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Effect of Ga predeposition layer on the growth of GaAs on vicinal Ge(0 0 1)

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Abstract

We report a detailed study of molecular beam epitaxial growth of GaAs films on vicinal Ge(0 0 1). Reflection high-energy electron diffraction was used to examine the atomic structures of the epitaxial surfaces. By using RHEED technique we show that clean Ge(0 0 1) vicinal surface has (1×2) single-domain reconstruction and consists of double-layer steps. After the deposition of Ga submonolayer coverage, transformation from double to single-layer stepped surface was observed. Transmission electron microscopy reveals a high density of anti-phase domains in the GaAs epitaxial films grown on single-stepped Ga covered Ge(0 0 1) vicinal surfaces and anti-phase domain free GaAs was grown on a double-layer stepped clean Ge(0 0 1). © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The near perfectly lattice-matched GaAs/Ge heteropair has attracted much attention in part because of its potential device applications: tandem solar cells [1], double heterojunction bipolar transistors [2] and in view of the recent success in growing rather low defect ($<4.0\times10^5$ cm^{-2}) epitaxial GaAs films on Ge covered Si(0 0 1) substrates [3]. Several groups have used (0 0 1) substrates of Si or Ge misoriented for 3–6° towards [1 1 0] to grow GaAs, which is free of anti-phase domains (APD) [4,5,8,15]. Two growth models were proposed in literature to explain suppression of APD when vicinal substrates are used. The first model suggests that the vicinal surface contains steps of double layer height, providing single-domain template for successive GaAs deposition [10]. The tendency to form steps of double-layer height was experimentally observed on both Ge(0 0 1) and Si(0 0 1) vicinal surfaces [6,7]. The second model regards the vicinal surface as a single-layer

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staircase, which according to Chady's notation consists of two types of steps – S_A and S_B [9]. It is intuitively expected that at the initial stage of growth for each atom species only one kind of step is energetically preferable thus providing a perfect atomic stack of polar material atoms [4,8,15]. One of the purposes of this paper is to define what kind of mechanisms described above is responsible for APD suppression in GaAs when growth on vicinal stepped Ge(0 0 1) surface takes place.

Here, we report MBE of GaAs on Ge covered GaAs(0 0 1) vicinal substrates. By using in situ reflection high energy electron diffraction (RHEED) technique we demonstrate the effect of Ga or As_4 prelayer coverages on the steps' height of vicinal Ge(0 0 1) surface. MBE growth of GaAs thin films on double or single-layer stepped Ge(0 0 1) surface was done. It was found that the APD concentration strongly depends upon the step height on vicinal Ge(0 0 1) surface.

2. Experimental procedure

The epitaxial growth was done in a two-chamber all solid source MBE system for separate growth of Ge and III–V compound materials in order to minimize cross contamination, the background pressure in the chambers was better than 5.0×10^{-8} Pa. A semi-insulating 2″ in diameter GaAs(0 0 1) substrates misoriented by 5° towards [1 1 1]A were used. In each case an initial GaAs buffer layer of 0.5 μm under an excess As_4 flux was grown. Immediately after buffer layer deposition samples were transferred to the adjacent MBE chamber where Ge deposition took place. Epitaxial Ge films were grown up to 0.5 μm at a typical growth rate of 0.3 μm/h. In order to discourage cross-diffusion effects the substrate temperature was held near 200°C at the beginning of Ge growth and successively raised up to 500°C. The substrate temperature was measured to an accuracy of ±40°C by using preliminary experiments on GaAs(0 0 1) surface phase transitions as a function of temperature. After the Ge film has been grown, part of the samples were exposed to Ga for a period of 10–20 s and at a temperature range of 400–500°C. Ga flux density was determined by comparing the RHEED pattern fading as a function Ga dose deposited on Ge(0 0 1) surface at room temperature in As-free and III–V growth chambers. Assuming that equal Ga coverages produce the same RHEED pattern fading and taking into account that Ga effusion cell in the III–V chamber was previously calibrated by RHEED oscillations during GaAs growth, Ga flux rate in As-free chamber was estimated to be $J_{Ga} = 0.04$ ML/s (1 ML $= 6.24 \times 10^{14}$ atoms/cm^2). The epitaxial growth and Ga-induced surface transformations were monitored in situ by RHEED technique using a 30 keV electron beam. Deposition of Ga prelayer coverages took place in As-free chamber where Ge films were grown previously. Step height was determined by analyzing the RHEED pattern in azimuth along steps edges as described below. After several minutes of cooling, samples were transferred back to the III–V chamber where they were exposed to As_4 flux for several minutes. During this period substrates were heated from room temperature up to 600°C and then 1000 Å of GaAs was grown at As_4 rich growth conditions on clean or Ga treated Ge(0 0 1) surfaces. The defect structure of epitaxial GaAs films grown on clean and Ga-treated surfaces was examined by transmission electron microscopy (TEM).

3. Results and discussion

Fig. 1a presents a typical RHEED pattern of GaAs buffer layer at the $[1\,\bar{1}\,0]$ azimuth of incident beam parallel to the steps' edges. RHEED pattern at this azimuth exhibits streaks, which consists of series of declined slashes. Step height and terrace length could be easily obtained from this pattern. It was determined by comparing the separation between adjacent slashes and adjacent streaks which in reciprocal space corresponds to $2\pi/L$ and $2\pi/a_{\parallel}$, respectively, where L is the distance between step edges and $a_{\parallel}$ the distance between equivalent rows of atoms parallel to the incident beam [14]. Keeping in mind that in our case $a_{\parallel} = a_0/\sqrt{2}$, where a_0 is the lattice parameter of GaAs, we obtain that $L = 32$ Å. Assuming that the GaAs(0 0 1) vicinal surface is double-layer stepped, the angle of misorientation could be determined to be equal to 5°,

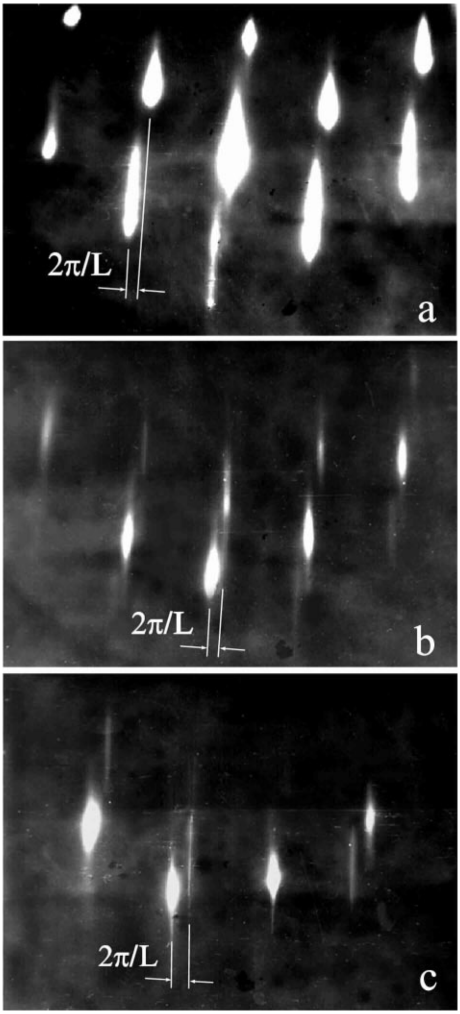

Fig. 1. [1 $\bar{1}$ 0] RHEED patterns along the step edges: (a) from GaAs buffer layer, where L is the distance between step edges, (b) from clean double-layer stepped Ge(0 0 1) surface and (c) from Ga-treated single-layer Ge(0 0 1) surface.

which correlates well with independent verification by X-ray technique.

Fig. 1b shows a typical RHEED pattern of clean Ge(0 0 1) vicinal surface at the same incident beam direction. It must be mentioned that 1/2 order streaks are much more intensive while the incident beam has a direction down the steps similar to the azimuth parallel to the steps. From this observation it could be concluded that vicinal Ge(0 0 1) surface in our experimental conditions is presumably single-domain and consists of double-layer steps of D_B type according to Chady's classification [9]. Following the procedure described above step height of $a_0/2$ could be easily obtained. This is another argument confirming single-domain surface structure of Ge(0 0 1) vicinal surface existence.

No effect on the step height was observed after the exposure of clean double-layer stepped Ge(0 0 1) surface to the molecular As_4 flux of about $J_{As_4} = 1.0 \times 10^{15}$ atoms/cm^2 s as the substrate was heated from room temperature up to 400–600°C. Similar results were reported by Bringans et al. [11] for the case of As_4 interaction with Si(0 0 1) double-layer vicinal surface.

The effect of Ga submonolayer coverages was studied at substrate temperature in the range of 400–600°C. After deposition of approximately 0.5 ML of Ga on Ge(0 0 1) double-layer stepped surface, the RHEED pattern significantly changes: the distance between two adjacent slashes increases two times (Fig. 1c). It means that step height is reduced twice and becomes $a_0/4$ now. The same effect of Ga-induced step transformation from double- to single-layer height was demonstrated at vicinal Si(0 0 1) surface [12,13]. It should be emphasized that the same quantity of Ga (0.5 ML) is necessary to split double-layer steps on either Si or Ge vicinal surfaces. Additional deposition of Ga up to 1 ML reveals sharp and streaky (7×7) RHEED pattern on either vicinal or exactly oriented Ge(0 0 1) surfaces. Clean double-layer and Ga treated single-layer stepped surfaces were used for successive GaAs growth in order to clear up the role of step height on the formation of APD. After growth of several monolayers of GaAs on double-layer Ge(0 0 1) surfaces, RHEED pattern always demonstrated well resolved single-domain (2×4) reconstruction, indicating APD free mode of GaAs growth. The mixed two-domain (4×4) reconstruction was repeatedly observed during the entire period of growth, when growth was taking place on a single-layer surface. In all the cases the films were grown up to 1000 Å and the growth temperature was about 550°C. The key role of step height in the APD formation was fully confirmed by TEM observations. TEM plan-view studies revealed a very high density of APD in the GaAs grown on Ga treated single-layer surface and no APD were found in the samples grown on bare double-layer stepped Ge(0 0 1) surfaces.

4. Summary

Epitaxial MBE growth of GaAs on Ga or As_4 treated Ge(0 0 1) vicinal surfaces was performed. Unambiguous correlation between step height and APD density was observed in the GaAs/Ge heterosystem. RHEED technique was used to reveal Ga induced step splitting at elevated temperature from double- to monolayer step height on vicinal Ge(0 0 1) surfaces. APD with a density in the range of 10^6–10^7 cm^{-2} was observed in the GaAs films grown on Ga treated Ge(0 0 1) vicinal surfaces consisting of single-layer steps. Annealing of initially double-layer Ge surfaces under As_4 flux preserves double-layer surface structure providing single-domain (APD free) growth mode of GaAs.

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