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Transmission electron microscopy study of Si δ-doped GaAs/AlGaAs/InGaAs/GaAs pseudomorphic high electron mobility transistor structures

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Abstract

A high electron mobility transistor (HEMT) structure grown by molecular beam epitaxy consisting of a 2-nm $In_{0.3}Ga_{0.7}As$ channel limited by a thick GaAs layer at the bottom and a 5-nm $Al_{0.3}Ga_{0.7}As$ spacer at the top has been characterised by transmission electron microscopy (TEM) and high-resolution electron microscopy (HREM). The carrier supplier of this structure is a Si δ-doped layer centred within a 1.7-nm wide GaAs quantum well grown on the spacer. (200) dark field (DF) TEM and HREM show well-defined InGaAs/GaAs and AlGaAs/InGaAs interfaces. The interface abruptness, the InGaAs layer thickness and its In composition have been quantitatively determined by strain measurements from ⟨110⟩ HREM images. The compositional profile obtained confirms an average InGaAs layer thickness of 7 group III monolayers (ML). All the layers are pseudomorphic, without dislocations or stacking faults. An inhomogeneous intensity distribution in DF TEM along the Si δ-doped GaAs layer suggests lateral Si segregation or strain modulation of which no evidence has been found by HREM. HREM reveals, however, an unusually large average lattice contraction at the position of the δ-doped layer which can be explained by atoms occupying non-lattice sites (DX centres). © 1997 Published by Elsevier Science S.A.

Keywords: Heterostructures; Interfaces; Semiconductors; Transmission electron microscopy

1. Introduction

Carrier trapping effects in $Al_xGa_{1-x}As$ ($x > 0.2$) barrier layers of high electron mobility transistors (HEMT) can be reduced by Si δ-doping [1–3]. Ideally, a Si δ-doping layer should consist of a single group III monolayer (ML) of Si within the matrix. However, it has been shown before by electrical transport and photoluminescence measurements on our sample [4] that the Si δ-doping in the GaAs is non-ideal, the Si atoms forming a Gaussian distribution spreading into the GaAs layer. Similar dopant spreading has previously been reported by Clegg and Beall [5] and has been shown to depend on the growth temperature and the doping level [6–8]. The roughness of both interfaces of the $In_{0.3}Ga_{0.7}As$ channel and its width are important device parameters controlling the electrical properties of the HEMT structure.

This work presents a study by transmission electron microscopy (TEM) of the InGaAs channel and the Si δ-doped GaAs layer of a HEMT structure.

2. Experimental

The HEMT structure was grown by molecular beam epitaxy (MBE) on a (001) GaAs substrate at 550°C. It consists of a 2-nm $In_{0.3}Ga_{0.7}As$ channel limited by a thick GaAs layer underneath and a 5-nm $Al_{0.3}Ga_{0.7}As$ spacer at the top. The carrier supplier is a 2.45×10^{12} cm^{-2} Si δ-doped layer centred within a 1.7-nm wide GaAs quantum well on the spacer. More details on the growth conditions, optical and transport properties of this structure have been published previously [4,9].

The techniques used in this study are conventional

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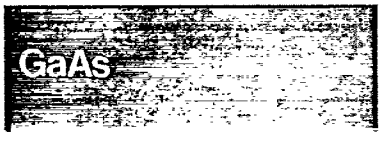
cross-sectional TEM and high-resolution electron microscopy (HREM). TEM specimens were prepared along the [110] direction by cutting, mechanical thinning and subsequent Ar^+ ion-milling under liquid nitrogen cooling. A reduced ion energy of 2.5 keV was used towards the end of the thinning procedure to reduce surface contamination and amorphous layers which could result in artefacts. The TEM and HREM work was performed in electron microscopes of the types JEOL 2000EX (at 200 kV) and JEOL 4000EX-II (at 400 kV), respectively.

3. Results and discussion

Fig. 1 shows a compositional sensitive (002) dark field (DF) TEM image of the HEMT structure. No microstructural defects have been observed. A visual inspection suggests rather uniform composition within the InGaAs as well as the GaAs(Si) layer. Densitometry of the scanned negative, however, reveals intensity fluctuations in the Si δ-doped GaAs layer along the $[1\bar{1}0]$ direction in the (001) growth plane. Intensity profiles of the DF image along $z = [001]$ projected over 1.3 nm along $[1\bar{1}0]$ are shown in Fig. 2. For most of the length of the GaAs:Si layer, the DF



AlGaAs

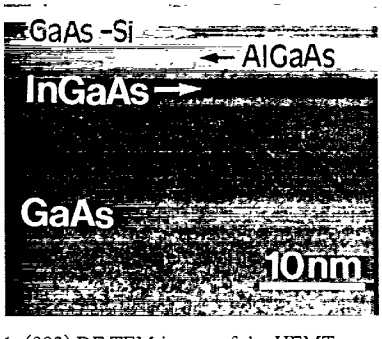


Fig. 1. (002) DF TEM image of the HEMT structure.

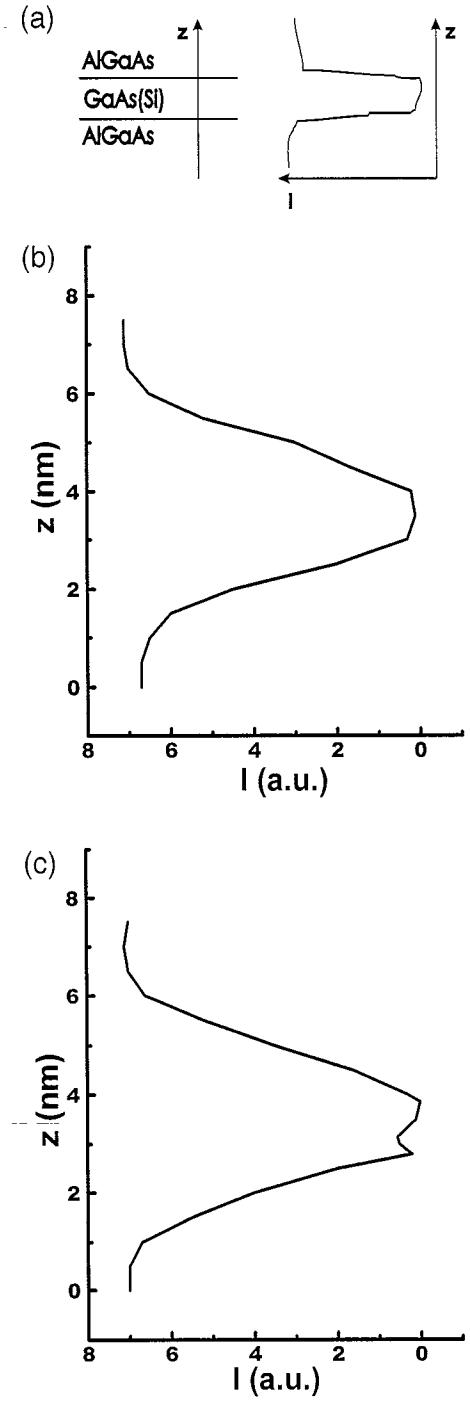


Fig. 2. Profile analysis of the Si δ-doped GaAs layer. (a) Profile acquisition; (b) most usual obtained profile; (c) exceptionally obtained profile.

intensity profiles are similar to that in Fig. 2b, but in some areas, the intensity profile across the GaAs(Si) layer contains a signal within the layer as depicted in Fig. 2c. This suggests lateral non-uniformity of the doping layer or interface roughness.

The InGaAs channel and the GaAs(Si) layer have been studied by HREM. Fig. 3 shows an HREM image of the

channel layer. The approximate position of the AlGaAs/InGaAs and the InGaAs/GaAs interfaces have been marked by straight lines. As the image pattern hardly changes from one material to the other, the interfaces are not apparent to the eye but can be quantitatively characterised by measuring the lattice distortion in the HREM image. Fig. 4b is a scan of the lattice spacings along the [001] growth direction by averaging the image intensity over 30 nm along the layers, obtained by fitting the projected peak maxima by a centre-of-mass calculation and differentiating the scan of peak positions. Linear elasticity theory, with a Poisson coefficient of 0.33, and Vegard's law allow the conversion of the lattice spacings of Fig. 4b into compositional values as depicted in Fig. 4c, provided the lattice distortions of the strained layer are tetragonal as in the bulk and not rendered monoclinic by surface relaxation. Non-tetragonal distortions should be negligible when the layer thickness is small compared to the specimen thickness over which is averaged, which has been verified by image simulations for ⟨110⟩ InGaAs/GaAs specimens thicker than about 30 nm and small underfoci [10]. The compositional profile of Fig. 4c gives an average channel thickness of 7 group III monolayers (i.e., 2.0 nm) and a peak composition of $x(\mathrm{In}) = 0.24$. It should also be noted that the lattice contraction of 0.0056 ± 0.0011 nm (error bar: standard deviation of the average lattice spacings in GaAs) observed in Fig. 4b at precisely the nominal position of the Si δ-doped layer is two orders of magnitudes larger than expected for the doping level given from Si atoms on either Ga or As lattice sites. Such a strong contraction of the lattice in Si δ-doped GaAs has also been observed by Fresnel-imaging [11] and can only be understood if a proportion of Si atoms occupies non-lattice sites as, e.g., in the configuration of DX-centres [12] where the local atom displacements are the order of 0.1 nm and, thus, may influence the lattice spacing averaged over the sample thickness sufficiently.

The carrier concentration of MBE grown Si δ-doped GaAs has been shown to depend on the growth temperature only for certain doping concentrations. In particular, for the temperature range of 410–660°C, this carrier concentration is not dependent on the growth temperature for Si doping concentrations below 4×10^{12} cm^{-2} [6]. Hence, as the Si doping concentration is nominally 2.45×10^{12} cm^{-2} in the sample studied here, the observed Si segregation will be expected to occur not only at the growth temperature of our specimen but over the whole temperature range given above.

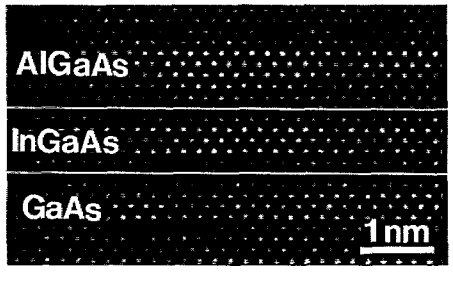


Fig. 3. [110] HREM image of the InGaAs channel layer.

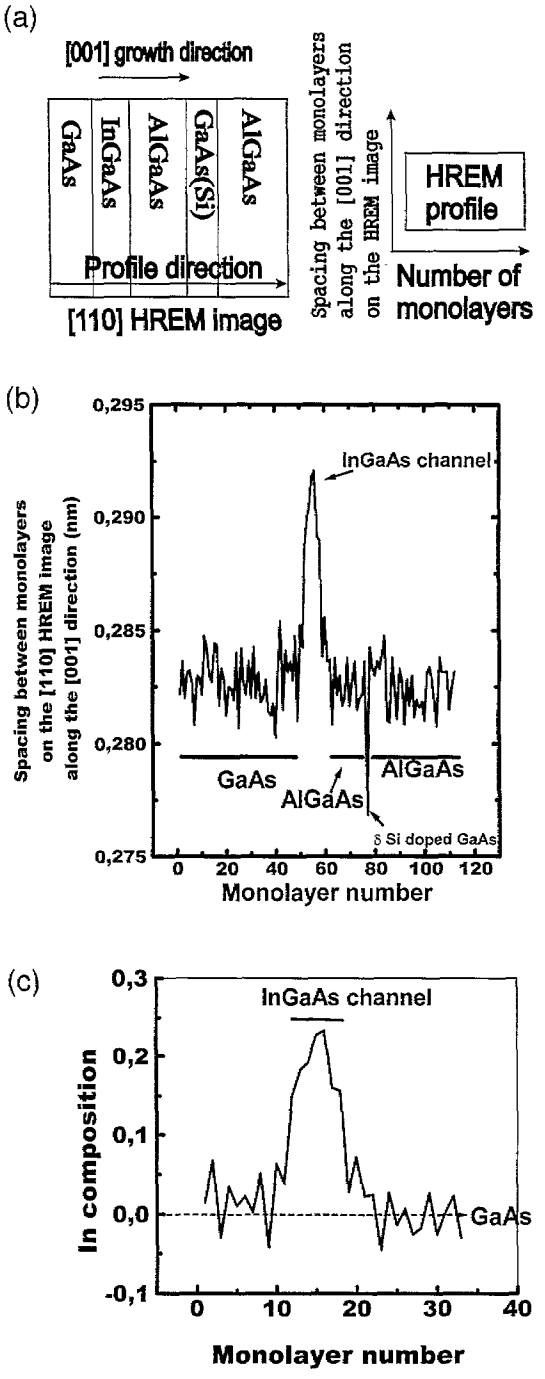


Fig. 4. Analysis of [110] HREM images. (a) Acquisition procedure of profiles for strain measurements. (b) Example of spacing profile containing a strong signal in the GaAs(Si) layer. (c) Composition profile obtained from the spacing profile of (b) in the InGaAs channel.

4. Conclusions

DF TEM and HREM show that the interfaces between the 2-nm InGaAs channel and the adjacent layers (GaAs and AlGaAs) of a HEMT structure are well defined.

A strong lattice contraction of GaAs:Si is explained in terms of atoms occupying non-lattice sites as, e.g., in DX-centres.

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