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GROWTH OF (110) GaAs/GaAs BY MOLECULAR BEAM EPITAXY

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ABSTRACT

The simultaneous molecular beam epitaxy (MBE) growth of (100) and (110) GaAs/GaAs intentionally doped with Si(~1E16/cm^3) was studied as a function of substrate temperature, arsenic overpressure, and epitaxial growth rate. The films were analyzed by scanning electron and optical microscopy, liquid helium photoluminescence (PL), and electronic characterization.

For the (110) epitaxal layers, an increase in morphological defect density and degradation of PL signal was observed with a lowering of the substrate temperature from 570C. Capacitance-voltage (CV) and Hall Effect measurements yield room temperature donor concentrations for the (100) films of n~7E15/cm^3 while the (110) layers exhibit electron concentrations of n~2E17/cm^3. Hall measurements at 77K on the (100) films show the expected mobility enhancement of Si donors, whereas the (110) epi layers become insulating or greatly compensated. This behavior suggests that room temperature conduction in the (110) films is due to a deeper donor partially compensated by an acceptor level whose concentration is of the same order of magnitude as that of any electrically active Si. Temperature dependent Hall effect indicates that the activation energy of the deeper donor level lies ~145 meV from the conduction band. PL and Hall effect indicate that the better quality (110) material is grown by increasing the arsenic flux during MBE growth. The nature of the defects involved with the growth process will be discussed.

INTRODUCTION

The (110) non-polar orientation of GaAs has been well studied by surface scientists for its reconstruction and bonding properties [1,2]. It has also been of interest as a proven source for a more efficient optical modulator [3] and, recently, as a possible orientation for growth of GaAs on Ge [4,5]. In order to improve the quality and better understand the origin and effects of defects in GaAs on device performance, it is important to examine the morphology and electrical and optical properties of GaAs in the little studied (110) orientations.

This paper reports the investigation of simultaneously grown (100) and (110) GaAs/GaAs by molecular beam epitaxy. The parameters varied include substrate temperature, arsenic overpressure, and epitaxial growth rate. The substrate temperatures ranged from 590C to 510C. The As overpressure was then increased from 1.1E-5 Torr to 1.6E-5 Torr for additional growths at varying temperatures. The growth rate was decreased to one half and then one quarter for what appeared to be the optimal growth temperature of 570C. Finally, the combined parameters of substrate temperature (Ts=570C), arsenic overpressure (P,As=1.6E-5T), and one quarter growth rate were grown. Each substrate was intentionally doped with Si~1E16 cm-3.

The results from microscopy studies correlated with electrical and optical data from the various growth conditions are discussed in terms of material morphology and GaAs epitaxial properties.

EXPERIMENTAL

The polished (110) and Cr-doped (100) substrates utilized were semi-insulating and chemically etched (H_2SO_4:H_2O_2:H_2O=4:1:1) and cleaned before growth in the Varian Gen II MBE system. The substrates were held with indium to the rotating substrate holder, and were heat cleaned in the

growth chamber at 630C for 15 minutes, after which time the As4 oven opened at Ts=550C. The growth rates varied from 1.4 microns/hr to 0.36 microns/hr with the normal As4 pressure.

The epitaxial surface layer was examined by Nomarski optical microscopy and STEM mode of a JEOL 200CX transmission electron microscope. The samples were also studied via temperature dependent Hall effect with In alloyed dot contacts and a magnet of 5KG. PL measurements were performed at sample temperatures of <4K with a 676nm line of a krypton laser. The light beam was mechanically chopped and the sample luminescence was analyzed with a SPEX monochrometer and detected with a dry ice cooled S-1 photomultiplier using standard lock-in methods. With a 1200 line/mm spectrometer grating and 0.4mm slit, system resolution is ~1.6 Angstroms.

RESULTS AND DISCUSSION

Figures 1-2 show the Nomarski photographs for the growth conditions applied (1000X). For all of them, it is seen that faceted structures form on the (110) epi layer in various densities and sizes. An independent Laue X-ray diffraction study showed these facets to be oriented along the <110>. Other surface features include small droplet-like deposits uniformly distributed across the layer. An enlargement in the STEM mode (8000X) of the JEOL 200CX microscope (Figure 1.e) shows evidence that the large facets may originate from these deposits, assumed to be Ga clusters.

Figure 1a-1d shows the surface of (110) GaAs epi as a function of substrate temperature. A defect density count from lower magnification micrographs reveals growth at 570C and 590C to yield the lowest defect count of ~9.1E4 and ~9.6E4/cm2, respectively. These are compared to an EPD (110) substrate count at 1.4E4/cm2. The (100) surface appeared smooth for both substrate and epi. These substrates were grown with a V/III ratio of ~8:1, and the (110) epi layers look similiar in nature to one of those reported by Wang[6]. Figure 2a-2d shows the Nomarski (110) GaAs surface for those MBE runs at higher As overpressures (Ts-570C,550C) and at slower growth rates (Ts= 570C). It is seen that the higher As overpressure at 570C changes the surface morphology appreciably.

Hall effect measurement data are shown in Table I for both (100) and (110) epitaxial layers. The simultaneously grown (100) layers indicate an expected doping concentration of ~7E15/cm3 for each of the substrate growth temperatures, with resulting concentrations and mobilities slightly worsening with the lowering of Ts to 510C. Donor concentrations were confirmed with capacitance-voltage measurements. The (110) epitaxial layers, on the other hand, exhibit anomalously high conductivity at room temperature with carrier freezeout at 77K for substrate temperatures of 590C, 570C, and 550C. At 510C, the epi layer becomes p-type with a low carrier concentration of 1E10cm-3. For growth with an increased As overpressure to V/III~15:1, the (110) sample grown at 570C indicates the same room temperature conductivity, but does not freeze out at 77K. Instead, the observed conductivity is near to that of the expected doping concentration. A reduction in growth rate and the combination of growth parameters inhibits carrier freezeout, as well, but electron concentration still remains extremely high.

These measurements indicate that at room temperature, electrical conduction in the (110) films is due to the presence of a deeper donor which is partially compensated by an acceptor level. This acceptor level must be of the same order of magnitude as that of the intentionally doped Si for those samples which freeze out at ~77K. Thus, at or below liquid N2 temperatures, the deeper donor level and the Si n-type level are, respectively, frozen out and compensated. For growth at Ts=510C, it is expected that the amphoteric Si dopant prefers the As site due most likely to the increased availability of the Group V sites from the Ga-rich conditions and even shorter physisorption times. An increase in As flux aids in the probability of correct site chemisorption to improve the stoichiometry, and

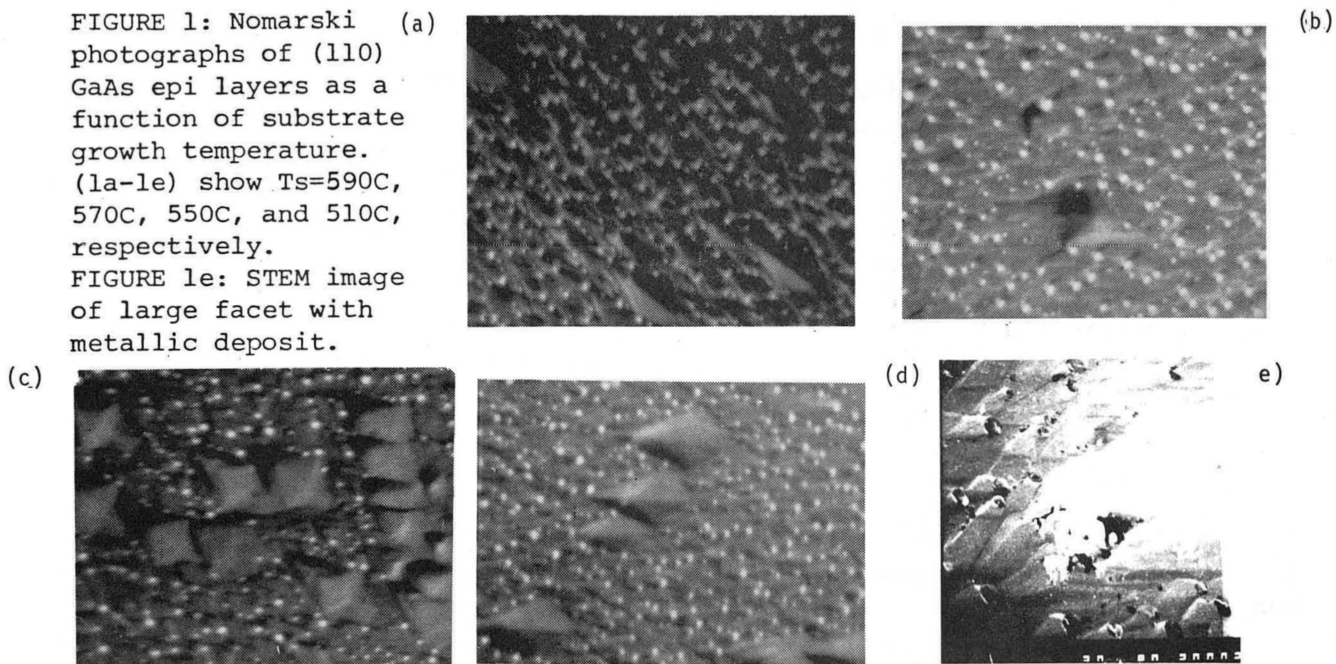


FIGURE 1: Nomarski photographs of (110) GaAs epi layers as a function of substrate growth temperature. (1a-1e) show Ts=590C, 570C, 550C, and 510C, respectively.
FIGURE 1e: STEM image of large facet with metallic deposit.

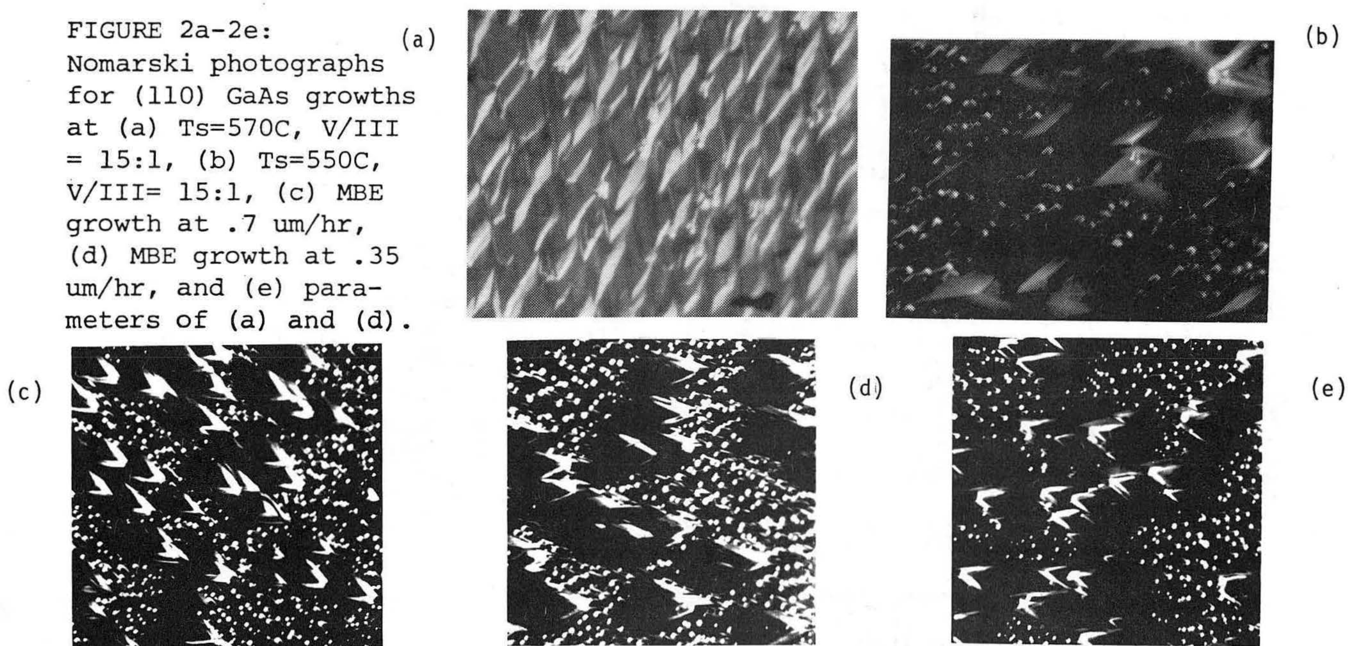


FIGURE 2a-2e: Nomarski photographs for (110) GaAs growths at (a) Ts=570C, V/III = 15:1, (b) Ts=550C, V/III= 15:1, (c) MBE growth at .7 um/hr, (d) MBE growth at .35 um/hr, and (e) parameters of (a) and (d).

it is felt that the Si dopant can again incorporate at the normally preferred Group III site without freezeout from a highly compensating acceptor level.

A preliminary temperature dependent Hall effect study was carried out for Ts=590C to find out the activation energy of the deeper donor level. Figure 3 shows the normal (100) Hall data along with that of the (110) epi layer. It is seen that the deeper donor level freezes out by 57K and an activation energy is calculated to be 145 meV from the conduction band. The remaining n-type conductivity is most likely due to the shallow Si doping level, highly compensated by an acceptor level. As indicated by the level of freezeout and assuming an incorporated doping of 7E15cm-3, the compensating acceptor level has a concentration of p~4E15.

The Hall effect data are compared to the liquid helium PL studies whose curves are shown in Figures 4-6. Figure 4 shows the recombination peaks for the (110) and (100) substrate temperature variation, Figure 5(a,b) for that of increased As flux, Figure 5(c,d) for that of decreased growth rates, and Figure 6 indicates those peaks obtained for the combination of growth parameters.

Table 1. Hall Effect Data

Substr Temp (C)	Substr Orient.	Room Temp Conductivity (cm-3)	Room Temp Mobility (cm^2/V-s)	Liquid N2 Conductivity (cm-3)	Liquid N2 Mobility (cm^2/V-s)	Peak Ratio Ao:x
590	(100)	n~7.97E15	5926	n~9.30E15	21511	0.63:1
570	(100)	n~8.59E15	5615	n~9.40E15	20412	1.6 :1
550	(100)	n~8.88E15	5472	n~9.50E15	20135	1.6 :1
510	(100)	n~9.47E15	4636	n~1.00E10	3465	1.4 :1
590	(110)	n~2.10E17	1446	<1E10	----	5.2 :1
570	(110)	n~1.50E17	1779	<1E10	----	8.3 :1
550	(110)	n~1.00E17	368	<1E10	----	8.9 :1
510	(110)	p~8.20E15	172	p~1.40E10	6044	5.5 :1
variable: increased As flux						
570	(100)	n~1.04E16	5218	n~1.13E16	18462	0.16:1
550	(100)	n~1.05E16	4979	n~1.13E16	17354	0.38:1
570	(110)	n~2.30E17	2018	n~9.10E15	4480	1.8 :1
550	(110)	n~2.90E18	2219	<1E10	----	3.3 :1
variable: growth rate						
570,1/2	(100)	n~6.90E15	4585	n~8.20E15	17772	1.9 :1
570,1/4	(100)	n~7.50E15	5097	n~8.70E15	18252	5.4 :1
570,1/2	(110)	n~1.49E20	1709	n~2.10E20	388	3.1 :1
570,1/4	(110)	n~3.10E18	1997	n~1.50E18	170	3.8 :1
variables: 1/4 growth rate, increased As flux						
570	(100)	n~8.00E15	5041	n~9.60E15	18673	6.5 :1
570	(110)	n~1.00E17	1038	n~2.50E14	2462	24.3:1

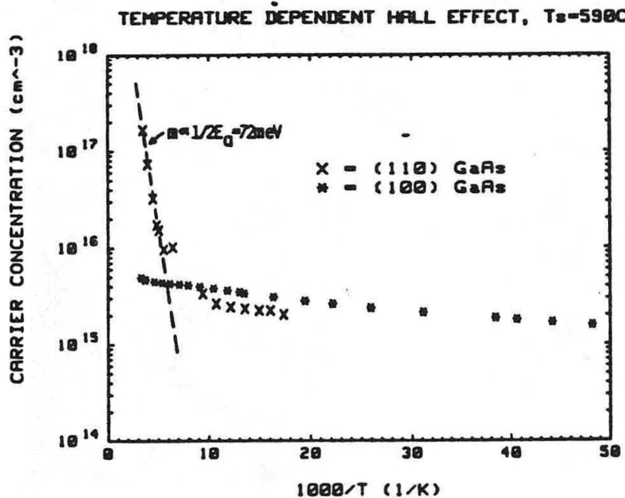
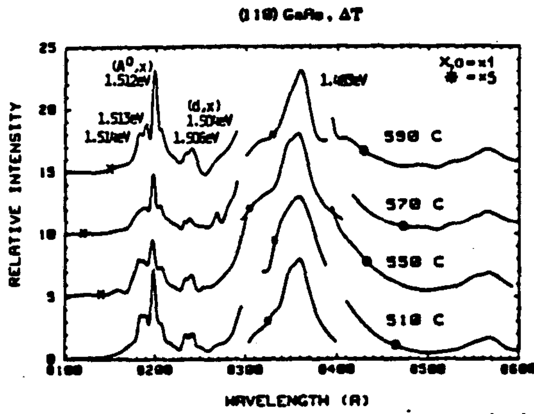


FIGURE 3: Temp.-dependent Hall data shows deeper donor freezeout and activation energy of ≅145 meV. Residual donor concentration shows compensating acceptor level N_A≅5E15.

For (100) GaAs, the dominant peaks appear at 1.514 eV and 1.491 eV. The latter is associated with a carbon acceptor peak (Do,CAso) and the former has been attributed to the range of neutral acceptor, exciton transitions from 1.512-1.517 eV, (Ao,x). It is well known that carbon is a dominant residual acceptor for MBE material. The 1.5145 eV peak has been observed by others [7] and falls within the latter range of transitions. In (110) GaAs, it is interesting to note the split peaks at 1.512, 1.513, and 1.514 eV. Again, these are associated with the neutral acceptor, exciton transitions (Ao,x). The 1.504 and 1.506 split peak is thought to be the 'defect-induced' bound exciton (d,x) transition band of the kind reported by Kunzel and Ploog [8]. The dominant peak at 1.483 eV is near to the conduction band, neutral Si acceptor transition (e,SiAso) and the small 1.448 eV peak near the Si LO phonon replica peak reported by Wang [6] and others.

A strong exciton peak for both (100) and (110) GaAs is indicative of



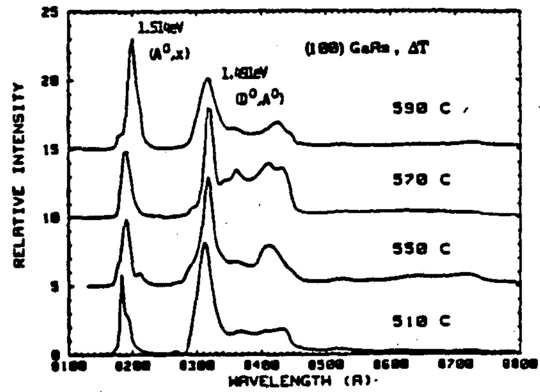
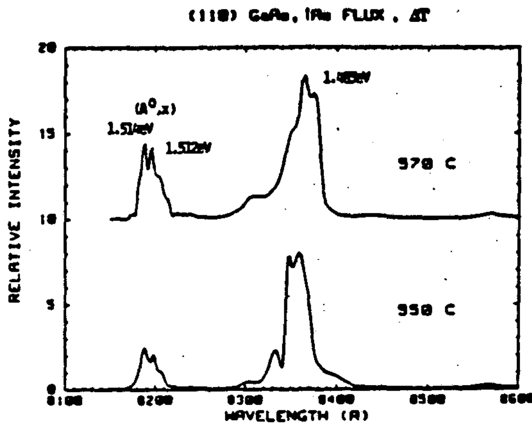


FIGURE 4a-4b: Liquid He PL intensities for variation in MBE substrate growth temperatures



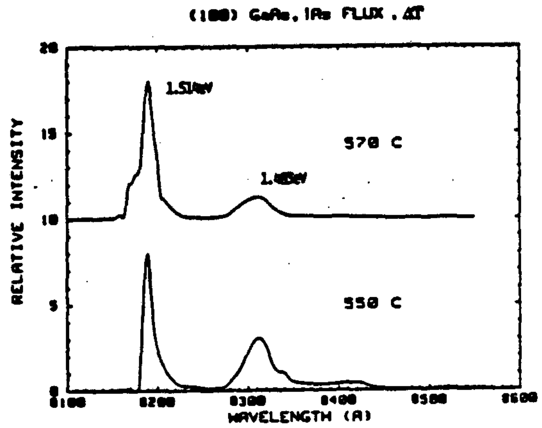
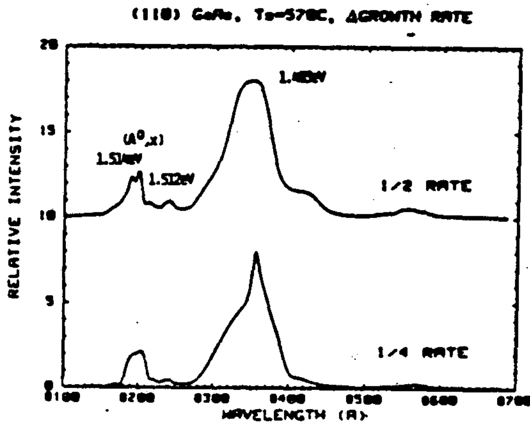


FIGURE 5a-5b: PL intensities for MBE epi layers with increased As_4 flux



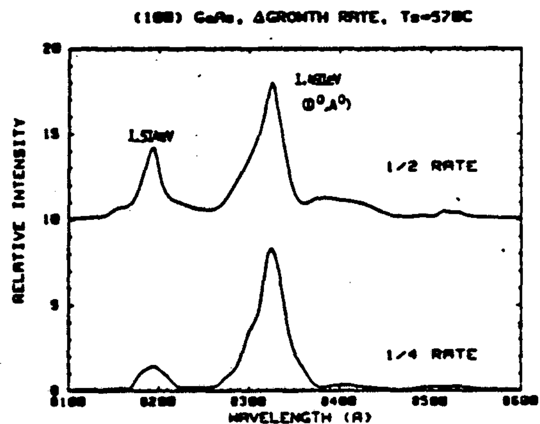
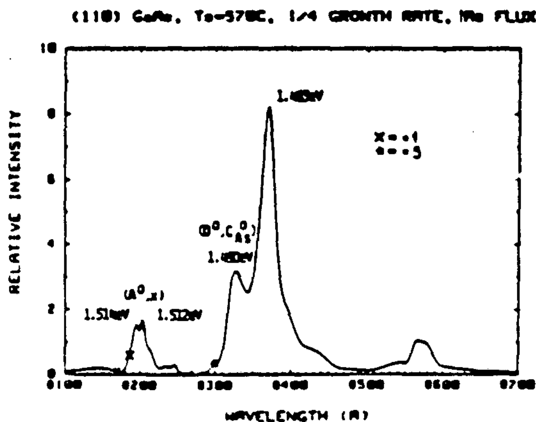


FIGURE 5c-5d: PL intensities for decreasing Ga flux (growth rate).



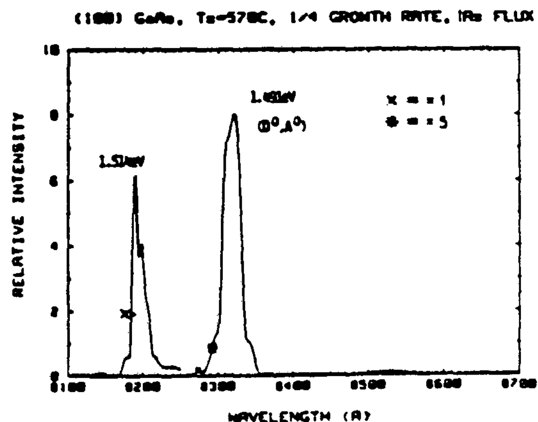


FIGURE 6: PL intensities for (110) and (100) GaAs epi layers grown with combination of optimized growth parameters.

high quality epitaxial material. The relative intensity ratios of the dominant neutral acceptor (Ao) to the exciton (x) luminescence for each of the crystals examined are shown in Table 1. It is seen that the (100) material degrades slightly with a decrease in substrate growth temperature, as does the (110) material. Further examination of these materials at higher growth temperatures may prove fruitful. For the (110) case, a great improvement in peak ratio is seen for an increase in As overpressure for Ts = 570C. It is noted that the 'defect-induced' bound exciton transitions disappear as well. This correlates well with the Hall data. The combination of growth parameters does not improve the PL data and, in fact, yields the highest peak ratio of about 24:1.

The results show a good correlation between morphological, electrical and optical data. Further study of the observed defects by temperature dependent Hall effect and TEM will be useful in determining exact defect nature, thereby aiding in their elimination by means of substrate orientation or a modified growth condition (i.e. As4 cracker).

CONCLUSION

(110) GaAs simultaneously grown by MBE with (100) GaAs has found to be improved for the (110) case by increased As flux. The morphology observed indicate defect formation from metal clustering and may be in part due to the extremely low sticking coefficient of As in the (110) orientation.

Electrical measurements show a deeper donor level with an activation energy of ~145 meV. PL shows a weak exciton peak, indicative of the high defect concentration. Further investigation of the defects by temperature dependent Hall effect and by TEM will be a worthwhile study in order to understand and eliminate the defect nature and formation.

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