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Formation of Uniform GaAs Multi-Atomic Steps with 20–30 nm Periodicity and Related Structures on Vicinal (111)B Planes by MBE

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We studied morphology of GaAs surfaces and the transport properties of two-dimensional electron gas (2DEG) on vicinal (111)B planes. Multi-atomic steps (MASs) are found on the vicinal (111)B facet grown by molecular beam epitaxy, which will affect electron transport on the facet. We also studied how the morphology of GaAs epilayers on vicinal (111)B substrates depends on growth conditions, especially on the As_4 flux. The uniformity of MASs on the substrates have been improved and smooth surfaces were obtained when the GaAs was grown with high As_4 flux, providing step periodicity of 20 nm. The channel resistance of the 2DEG perpendicular to the MASs is reduced drastically with this smooth morphology. These findings are valuable not only for fabricating quantum devices on the (111)B facets but also those on the vicinal (111)B substrates.

Key words: (111)B, GaAs, multi-atomic steps, two-dimensional electron gas (2DEG)

INTRODUCTION

It is important to make smooth facet structures for fabricating quantum microstructures such as edge quantum wires (QWRs) and ridge QWRs.[1–3] In particular, the smoothness of the n-AlGaAs/GaAs heterojunction on the facet is essential for transport properties of edge QWRs since the electron conduction in the wire will be degraded by the roughness of the facet surface. In this paper, we studied smoothness of (111)B facets grown by molecular beam epitaxy (MBE) and observed multi-atomic steps (MASs) on the facets by atomic force microscopy (AFM).[4] To investigate growth condition dependence of the smoothness more in detail, the morphology of GaAs epilayers grown on vicinal (111)B substrates was also studied, where we found that uniform MASs with their period of 20 nm was obtained with forming smooth (111)B surfaces.[5,6] Such smooth (111)B surfaces are valuable also for quantum well lasers with low threshold current.[7] Furthermore, a two-dimensional electron gas (2DEG) was formed on this smooth GaAs surface by growing selectively doped n-AlGaAs. Then, the relation between the surface morphology and the conductance of 2DEG was studied.

DISCUSSION

(111)B facet structures were formed by selective MBE growth on patterned (001) substrates, where mesa-stripes were almost parallel to [110] direction but have slight misorientation $\Delta\theta$ of 2° from [110]. Therefore, vicinal (111)B surface will be formed on the facet. 0.7 μm thick GaAs layer was grown on these mesa-stripes at the substrate temperature T_s of 580°C with the growth rate of 0.26 μm/h measured on an unpatterned (001) plane. The morphology on the facets was observed by AFM. Then, quasi-periodic MASs with typical period of 30 nm were found on the facet surface as shown in Fig. 1a. This result is shown schematically in Fig. 1b, where the roughness will seriously influence transport properties of the edge QWR on the facet. In order to investigate the relation between the surface morphology and the transport properties more in detail, we studied GaAs and n-AlGaAs/GaAs epilayer grown on the vicinal (111)B substrates.

First, we studied how the morphology of GaAs epilayer depends on MBE growth condition, especially on the As_4 flux. The vicinal (111)B GaAs substrates have misorientation angles of 2° toward the

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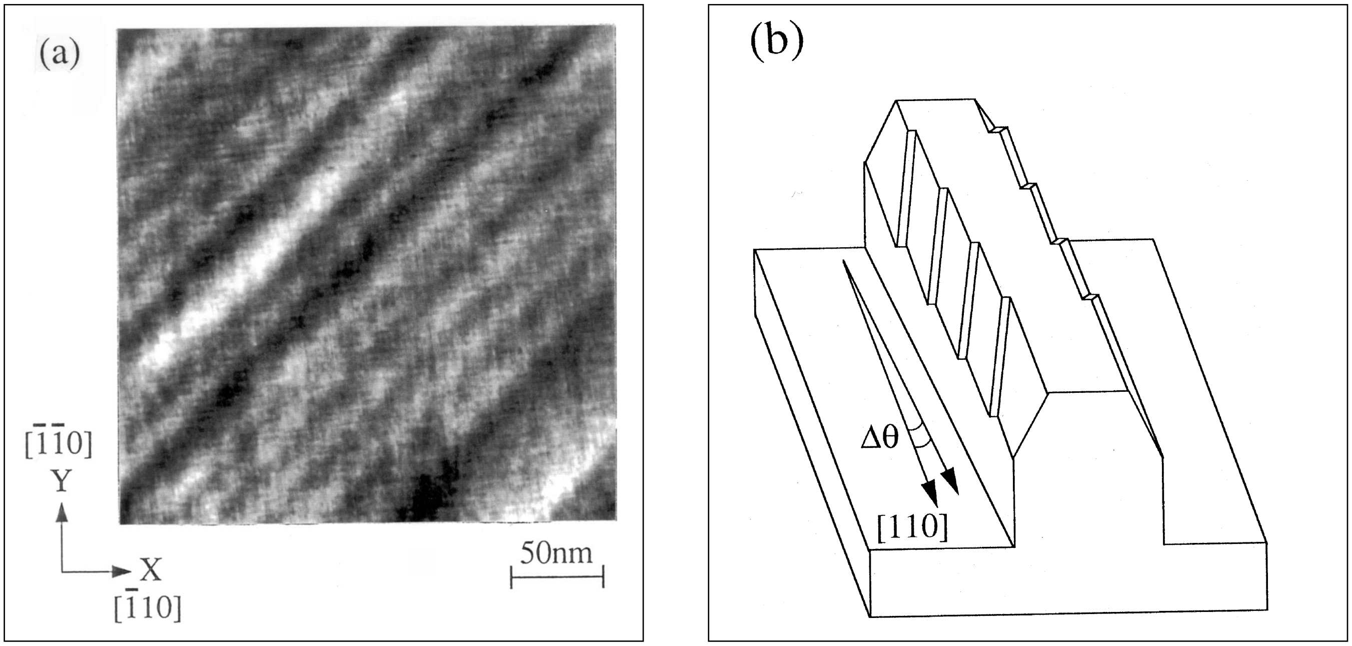

Fig. 1. (a) AFM image of (111)B facet surface formed on patterned (001) substrate, where multi-atomic steps with 30 nm periodicity is observed, and (b) schematic illustration of (111)B facet with MASs.

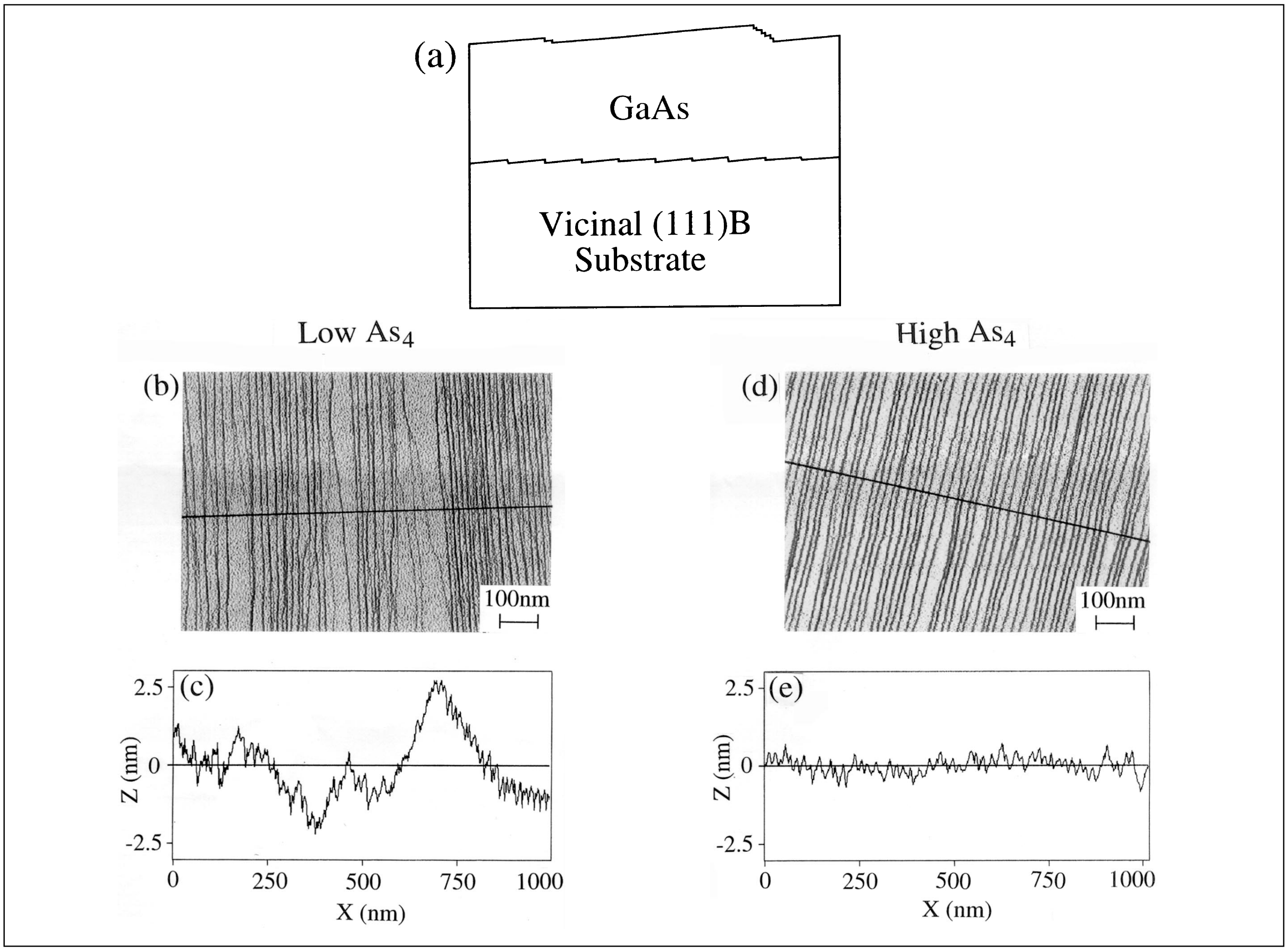

Fig. 2. (a) Cross-sectional diagram of GaAs epilayer on vicinal (111)B substrate, (b) AFM image taken in derivative mode for a (111)B surface grown with low As_4 flux, and (c) cross-sectional height profile (c). Corresponding results on the sample grown with high As_4 flux are given in (d) and (e).

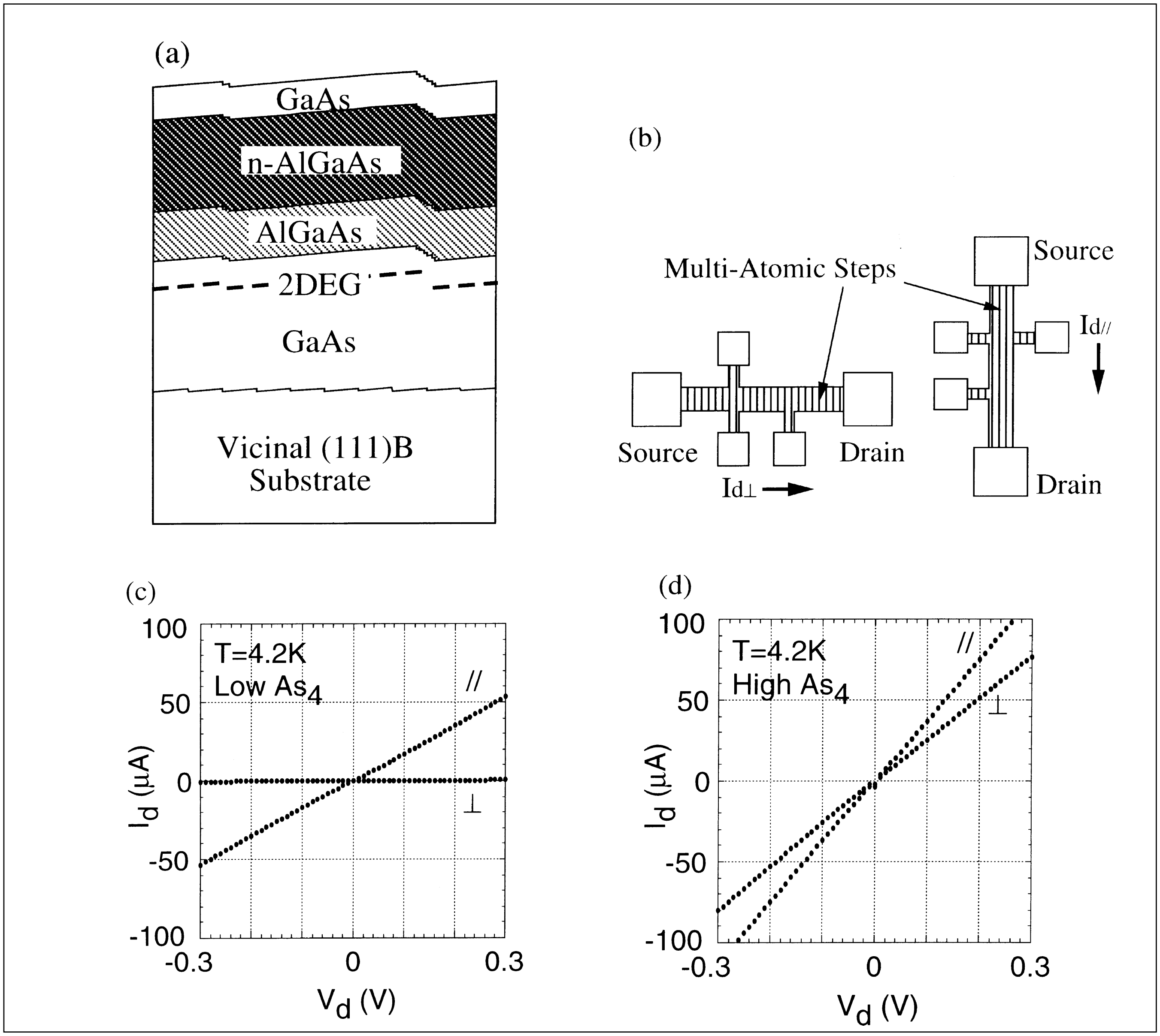

Fig. 3. (a) Cross-sectional diagram of modulation doped n-AlGaAs/GaAs heterojunction with a corrugated interface, and (b) FET patterns to measure the current $I_{d\perp}$ perpendicular to and $I_{d//}$ parallel to the steps. The data for the sample prepared under low and high As_4 flux are shown in (c) and (d), respectively.

nearest ($\bar{1}0\bar{1}$) plane. As described in a separate paper,[6] MASs are parallel to the inter-section line of ($\bar{1}\bar{1}\bar{1}$) and the ($\bar{1}0\bar{1}$) plane. If other misorientation directions are used, the (111)B surfaces will be rough due to faceting. Two samples were grown with their cross section schematically shown in Fig. 2a, where the As_4/Ga flux ratios of beam equivalent pressure were set at 50 or 130, respectively. The thickness of GaAs layer was 0.6 µm, and other parameters such as growth rate and T_s were the same as the above work of the facet. In Figs. 2b and 2d, AFM images taken in derivative mode of the surface of the GaAs epilayers are shown, where dark lines and bright regions correspond to MASs and flat terraces, respectively. In case of low As_4 flux, the period of MASs is not uniform and the surface has large amplitude steps with heights of ~3 nm as shown in the cross-sectional height profile of Fig. 2c. On the other hand, in case of high As_4 flux, the uniformity is improved, and the regular steps with the average period of 20 nm are observed (See Fig. 2d). In Fig. 2e, its cross-sectional profile shows typical height of 0.4~0.7 nm, which corresponds to about two monolayers of GaAs on the (111) plane.

To understand the above experimental result, we discuss the dependence of the step uniformity on As_4 flux. It is well known that when adatoms are incorporated preferentially at up-steps, uniformly spaced steps will appear on the vicinal surfaces. In case of this type of vicinal (111)B plane, As atoms stick with single bonds at step edges, and the probability of the As atom occupying the step edge can be enhanced by increasing the As_4 flux. The existence of these As atoms at the step edges may enhance the possibility of Ga-atom incorporation at up-steps, contributing to the step equalization.

Second, we investigate how the surface morphology on the vicinal (111)B substrate affects the transport of the 2DEG. An n-type AlGaAs layer was grown on the two types of GaAs surface with multi-atomic steps as shown in Fig. 3a. After growing a 0.6 μm thick GaAs, we grew a 20 nm thick undoped $Al_{0.33}Ga_{0.67}As$ spacer layer, a 90 nm thick Si doped $Al_{0.33}Ga_{0.67}As$ with the dopant density of 6×10^{17} cm^{-3}, and a 20 nm thick GaAs cap layer. The growth conditions were similar to those of the first study on the vicinal substrate, where As_4/Ga flux ratios of beam equivalent pressures were set at 55 and 170 for the each sample. These samples were processed to Hall bar geometry as shown in Fig. 3b, where the channel width and length are 50 and 600 μm, respectively. Note that 2DEG at these corrugated heterojunctions will flow either perpendicular (⊥) to or parallel (//) to the MASs. From Hall measurement at 14K on the sample grown with high As_4 flux, the mobility, μ, and concentration, N_s, of electrons are 80,000 cm²/Vs and 1.9×10^{11} cm^{-2}, respectively.

For each sample, current I_d-voltage V_d characteristics were measured at 4K for the two current directions as shown in Fig. 3c and 3d, respectively. In Fig. 3c for the case of low As_4 flux, the current $I_{d//}$ flowing parallel to the steps is large but current $I_{d\perp}$ perpendicular to the steps is extremely small, indicating an extremely large anisotropy. Only the current $I_{d\perp}$ perpendicular to the steps is blocked probably by the large potential barriers. These potential barriers seem to originate from the large roughness at the heterojunction shown in Fig. 2c. In the sample grown with high As_4 flux, magnitudes of the currents for both directions are almost isotropic (see Fig. 3d), and they are as large as the parallel current $I_{d//}$ of the sample grown with low As_4. These results indicate that highly conductive channels are formed even for the direction perpendicular to the steps when GaAs is grown with high As_4 flux. Hence, high quality transport devices and QWRs can be prepared on (111)B planes.

SUMMARY

We studied surface morphology on GaAs vicinal (111)B plane. Multi-atomic steps were observed on the (111)B facet and on the epilayers on vicinal (111)B substrates. We have found that uniform multi-atomic steps can be prepared with 20 nm periodicity when GaAs is grown with high As_4 flux. Then, we have also found that highly conductive 2DEG can be formed even perpendicular to the multi-atomic steps, which is important to fabricate quantum devices.

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