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Molecular beam epitaxial growth and structural design of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ HEMTs

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Lattice-matched $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ layers and two-dimensional electron gas (2DEG) structures have been grown on (100) InP substrates by molecular beam epitaxy (MBE) with dimeric or tetrameric arsenic species. Surface morphology of 0.5 μm $In_{0.53}Ga_{0.47}As$ layers is strongly influenced by the As_4 to group III flux ratio, and also by the arsenic species used in the growth. The RHEED oscillation study shows that the uses of As_2 or higher As_4 flux reduce the group III adatoms surface diffusion, hence improving the interface or surface roughness caused by the alloy clustering. This behavior is more obvious in the growth of $In_{0.53}Ga_{0.47}As$ layers than $In_{0.52}Al_{0.48}As$. Two-dimensional electron mobilities of over 11,080 $cm^2/V \cdot s$ at 300 K and 33,500 $cm^2/V \cdot s$ at 77 K with sheet charge of 3.9×10^{12} cm^{-2} have been achieved from this study.

1. Introduction

The ternary compound, $In_{0.53}Ga_{0.47}As$, lattice matched to InP has attracted growing attention in recent years because its superior electron transport properties for ultra high speed operations [1] and its band gap compatibility to the 1.3–1.6 μm wavelength window of low transmission loss optical fiber [2]. Though considerable progress has been made to achieved better device performance, the fundamental growth process of these ternary compounds is still not well understood.

During the MBE growth of GaAs, in order to obtain smooth and atomically abrupt interface, it is sometimes desirable to enhance the cation surface migration so that the two-dimensional MBE growth process can be enhanced. This process is evident by observing the oscillation in the refraction high electron energy diffraction (RHEED) pattern [3]. However, in the case of ternary compounds such as $Al_xGa_{1-x}As$ and $In_{0.53}Ga_{0.47}As$, this enhancement of cation surface migration does not yield the same improvement, possibly due to preferential cation clustering [4]. The growth conditions which give good RHEED oscillations do not produce smooth and featureless surface morphology, thus disconnecting the correlation between growth front smoothness and the growth conditions set by the initiation of RHEED oscillation.

Earlier efforts using As_2 and optimizing the growth conditions have made considerable progress in producing higher quality $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ layers [5–7]. However, a comprehensive study of the various growth conditions on both uniform and planar doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ HEMT structures has yet to be reported. In this paper, we present a comparative study of As_2 and As_4 growth of 0.5 μm $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ epitaxial layers, and report the resulting 2DEG properties of the $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ HEMT structures with uniform and planar doping schemes under optimized growth conditions. Based upon this study, we have achieved state-of-the-art 2DEG material properties and planar doped HEMT performance.

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2. Experimental

MBE growth of lattice-matched $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ epitaxial layers and 2DEG heterostructures was performed in a modified Varian MBE GEN-II system with two-inch non-indium bonded semi-insulating InP substrates. The typical growth rate of $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ is 0.3 μm/h, with a normal substrate temperature of 490 °C. The composition of the ternary layers was determined using the RHEED oscillation technique performed on both GaAs and InP substrates. The epitaxial surface morphology was studied by Nomarski phase contrast microscopy, and Hall measurements were used to provide electrical characterization of the 2DEG sheet charge density and electron mobility. The basic HEMT structure used in this study is as follows: a 2500 Å $In_{0.52}Al_{0.48}As$ undoped buffer, a 320 Å undoped $In_{0.53}Ga_{0.47}As$ layer to form the 2DEG channel, a 30 Å $In_{0.52}Al_{0.48}As$ undoped spacer, either a uniform or pulse planar Si-doped $In_{0.52}Al_{0.48}As$ layer, where the doped sheet charge or/and pulse layer thickness were varied to study the resulting electrical properties, a 250 Å undoped $In_{0.52}Al_{0.48}As$ layer, and a 30 Å undoped $In_{0.53}Ga_{0.47}As$ surface layer was grown to reduce the effects of oxidation and surface contamination on the 2DEG electron properties.

3. Results and discussion

Fig. 1 shows some typical RHEED oscillation data taken during the growth of $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ on InP. It is shown that the specular beam intensity damps faster in the case of As_2 compared to As_4 for both $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ growth, indicating reduced cation diffusion on the growth front with As_2 coverage [8]. Fig. 2 shows the surface morphology of 0.5 μm thick, moderately Si-doped $In_{0.52}Al_{0.48}As$ epitaxial layers grown with As_4 (figs. 2a and 2b) and As_2 (figs. 2c and 2d) sources, with the same group V to group III flux ratio of 14. There was almost no difference in either surface morphology or electron mobility (~ 410 cm^2/V · s at 300 K) between the dimeric and tetrameric arsenic growth. Further

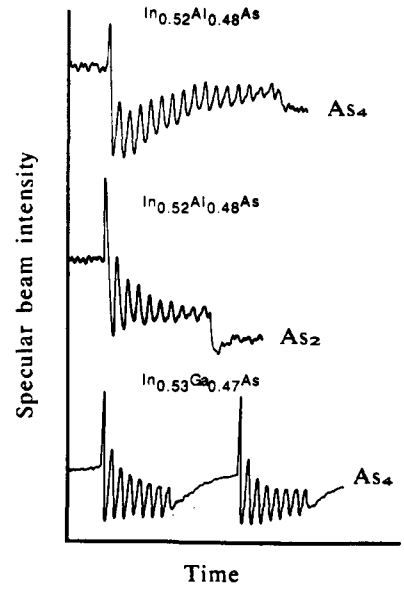

Fig. 1. RHEED intensity oscillations of $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ with As_2 and As_4 sources.

increase of the As_4 or As_2 V/III flux ratios showed little change in either surface morphology or electrical properties of the $In_{0.52}Al_{0.48}As$ epitaxial layers. However, in the case of $In_{0.53}Ga_{0.47}As$, the situation is quite different. Fig. 3 shows how the growth morphology of $In_{0.53}Ga_{0.47}As$ is influenced by the arsenic species and its strong dependence on the V/III flux ratio with As_4 growth. The poor surface morphology of fig. 3a occurred at a relative low V(As_4)/III flux ratio of 16; however, this is the same flux ratio used in fig. 1 where RHEED oscillations were observed during the growth of $In_{0.53}Ga_{0.47}As$. If the As_4 flux is increased further, the $In_{0.53}Ga_{0.47}As$ surface morphology improves, as shown in figs. 3b and 3c. This is a clear indication that the growth of the $In_{0.53}Ga_{0.47}As$ is vulnerable to cation (i.e., Ga and In) surface segregation, which is strongly affected by the cation surface mobility which is mainly controlled by the surface arsenic coverage. Since the surface texture in figs. 3a and 3b is not microscopically uniform throughout the surface, it is not likely that the poor surface morphology is due to As-vacancies or their related defect complexes as intuitively speculated. Fig. 3d shows a smooth epitaxial surface of $In_{0.53}Ga_{0.47}As$ achieved with As_2

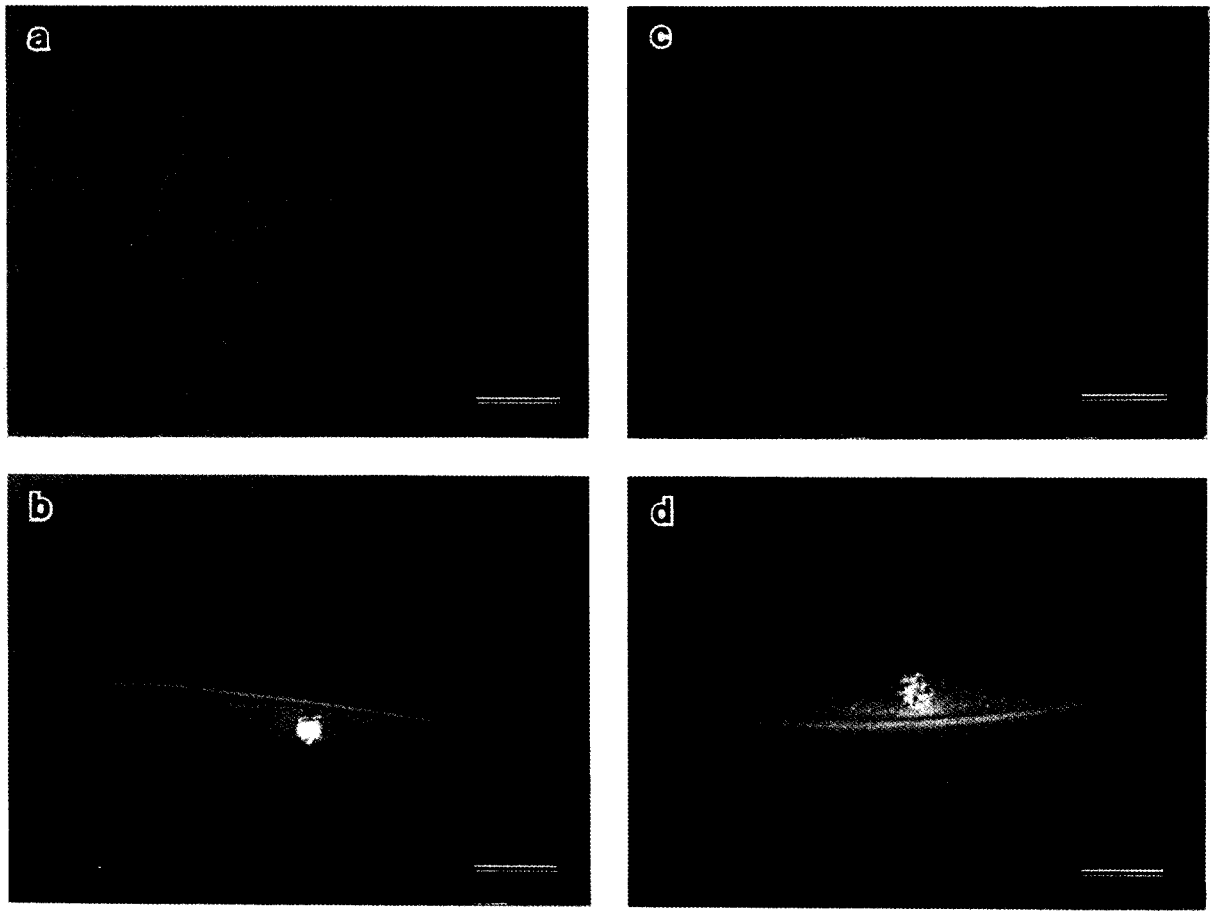

Fig. 2. Epitaxial surface morphology and particle related growth defect on $In_{0.52}Al_{0.48}As$ grown under As_4 (a, b) and As_2 (c, d). The markers represent 50 μm (a, c) and 20 μm (b, d).

growth, even at a relatively low V/III flux ratio of 14.

After recognizing the influence of arsenic species on thick ternary compounds of $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$, the next step was to examine the influence of arsenic species on 2DEG structures. Fig. 4 shows the planar doped 2DEG electron sheet charge density and mobilities as a function of spacer layer thickness, with the doped sheet charge held constant at 5×10^{12} cm^{-2}. The major difference in 2DEG properties between As_2 or As_4 growth appears to be in the 77 K electron mobility, where a substantial increase (30–50%) of mobility is obvious with As_2 growth. Since the 2DEG sheet charge densities remain relatively constant, the most reasonable explanation is that the heterointerface of the 2DEG quantum well is microscopically smoother with As_2 growth. This is consistent with our earlier discussion on surface morphology.

To show the influence of different doping schemes (i.e., uniform versus planar doped structures) on 2DEG electrical properties, table 1 gives the results of varying the doping structure from a three-dimensional uniformly doped layer to a two-dimensional, planar pulse doped layer. The sheet doping densities were constant at 5×10^{12} cm^{-2} and As_4 was used as arsenic species. It is evident that the 2DEG sheet charge increases as the doping pulse width decreases (thus increasing the heterointerface 2DEG confining electric field). The electron mobility, on the other hand, in-

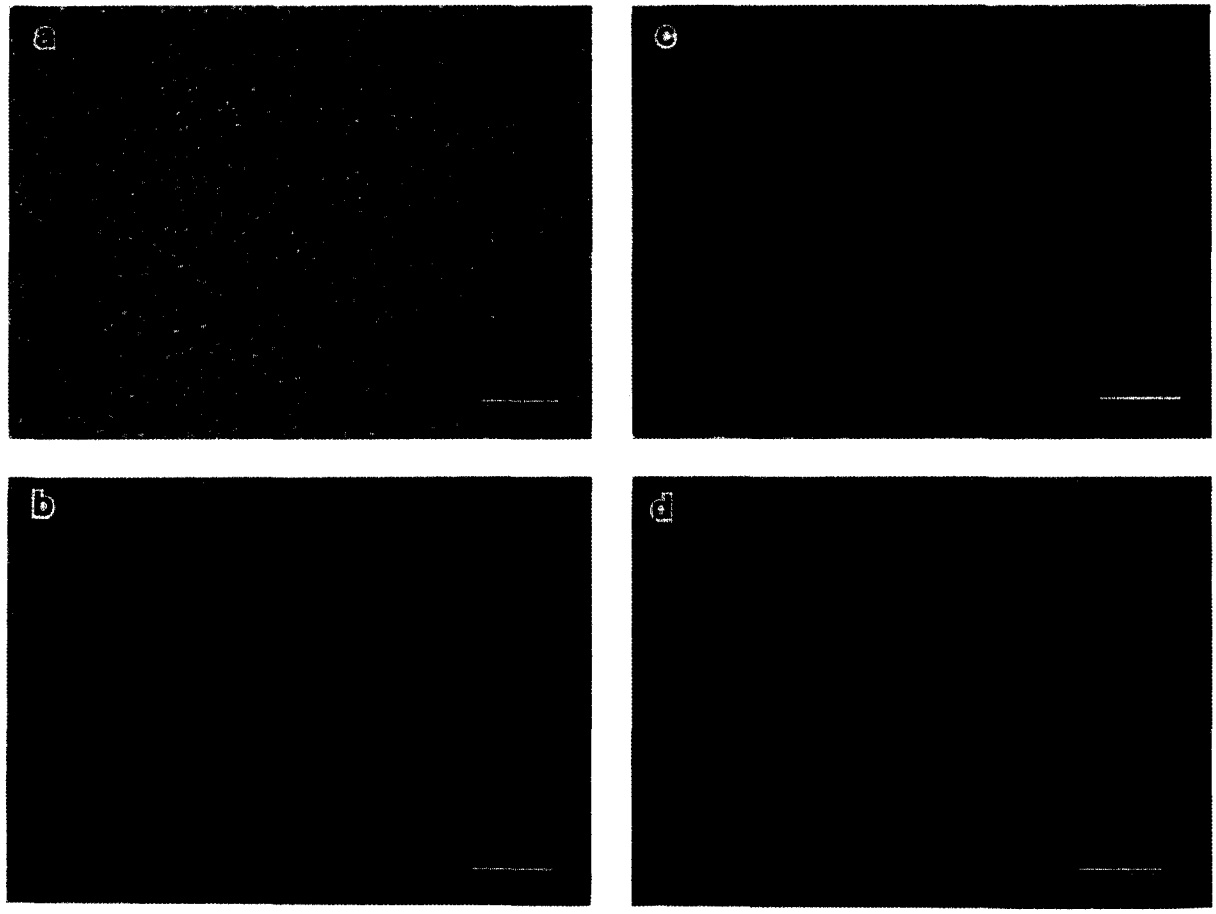

Fig. 3. Epitaxial surface morphology of $In_{0.53}Ga_{0.47}As$ layers grown under different arsenic conditions: (a) As_4 with V/III ratio of 16; (b) As_4 with V/III ratio of 26; (c) As_4 with V/III ratio of 36; (d) As_2 with V/III ratio of 14. The marker represents 50 μm.

creases gradually with increasing 2DEG sheet charge density, consistent with increased electron screening [9] of the Coulombic interaction (i.e., scattering) with the host impurities. This experiment showed definite advantages of the planar doped structure over uniformily doped ones. In order to acquire even higher 2DEG sheet charge with planar doped structure, we undertook the

Table 1
Comparison of 2DEG properties between uniform and planar doped HEMT structures

Structure type	Doping level/thickness	Spacer (Å)	2DEG (300 K)	
			Sheet charge (cm^{-2})	Mobility ($cm^2/V \cdot s$)
Uniform	$2\times10^{18}\,cm^{-3}/250$ Å	30	2.35×10^{12}	10,100
Uniform	$4\times10^{18}\,cm^{-3}/125$ Å	30	2.72×10^{12}	10,500
Planar	$5\times10^{12}\,cm^{-2}$	30	2.95×10^{12}	11,020

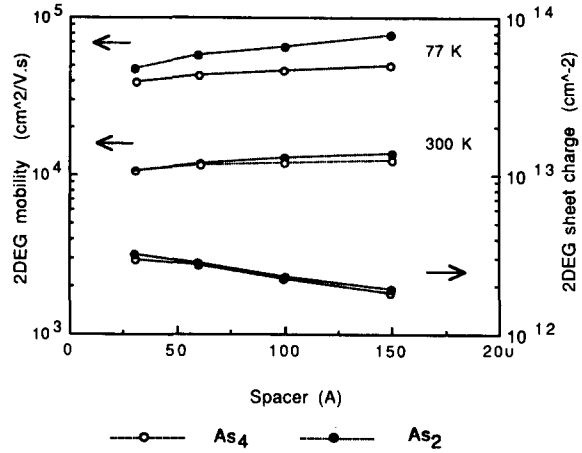

Fig. 4. Comparison of the planar doped 2DEG electron sheet charge density and electron mobility as functions of the spacer layer thickness and arsenic species. The Si sheet doping density was constant at 5×10^{12} cm^{-2}.

following experiment with As_2 growth, since As_2 offers superior 2DEG electrical properties. Fig. 5 shows that with further increase in the planar Si-doped sheet charge, the 2DEG sheet charge density increases continuously, without degrading the room temperature electron mobility. 2DEG electron mobilities of 11,080 cm^2/V · s at 300 K and 33,500 cm^2/V · s at 77 K with sheet charge of 3.9×10^{12} cm^{-2} have been achieved; this is so far the best reported room temperature mobility with such high sheet charge density.

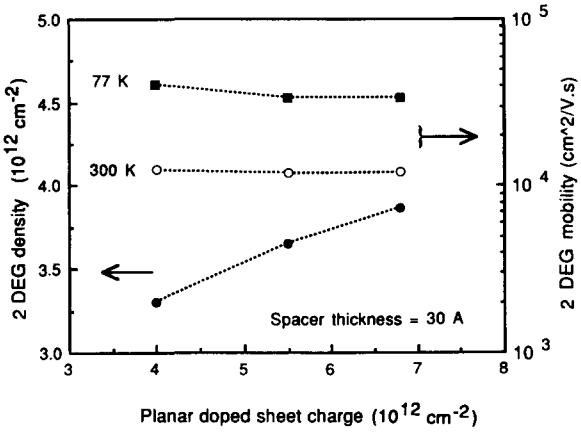

Fig. 5. Planar doped 2DEG electron sheet charge density and mobility as a function of the sheet charge density in Si pulse doped layer, with a 30 Å thick spacer layer.

Based on these epitaxial material results, we have fabricated a state-of-the-art, $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ HEMT with sub-0.1 μm gate length. This device has achieved an intrinsic current gain cut-off frequency of over 288 GHz [10], which is among the highest cut-off frequencies reported to date for any three-terminal devices.

4. Conclusion

The MBE growth of $In_{0.52}Al_{0.48}As/InP$ is relatively insensitive to both the arsenic species used and the V/III flux ratio. However, $In_{0.53}Ga_{0.47}As$ is strongly influenced by these parameters. The use of dimeric arsenic produces superior epitaxial $In_{0.53}Ga_{0.47}As$ surface morphology and higher low temperature 2DEG electron mobility. This improvement of low temperature 2DEG mobility is attributed to the microscopically smoother heterointerface obtained with As_2 growth. Due to the large $\Gamma - L$ valley separation of the $In_{0.53}Ga_{0.47}As$ channel layer, the room temperature 2DEG electron mobility remains relatively constant over a wide range of 2DEG sheet charge density, between 2.3 to 3.9×10^{12} cm^{-2}. A room temperature 2DEG mobility of 11,080 cm^2/V · s with a corresponding sheet charge density of 3.9×10^{12} cm^{-2} has been demonstrated, and state-of-the-art device performance has been achieved with MBE grown, planar doped HEMT structures.

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