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Surface diffusion length of Ga adatoms in molecular-beam epitaxy on GaAs(100)-(110) facet structures

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Abstract

By the molecular-beam epitaxial (MBE) growth of GaAs on [001]-mesa stripes patterned on GaAs(100) substrates, (110) facets were formed on the mesa edges defining (100)-(110) facet structures. The surface diffusion length of Ga adatoms along the [010] direction on the mesa stripes was obtained for a variety of growth conditions by in-situ scanning microprobe reflection high-energy electron diffraction (μ-RHEED). Using these values and the corresponding growth rate on the GaAs(110) facets, the diffusion length on the (110) plane was estimated. We found that the Ga diffusion length on the (110) plane is longer than that on the (100) and (111)B planes. The long diffusion length on the (110) plane is discussed in terms of the particular surface reconstruction on this plane.

1. Introduction

The fabrication of low-dimensional quantum structures by the molecular-beam epitaxial (MBE) growth on patterned substrates has been investigated during the last few years [1]. Very recently we showed that by the MBE growth of GaAs, (110) facets can be formed on the sidewalls of [001]-oriented mesa stripes on GaAs(100) substrates [2]; these facets are very useful for the fabrication of quantum wires and boxes because of their extremely low growth rates [3]. Similar results have been reported by Liu et al. [4]. The surface diffusion of Ga adatoms during the MBE growth is a determining factor for the successful fabrication of the above-mentioned structures. Therefore, it is important to obtain information concerning the Ga adatom diffusion, such as the surface diffusion length on the [001]-mesas as well as that on the GaAs(110) facets.

In-situ scanning microprobe reflection high-energy electron diffraction (μ-RHEED) is a powerful technique for studying MBE growth on patterned substrates [5]. Using this technique, Hata et al. obtained the surface diffusion length of Ga adatoms along the [011] and [0$\bar{1}$1] directions on the GaAs(100) surface [6]. Similar experiments were reported by Shen and Nishinaga [7]. The above-mentioned experiments were limited to the investigation of the diffusion length of Ga adatoms along the [011] and [0$\bar{1}$1] directions; so far there has been no report concerning the surface diffusion length along the [010] direction by μ-RHEED.

On the other hand, concerning the GaAs growth on the (110) plane, RHEED oscillations

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with twice the period corresponding to one layer of GaAs growth have been observed under certain growth conditions [8]. This anomalous behavior makes it difficult to obtain the Ga diffusion length on the (110) plane by methods based on observations of the RHEED oscillations.

In the present work, first we obtained by μ-RHEED the surface diffusion length of Ga adatoms along the [010] direction on [001]-mesa stripes for a variety of growth conditions. Then, we estimated the Ga diffusion length on the (110) plane, using the above values for the diffusion length along the [010] direction, and the corresponding growth rate on the (110) facets.

2. Experiments

GaAs(100) substrates were patterned by photolithography and chemical etching with mesa stripes of 100 μm width and 1 μm depth oriented along the [001] direction, as shown in the inset of Fig. 1. The mesa stripes had sidewalls making an external angle of 100° relative to the (100) bottom plane. The sample was positioned in the μ-RHEED system, so that the electron beam was aligned along the mesa stripes at a glancing angle of about 1°. The GaAs growth rate near the mesa-edge was obtained from the period of the RHEED intensity oscillations using the line-scan mode of the in-situ μ-RHEED system. Details concerning the measuring method were described previously [6]. The experiments were performed using a constant GaAs growth rate of 0.58 ML/s, measured at a point far from the mesa edge. The As_4 beam-equivalent pressure (BEP) was varied from 7.3×10^{-4} to 1.2×10^{-3} Pa, as measured by an ion gauge; the substrate temperature was varied from 510 to 630°C.

3. Results and discussion

Under all growth conditions we observed an increase in the GaAs growth rate near the edge of the mesa top (100) plane. Fig. 1 shows the increase in the growth rate as a function of the distance from the edge for different growth conditions. The increase in the growth rate was caused by a lateral flow of Ga atoms from the sidewall to the (100) plane. As observed in Fig. 1, the increase in the growth rate decreased exponentially as a function of the distance from the edge. We obtained the Ga diffusion length along the [010] direction from the gradient of each line in Fig. 1 [6]. Fig. 2 shows the Ga diffusion length as a function of the temperature with the As_4 BEP as a parameter. The diffusion length was 0.2 μm at 510°C with an As_4 BEP of 1.2×10^{-3} Pa, and increased up to 4.3 μm upon both increasing the substrate temperature to 630°C and reducing the As_4 BEP to 7.3×10^{-4} Pa. Liu et al. obtained by transmission electron microscopy a value of 0.4 μm for the diffusion length along the [010] direction at a substrate temperature of 570°C under an As_4 pressure of 1.3×10^{-3} Pa [4]. From Fig. 2 we obtained a value of about 0.6 μm for similar growth conditions. As observed in Fig. 2, the diffusion length strongly depended on the substrate temperature as well as on the As_4 pressure; therefore, the difference between our value and that of Liu et al. could be due to differences

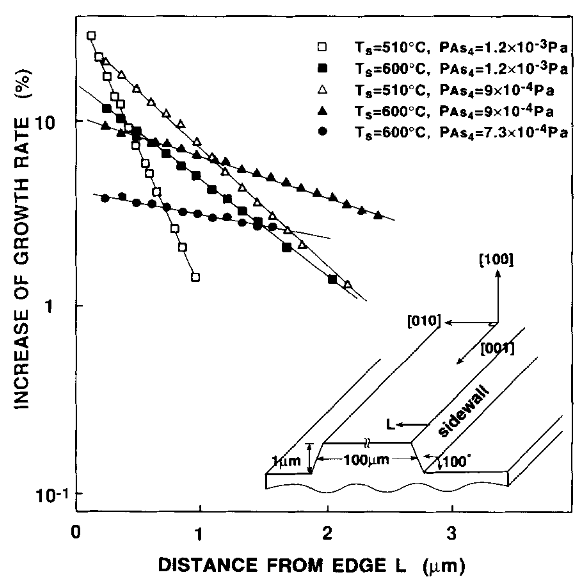

Fig. 1. Increase in growth rate on the (100) plane as a function of distance from the mesa edge. The inset is a schematic illustration of the mesa.

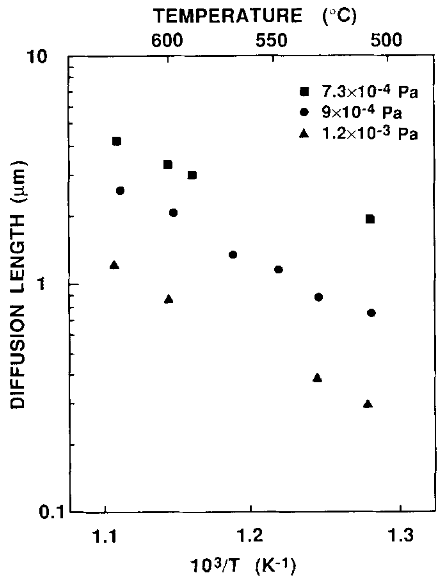

Fig. 2. Surface diffusion length along the [010] direction on the GaAs(100) plane for a variety of growth conditions.

in the substrate temperature and/or the As_4 pressure.

Hata et al. reported that at 580°C with an As_4 BEP of 5×10^{-4} Pa, the diffusion lengths along the [011] ($\lambda_{[011]}$) and [0$\bar{1}$1] ($\lambda_{[0\bar{1}1]}$) directions were 1 and 8 μm, respectively [6]. In similar experiments, Shen and Nishinaga obtained similar values for $\lambda_{[011]}$; however, their largest value for $\lambda_{[0\bar{1}1]}$ was 1.2 μm [7]. We calculated a value for $\lambda_{[0\bar{1}1]}$ using the diffusion length along the [010] direction and compared it with the above-mentioned values. The diffusion coefficient on the (100) plane along a direction making an angle of θ with the [011] direction is [9]

$$D_\theta = D_{[011]} \sin^2\theta + D_{[0\bar{1}1]} \cos^2\theta, \qquad (1)$$

where $D_{[011]}$ and $D_{[0\bar{1}1]}$ are the diffusion coefficients along the [011] and [0$\bar{1}$1] directions, respectively. The diffusion length is related to the diffusion coefficient by the Einstein relation, $\lambda^2 = D\tau$, where τ is the life-time of the adatoms. Considering that τ is common to all directions in Eq. (1) [9], the diffusion length along the [010] direction can be written as

$$\lambda_{[010]} = \left(\lambda^2_{[011]}/2 + \lambda^2_{[0\bar{1}1]}/2\right)^{1/2}. \qquad (2)$$

From the results of the present work, $\lambda_{[010]}$ is 5 μm at 560°C under an As_4 BEP of 5×10^{-4} Pa; and taking $\lambda_{[011]}$ as 1 μm, from Eq. (2), a value of 7 μm for $\lambda_{[0\bar{1}1]}$ is obtained, which is close to the value of 8 μm reported by Hata et al. [6]. The disagreement between this value and that of Shen and Nishinaga may be due to differences in the As_4 pressure values. They obtained the As_4 pressure by measuring the RHEED oscillations induced by As incorporation [7], while we measured it with an ion gauge.

Next, we turn to the GaAs growth on the (110) facets which are formed on the sidewalls of the mesa stripes. The (110) facets appeared under all growth conditions; however, the GaAs growth rate on the (110) facets depended on the substrate temperature and the As_4 BEP. We have previously reported [2] the growth rate on the (110) facets ($R_{(110)}$) relative to that on the (100) plane ($R_{(100)}$) for different growth conditions. We observed a slow growth rate on the (110) facets; for example, the growth rate ratio $R_{(110)}/R_{(100)}$ was about 0.02 at 600°C under an As_4 BEP of 9×10^{-4} Pa. This very slow growth rate suggests a long diffusion length of Ga adatoms on the (110) plane, such that the incoming Ga atoms on

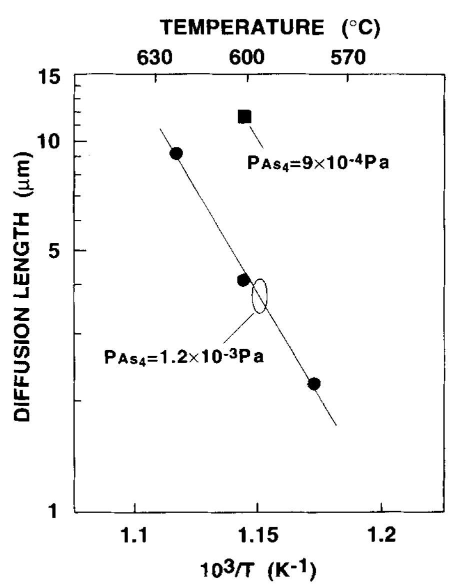

Fig. 3. Calculated surface diffusion length on the GaAs(110) plane.

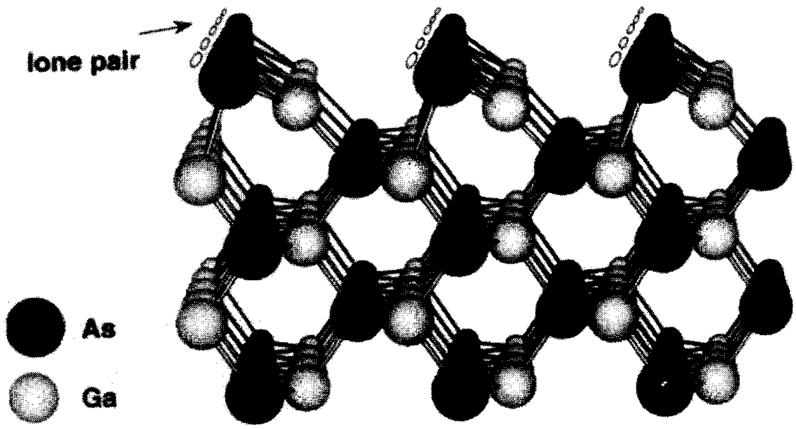

Fig. 4. Surface reconstruction of the GaAs(110) plane.

the (110) facets diffuse easily to the (100) plane. We can make an estimation of the diffusion length on the (110) plane ($\lambda_{(110)}$) using an approach similar to that used by Koshiba et al. [10] for a (100)-(111)B facet structure. The growth rate on the (110) facet normalized to the growth rate on the (100) plane can be expressed as [10]

$$\frac{R_{(110)}}{R_{(100)}} \approx \frac{a_{(110)}}{a_{[010]}} \left(\frac{\lambda_{[010]}}{\lambda_{(110)}} \right)^2 = \frac{1}{\sqrt{2}} \left(\frac{\lambda_{[010]}}{\lambda_{(110)}} \right)^2. \quad (3)$$

Here, $a_{(110)}$ and $a_{[010]}$ are the interatomic distance along the $[1\bar{1}0]$ direction on the (110) plane and along the [010] direction on the (100) plane, respectively. $\lambda_{(110)}$ was estimated using Eq. (3) with $R_{(110)}/R_{(100)}$ from Ref. [2], and the corresponding values of $\lambda_{[010]}$ given in Fig. 2. As shown in Fig. 3, $\lambda_{(110)}$ increased drastically upon increasing the substrate temperature, or decreasing the As_4 BEP. The Ga diffusion length is longer on the (110) plane than on other planes; for example, it is ~ 12 μm at 600°C under an As_4 BEP of 9×10^{-4} Pa, compared with 2 μm of $\lambda_{[010]}$, and 3 μm on the (111)B plane($\lambda_{(111)}$) under similar growth conditions [11].

We think that the diffusion of Ga adatoms on the (110) plane may be strongly affected by the particular surface reconstruction on this plane. As shown in Fig. 4, the GaAs(110) surface is reconstructed such that each Ga surface atom moves towards an sp^2 configuration and uses all of its three electrons to bond with its nearest neighbors; each As atom rotates out of the surface to an s^2p^3 arrangement with three p electrons forming bonds with its three nearest neighbors and two s electrons forming s^2 orbitals [12]. These orbitals are usually called "lone" pairs and are known to be very stable [13]. Therefore, the incoming Ga atoms can diffuse easily on the reconstructed (110) surface because they hardly react with the satisfied As surface atoms.

4. Summary

GaAs(100)-(110) facet structures were formed by the GaAs growth on [001] mesa stripes on GaAs(100) substrates. First, we obtained by μ-RHEED the Ga diffusion length along the [010] direction on the [001]-mesas. Then we made an estimation of the Ga diffusion length on the (110) facets. We found that the Ga diffusion length on the (110) plane is longer than that on the (100) and (111)B planes. The surface reconstruction on the (110) plane could be the cause for the long diffusion length on this plane.

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