PL results by changing the V/III ratios with the growth temperature of 480 °C at room temperature for the samples of direct growing InP on GaAs substrate using a constant growth rate of 25 nm/min and a thickness of 400 nm.

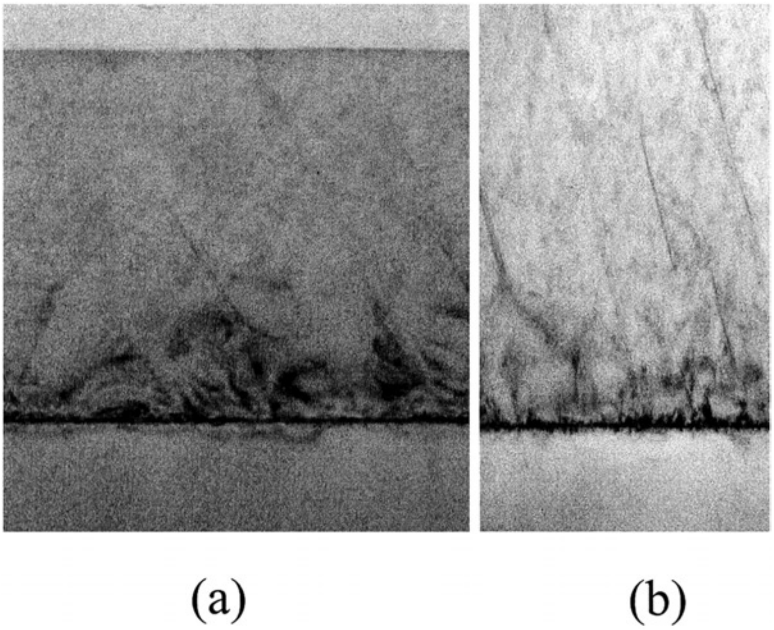

FIGURE 7 (a) The cross-sectional view of TEM image with the growth temperature of 480 °C, and (b) partially enlarged TEM image. The diffraction pattern of this sample is also shown in the inserted diagram.

grow high quality InP buffer layers on GaAs substrates. The cross-sectional view of TEM images for the sample of optimum result of the growth conditions (grow the film at 480 °C) is shown in Figure 7. The film thickness is about 400 nm with zincblende structure from the top to the interface. Direct growth of the InP layer on GaAs substrate is

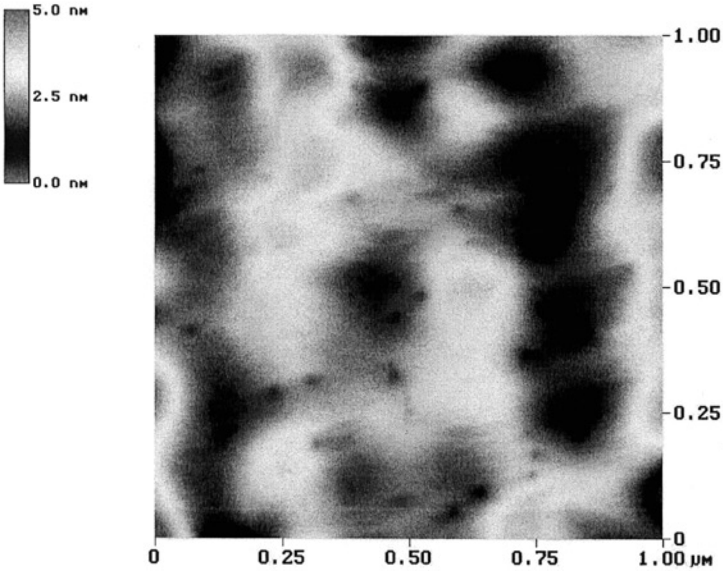

FIGURE 8 The measured surface roughness by AFM with a root-mean-square value of 2.8 nm.

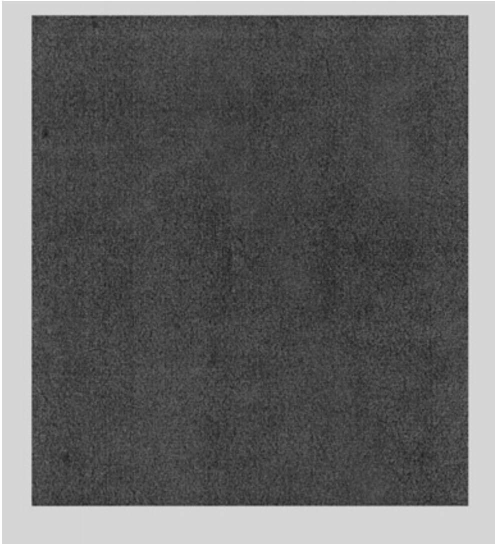

FIGURE 9 Mirror-like surface morphology displayed by optical microscopy with the growth temperature of 480 °C.

clearly differentiated. The low interface dislocations and defects can also be observed. The diffraction pattern for this sample is also shown in the inserted diagram of Figure 7. The zinc-blende pattern in this film and the single crystal structure of InP layer grown on GaAs substrate can also be realized in this figure. The rms surface roughness measured by AFM and surface morphology displayed by optical microscopy for this sample is shown in Figures 8 and 9. The rms surface roughness value is 2.8 nm and the surface morphology is mirror-

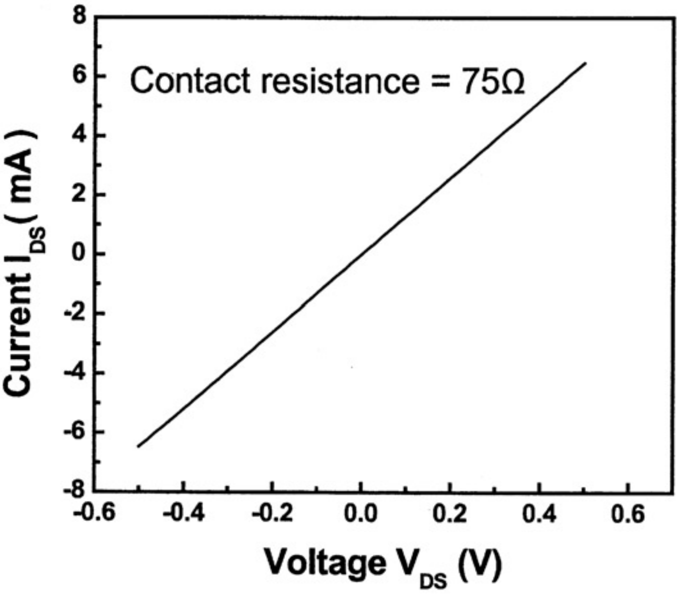

FIGURE 10 The I_{ds}–V_{ds} characteristic of InAlAs/InGaAs HEMT with gate floating.

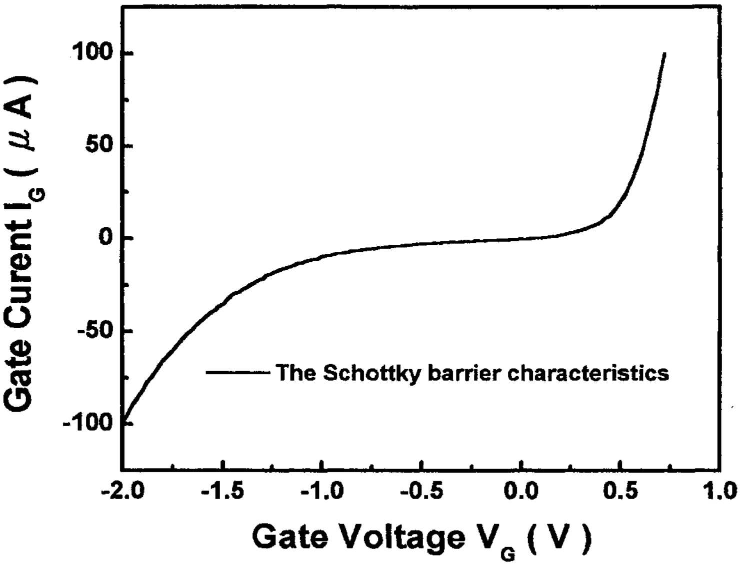

FIGURE 11 The I_G–V_G characteristic of InAlAs/InGaAs HEMT.

like with the total thickness of 400 nm. The measured results of this work are superior to those of previous reports. The smaller rms value can be excepted if the growth thickness is increased to overcome the large misfit between InP and GaAs layers.

For the InAlAs/InGaAs metamorphic HEMT, the measured I–V curve of the source-drain, specific contact resistance of the source-drain shown in Figure 10 is 75 Ω. The I/V curve is a straight line, so that we can ensure the source-drain is ohmic. From Figure 11, we can see that the gate is a Schottky barrier after the aluminum metal is evaporated. The I_{ds}–V_{ds} characteristics of InAlAs/InGaAs HEMT are shown in Figure 12 and demonstrate a negative region.

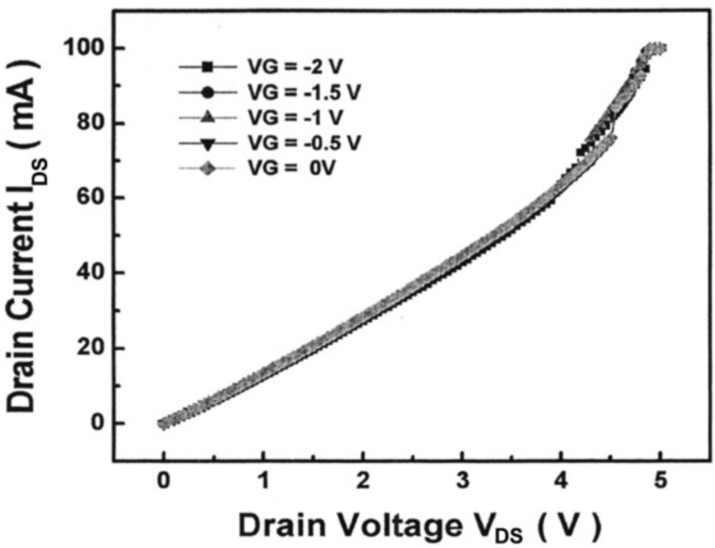

FIGURE 12 The I_{ds}–V_{ds} characteristic of InAlAs/InGaAs HEMT.

4 CONCLUSIONS

Direct growing InP buffer layers, instead of using graded or inverse-step methods, on GaAs substrates while maintaining high crystal quality, a mirror-like and uniform surface with the total thickness only 400 nm grown by LP-MOCVD is investigated. We find the growth temperature from 470 to 490 °C and the V/III ratios from 130 to 220 with the growth rate of 25 nm/min are the suitable regions to directly grow high quality InP layers on GaAs substrates. The measured FWHM of 28.7 nm by PL is better than 95.3 nm of InP substrate. The low interface dislocations and defects measured by TEM, surface roughness of 2.8 nm and mirror-like surface morphology measured by AFM and optical microscopy are the best results ever reported [3, 4]. The DC characteristics of the InAlAs/InGaAs HEMTs are also demonstrated and show the negative resistance. As can be seen, the technique of growing InAlAs for this structure can be improved, because InAlAs is a more difficult material to grow by LP-MOCVD. These results show the high potential of growing InP layers on GaAs substrates instead of using InP substrate in MMIC applications.

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