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Growth optimization of n-type GaAs on GaAs(201) substrates

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A study of the growth by molecular-beam epitaxy of Si-doped n -type GaAs on the GaAs(201) surface is presented. The motivation for attempting growth on this particular plane, apart from fundamental considerations, is in connection with an investigation of off-axis transport in GaAs. The effects of growth temperature and doping on GaAs(201) and GaAs(100) samples have been compared using the Hall effect, low-temperature photoluminescence (PL), and Nomarski interference contrast microscopy. These studies showed that the PL, onset of conduction, and mobility behavior were very similar for both orientations. It was possible to dope n-GaAs/GaAs(201) reliably from $N_{Si}\sim4\times10^{14}$ to 6×10^{18} cm^{-3}, the highest mobility of 96 000 $cm^2 V^{-1} s^{-1}$ measured at 77 K, being obtained for a sample doped at $N_{Si}\sim4\times10^{14}$ cm^{-3}.

Although the majority of homo- and heteroepitaxial GaAs-based structures are fabricated on the (100) crystallographic plane, recently, growth on non-(100)-oriented substrates has developed into an area of significant interest. A number of unusual properties have been identified in such systems. For example, molecular-beam-epitaxy (MBE) growth on (201), (211), and (311) GaAs faces results in the formation of mesoscopic surface configurations, as observed by reflection high-energy electron diffraction (RHEED)[1] and confirmed, in the case of GaAs(201), by atomic force microscopy.[2] The existence of such mesoscopic steps, with a lateral periodicity [230 Å for GaAs(201)], comparable to that of the exciton Bohr radius, provides an interesting means of tailoring the electro-optic properties of GaAs-based devices. At the same time, the high quality of the interfaces contained in short-period AlAs/GaAs superlattices grown on GaAs(201) is evident from the presence of distinct satellite peaks in the corresponding x-ray and Raman scattering data.[3]

The motivation for this particular study arises from calculations which have shown[4] that when a longitudinal electric field is applied to a specially orientated n-GaAs layer, charge accumulation occurs at the surfaces of the layer, thus producing a transverse field across the sample thickness. This transverse field arises from the anisotropic transport properties of the L valleys, when populated by electrically heated electrons. To date, this behavior has been observed in structures produced lithographically on (100) substrates.[5] Calculations indicate that the (201) plane approximates closely to the orientation which optimizes this transverse field effect; hence, the need for a prior understanding of the growth of both binary and ternary III-V compounds on (201)-oriented crystals.

Despite the profusion of experimental data on non-(100) orientations, systematic growth studies are relatively rare. To our knowledge, this is the first study of the growth temperature and Si doping dependence of n-GaAs/GaAs(201) layer properties and their optimization for good quality, optically active material.

The growth experiments were performed in a VG Semicon V80H MBE reactor. Semi-insulating (Cr-doped, $\rho\sim10^8$ Ω cm) on-axis GaAs(201)$\pm$0.5° substrate wafers, supplied by MCP Electronic Materials Ltd., were used for these investigations. Experimental details relating to the standard sample preparation, flux, and temperature calibrations have been presented elsewhere.[6,7] GaAs(201) and GaAs(100) wafers were mounted adjacently on standard VG Semicon solid Mo sample holders using In solder. Following oxide desorption, an undoped buffer layer of GaAs 0.4–0.5 μm thick was deposited at ~580 °C. The buffer layer coats any excess In solder with GaAs and so prevents temperature variations in the "active" region of the sample. During growth, the surface structure of GaAs/GaAs(201) and GaAs/GaAs(100) was examined by RHEED. After growth, each sample was characterized *ex situ* by Hall-effect measurements (using a van der Pauw clover leaf sample with annealed In ohmic contacts) at both room temperature and 77 K, by photoluminescence (PL) measurements at 4.2 K and by Nomarski interference contrast microscopy. A comparison was made between the electrical, optical, and surface morphological properties of GaAs/GaAs(201) and GaAs/GaAs(100), as a function of growth temperature within the range $350\leqslant T_G\leqslant650$ °C, and as a function of Si doping level within the range $4\times10^{14}\leqslant N_{Si}\leqslant5\times10^{18}$ cm^{-3}.

1-μm-thick GaAs/GaAs structures were grown onto the buffer layer using a constant Si dopant flux with the Si cell temperature set at $T_{Si}=900$ °C, corresponding to a doping level of $N_{Si}\sim2\times10^{16}$ cm^{-3}. Values for electron mobility μ and sheet carrier concentration n, as obtained from Hall-effect measurements carried out at both room (RT) and liquid-nitrogen (77 K) temperature, are shown in Fig. 1 for different growth temperatures. For growth temperatures below 450 °C the GaAs(201) layers were highly resistive due to excess incorporation of As;[18] however, for $T_G\geqslant450$ °C they were all conductive, exhibiting n-type behavior. For temperatures between 450 and 480 °C, μ^{RT} and n^{RT} increased to values between 6500 and 8000 $cm^2 V^{-1} s^{-1}$ (for μ^{RT}) and between 7×10^{15} and 1×10^{16} cm^{-3} (for n^{RT}), for growth temperatures in the range 480–650 °C. The electron mobilities in the GaAs/GaAs(201) layers were of the same order as those for the corresponding GaAs/GaAs(100) material. No appreciable degradation in mobility was observed even for growth temperatures up to $T_G=650$ °C demonstrat-

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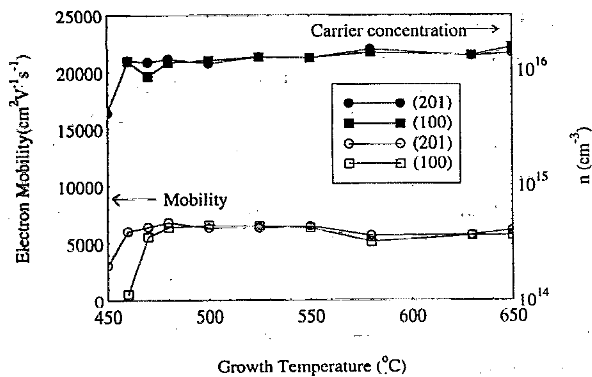

FIG. 1. Dependence of room-temperature mobility and sheet carrier concentration values on the growth temperature, for n-GaAs(100) and n-GaAs(210) layers (N_{Si}~2×10^{16} cm^{-3}).

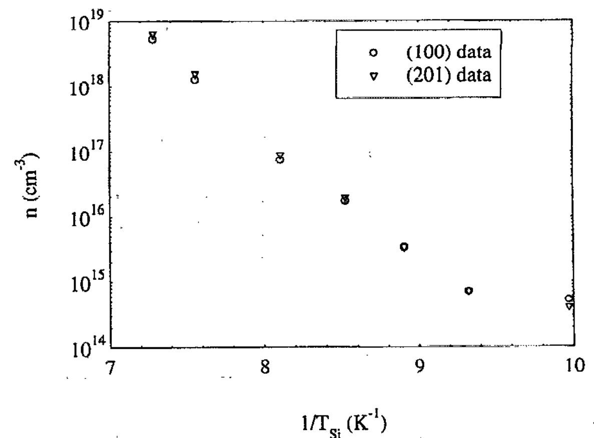

FIG. 3. Bulk carrier concentration as a function of reciprocal Si cell temperature, for both n-GaAs(100) and n-GaAs(201) layers.

ing that, like the GaAs/GaAs(100) system, high-quality GaAs(201) has a wide growth temperature window. Nomarski microscopy of the surfaces revealed that all GaAs/GaAs(201) surfaces were smooth irrespective of growth temperature.

Figure 2 displays 4.2 K PL spectra obtained from n-type GaAs epilayers (N_{Si}~2×10^{16} cm^{-3}) grown on GaAs(201) substrates at different temperatures. No luminescence was obtained for layers grown below $T_G\leqslant460$ °C. The PL intensity of the donor-bound exciton (D,X) increases continuously with growth temperature up to 500 °C, at which point the intensity remains independent of growth temperature up to $T_G\geqslant620$ °C. Above this growth temperature, the intensity of the (D,X) PL peak decreases relative to the lower-energy carbon-related PL bands at 1.493 eV (e,A_c^0), and 1.491 eV (D,A_c^0). Therefore, the PL and Hall-effect data suggest that both the optical and electrical properties of GaAs/GaAs(201) improve above a critical growth temperature ($450\leqslant T_G\leqslant480$ °C), approximately equal to the switch-on growth temperature for electically conductive material in the GaAs/GaAs(100) system.[6,9]

Several n-GaAs epilayers were grown with $T_G=580$ °C, using the conditions described earlier and Si cell temperatures T_{Si} in the range $730\leqslant T_{Si}\leqslant1100$ °C. The epilayer thickness Θ was varied to allow for substrate-to-epilayer and epilayer–to–free-surface depletion effects,[10] such that the thickness was Θ~6.6 μm for the lowest doped and Θ~1.1 μm for the highest doped layer. A plot of the bulk n-type carrier concentration, as determined from room-temperature Hall data against reciprocal Si cell temperature is shown in Fig. 3. A similar data set was obtained from 77 K Hall-effect measurements and it was found that on cooling very little, if any, carrier freeze-out occurred. It can be seen from the figure that the n-GaAs/GaAs(201) specimens followed the same trend as that μ^{RT} and $\mu^{77\ K}$ obtained with n-GaAs/GaAs(100). Figure 4 contains both μ^{RT} and $\mu^{77\ K}$ electron mobility data for n-GaAs(201) and n-GaAs(100) layers, plotted against the doping density N_{Si}. In view of the fact that adjacent GaAs(100) and GaAs(201) samples were subject to the same Si flux, it is of significance that the measured mobilities are remarkably similar for the two crystallographic orientations.

Figure 5 displays PL spectra obtained at 4.2 K from n-GaAs(100) and n-GaAs(201) layers grown simultaneously, with measured bulk doping concentrations of (a) $n\sim4\times10^{14}$ and (b) $n\sim1\times10^{16}$ cm^{-3}. The n-GaAs(100) PL spectra show

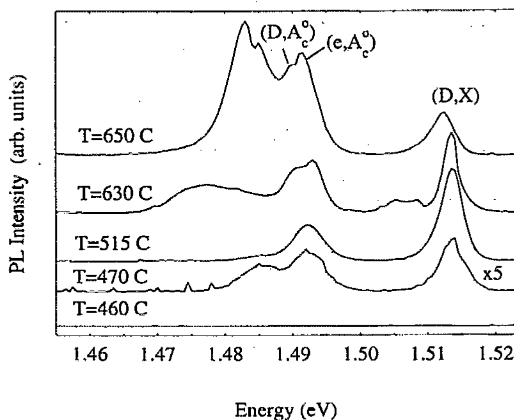

FIG. 2. 4.2 K PL spectra obtained from n-GaAs(201) (N_{Si}~2×10^{16} cm^{-3}) epilayers as a function of growth temperature.

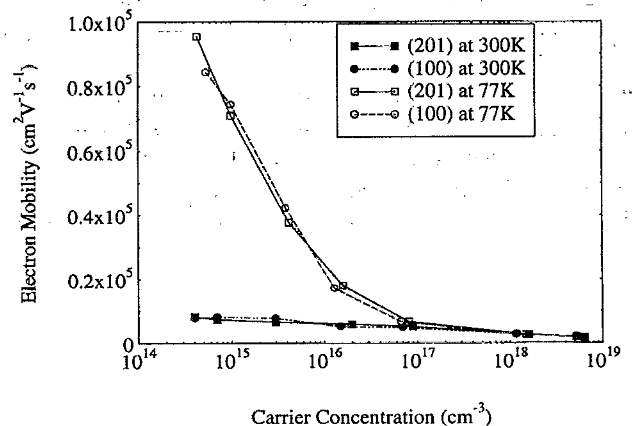

FIG. 4. Variation of electron mobility with free-carrier concentration, measured at room temperature and 77 K, for both GaAs(100) and GaAs(201).

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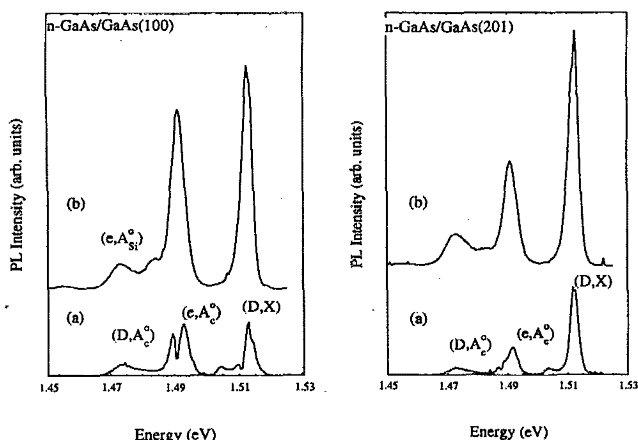

FIG. 5. Comparison of 4.2 K PL spectra obtained from n-GaAs(100) and n-GaAs(201), for Si doping levels of (a) 4×10^{14} and (b) 1×10^{16} atoms/cm^{-3}.

an excitonic peak centered at 1.5135 ± 0.0005 eV, which contains unresolved components from both free- and bound-exciton emission. The PL peak at 1.507 eV, observed for the low-doped sample ($n\sim4\times10^{14}$ cm^{-3}), is consistent with point-defect emission arising at Ga vacancies formed as a result of using As_4 in the growth process;[11] these Künzel–Ploog lines are not observed in more highly doped samples. The PL transitions at 1.493 eV ($e.A_c^0$) and 1.491 eV (D,A_c^0), correspond to recombination involving carbon acceptors. For the more highly doped samples the PL peak which appears at an energy of 1.485 eV arises from recombination between electrons and Si acceptors (e,A_{Si}^0). In comparison, the PL spectra of n-GaAs(201) displayed essentially similar features, but with a slightly different weighting between the donor–to–carbon-acceptor and conduction-band–to–carbon-acceptor transitions, the latter being more prominent for the lower-doped samples. Overall, the relative intensities were similar for both crystallographic orientations.

An optimum growth temperature window of 480–630 °C has been found for the deposition of smooth, conducting, optically active on-axis GaAs/GaAs(201) epilayers. The onset temperature for conduction is approximately equal to that of GaAs(100) and lower than that observed for on-axis GaAs(111)A ($T_G\geqslant475$ °C) and GaAs(111)B ($T_G\geqslant560$ °C).[12] As a consequence, the growth temperature plateau for good quality material is equal approximately to 150 °C for both GaAs(201) and GaAs(100) systems, more than double that available for GaAs(111)A and GaAs(111)B ($\sim$60 °C). In contrast to the investigation of n-GaAs/GaAs(111)B conducted by Woolf *et al.*,[7] where transitions between static surface phases and reconstructions could be related directly to changes in electrical and optical properties, no such correspondence has been found for n-GaAs/GaAs(201). Recently, a combination of RHEED and atomic force microscopy measurements have been used to probe the topography of the GaAs(201) surface.[2] It has been reported that for growth temperatures around 560 °C, there occurs a change from a stepped surface with a lateral periodicity of 13 Å and a height of about 3 Å, to a mesoscopic faceted array with a lateral periodicity of 230 Å and a height of around 10 Å. By studying the tilt angle of the RHEED streaks obtained from this surface, it has been possible to assign the orientation of the facet planes as those of vicinal planes tilted by approximately 6° relative to the (100) and (110) planes.[13] With this in mind, it is worth comparing the growth properties of GaAs(201), in relation to those of GaAs(100) and GaAs(110) individually. As noted earlier, both the growth temperature and Si doping dependencies of the GaAs(201) epilayers closely follow those of GaAs(100) samples grown at the same time. In comparison, for growth of on-axis GaAs(110) it is necessary to both decrease the growth temperature (to $\sim$480 °C) and substantially increase the As-to-Ga flux ratio.[14] Alternatively, it has been reported[15] that high-quality, facet-free growth becomes possible at 570 °C when misoriented GaAs(110) substrates [6°→(111)] are used in conjunction with an As-to-Ga flux ratio of 15.

To conclude, these results show that even though the (201) surface is comprised of slightly misoriented (100) and (110) facets, the growth properties closely follow those of the (100) orientation.

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