AlGaAs/GaAs (111) heterostructures grown by molecular beam epitaxy

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We have grown AlGaAs/GaAs heterostructures on (111) oriented GaAs substrates by molecular beam epitaxy. Materials with good optical and electrical properties, including mobility enhancement in two-dimensional electron and hole gases, have been obtained for the first time.

In recent years, AlGaAs/GaAs heterostructures have received considerable attention for device applications[1-3] and for basic physics studies.[4,5] Due to the differences in the band structure for different orientations, we believe that the studies of crystal orientation dependence of electronic properties of heterostructures will play an important role in the development of novel devices. The study of heterostructures on the three low index planes, namely, (100), (110), and (111), is therefore of fundamental importance since most of the physical properties of other high index planes will fall in between those of the three basic low index planes. In the growth of GaAs by molecular beam epitaxy (MBE), the (111) orientation is rarely used. An interesting exception is the work of Ballingall and Wood,[6] who reported that GaAs films grown on the (111) *B* orientation showed extremely weak photoluminescence efficiency compared to that of films grown on the (100) orientation, and the films were always semi-insulating. In this letter we report our study of AlGaAs/GaAs (111) heterostructures. We found that by slightly misorienting the substrates, dramatic improvement in electrical and optical properties of the films could be obtained. For the first time, we are able to obtain enhanced mobilities for two-dimensional electron and hole gases in modulation-doped structures.

The GaAs, AlGaAs, and AlGaAs/GaAs heterostructures in the present experiment were grown on undoped liquid-encapsulated Czochralski-grown semi-insulating GaAs by MBE. The (111) *B* substrates were 2° misoriented toward the (100) orientation. For comparison purposes, exactly (111) *B* oriented substrates were also used. Standard MBE substrate cleaning and growth procedures were employed.[7,8] The samples were characterized by van der Pauw Hall measurements and low-temperature photoluminescence (PL). For films grown on exactly (111) *B* oriented substrates, even 1×10^{18} cm^{-3} Si-doped GaAs is highly resistive, and the PL efficiency is extremely low, almost a factor of 1000 weaker than that of films grown on (100) oriented substrates (as will be described later). This indicates that the major cause of compensation for the (111) *B* orientation is due to deep level traps, which most likely are due to the complicated surface reactions between Ga and arsenic tetramers. Our results are consistent with those reported in Ref. 6. By using arsenic dimers, one might be able to improve the growth of GaAs on exactly (111) *B* oriented substrates, for which a detailed study is planned in the future.[9] However, when the substrates were tilted 2° off toward the (100) orientation, the electrical and optical properties of the epitaxial films improved significantly, and became similar to that of (100) oriented epitaxial materials. For example, Si-doped GaAs showed liquid nitrogen electron mobility of 2500 cm^2 V^{-1} s^{-1} at an electron concentration of 1×10^{18} cm^{-3}. This indicated a compensation ratio of approximately 0.3, which is comparable to that usually obtained for the (100) orientation. Modulation-doped (MD) $Al_{0.3}Ga_{0.7}As$/GaAs heterojunctions were also grown with an 18-nm undoped spacer layer, and the $Al_{0.3}Ga_{0.7}As$ was doped to 1×10^{18} cm^{-3} with Si. Hall measurement at 4.2 K showed electron mobility of 89 000 cm^2 V^{-1} s^{-1} at a sheet electron density of 3.8×10^{11} cm^{-2}. Similar experiments on Be-doped $Al_{0.4}Ga_{0.6}As$/GaAs heterojunctions with 26-nm undoped spacer layer showed hole mobility of 28 000 cm^2 V^{-1} s^{-1} at a sheet hole density of 3.5×10^{11} cm^{-2} at 4.2 K. These results indicated that heterointerfaces of reasonably good quality could be obtained, and we believe that with modest efforts significant improvement can be made in the future.

The low-temperature (6 K) PL of the undoped GaAs in modulation-doped structures grown on 2° misoriented substrates has been studied and compared to that of GaAs grown on exactly (111) *B* oriented substrates. Figure 1(a) is the PL of typical GaAs grown on (111) *B* oriented substrates and Fig. 1(b) is the PL of GaAs grown on 2° misoriented substrates. It can be seen that a thousand times improvement is obtained by slight misorientation of the substrates. Also, exciton structures, which are good indications of material quality, can be observed in Fig. 1(b). The PL intensity of the films grown on misoriented substrates is comparable to that of GaAs grown on (100) orientation, and is of device quality.

The exact reason for the drastic improvement of our results for epitaxial films grown on slightly misoriented substrates over previously reported results for films grown on exactly (111) *B* oriented substrates is not well understood at the present time, yet it is obvious that the introduction of surface steps due to slight misorientation of the substrates has profound influence on the electrical and optical properties of the (111) *B* films grown by MBE. We have also performed similar experiments on the (111) *A* orientation. We found that although improvement can be obtained by slight substate misorientation, the effect is smaller. Especially, without misorientation, Si-doped GaAs (111) *A* films already exhibit reasonably good p-type electrical properties. At the present time, the surface reconstruction of GaAs (111) *A* can be regarded reasonably well established.[10-13] Considering the vacancy model,[10,11] which states that the GaAs (111) *A* surface reconstructs into a (110)-like nonpolar surface, one would expect to be able to introduce electrically active impurities on GaAs (111) *A* orientation since it has been dem-

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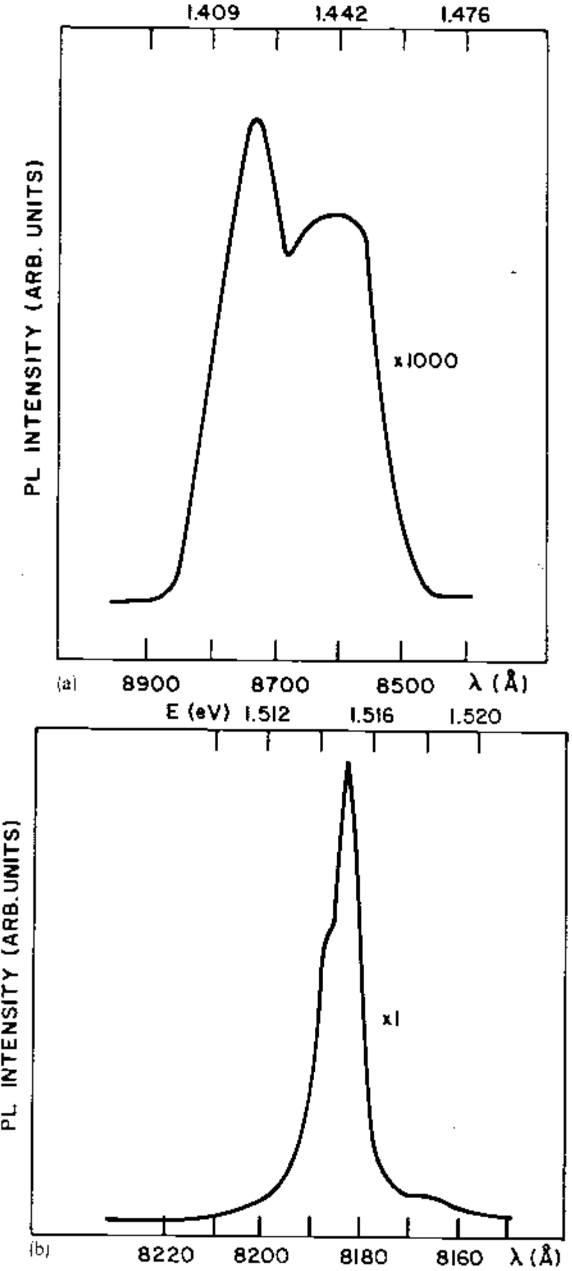

FIG. 1. 6 K photoluminescence of (a) GaAs grown on exactly (111) *B* oriented substrates, and (b) 2° misoriented substrates. The pump power density is 5 W/cm^2.

onstrated that one can dope GaAs (110) with Si.[6,14] However, the surface reconstructions of GaAs (111) *B* are largely unknown, and it has been shown[10–13] that the vacancy model is not adequate for the description of GaAs (111) *B* surfaces. A detailed understanding of our present results must therefore wait until the GaAs (111) *B* surface becomes better known.

In conclusion, we have found that by slightly misorienting the substrates, drastic improvement in electrical and optical quality can be obtained for epitaxial materials grown on GaAs (111) *B* orientation. The introduction of surface steps due to slight misorientation is the obvious reason for such improvement. However, a detailed understanding must wait until more information on the surface structures and the complicated surface reactions between gallium and arsenic becomes available.

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