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LP-MOCVD growth of ternary $B_xGa_{1-x}As$ epilayers on (0 0 1)GaAs substrates using TEB, TMGa and AsH_3

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Abstract

Zinc-blende $B_xGa_{1-x}As$ alloys have been successfully grown on exactly oriented (0 0 1)GaAs substrates using triethylboron, trimethylgallium and arsine sources. The growth has been accomplished in a vertical low-pressure metalorganic chemical vapor deposition (LP-MOCVD) reactor. Boron incorporation behaviors have been extensively studied as a function of growth temperature and gas-phase boron mole fraction. The evolution of surface morphology was also observed.

The maximum boron composition of 5.8% is obtained at the optimum growth temperature of 580 °C. RMS roughness over the surface area of $1 \times 1\,\mu m^2$ is only 0.17 nm at such growth conditions. Based on the experimental results, it has been clearly shown that boron incorporation will decrease significantly at higher temperature (>610 °C) or at much lower temperature ($\leqslant 550$ °C).

Keywords: Metalorganic chemical vapor deposition; BGaAs; GaAs; Triethylboron

1. Introduction

In the recent years, special effort has been put into the fabrication of long-wavelength (1.3–1.55 μm) semiconductor lasers, photodetectors and other high-performance optoelectronics devices on GaAs substrates in order to reduce the cost of optical network, which requires the development of new GaAs-based III–V semiconductors that which can act as the candidate for any InGaAsP/InP material system. Recently, GaInNAs material lattice matched to GaAs has become the most attractive candidate for the long-wavelength operation because it has been discovered that adding small amount of nitrogen into GaAs can result in the dramatic reduction of bandgap energy [1]. Being inspired by GaInNAs breakthroughs, researchers estimate that introducing boron (B) to substitute gallium (Ga) in GaAs may create the effects similar to incorporating nitrogen into GaAs, because there is a similarity between boron and nitrogen in small covalent radius. Subsequently, from the results simulated by first-principle calculation, we found that a photoluminescence wavelength of BGaInAs and BGaAsSb may cover the 1.3–1.55 μm working range of optical communications while they keep lattice matched to GaAs [2]. Thus, it has been expected that BGaInAs and BGaAsSb quaternary alloys may become the promising candidate for GaInNAs.

Nevertheless, growth mechanism and features of boron-contained III–V semiconductors are still not well understood because little attention has been paid to the growth of boron-contained III–V semiconductors. Few reports on the epitaxial growth and characterization of single-crystal zinc-blende BGaAs alloy have been available since Geisz carried out the pioneer works [3,4]. On the contrary, boron sources have been widely used as the p-dopant in the silicon-based microelectronics industry in the past few decades [5–7].

In this paper, we report the low-pressure metal-organic chemical vapor deposition (LP-MOCVD) growth

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of zinc-blende $B_xGa_{1-x}As$ alloys with boron composition up to 5.8% using triethylboron (TEB), trimethylgallium (TMGa) and pure arsine (AsH_3) sources, which is the first step towards the growth of BGaInAs and BGaAsSb alloys. We study the growth behaviors of $B_xGa_{1-x}As$ alloys with an attempt to fully understand the key factors that affect boron incorporation.

2. Experimental procedure

In this study, BGaAs samples have been grown on exactly oriented (0 0 1)GaAs substrates by LP-MOCVD. The growth process was performed in a $3\times 2''$ vertical reactor with the constant pressure of 100 Torr, total flow rate of 12 slpm and susceptor rotation speed of 100 rpm.TEB, TMGa and AsH_3 were used as B, Ga and arsenic (As) sources, respectively. Pd-cell purified hydrogen (H_2) was used as the carrier gas. The saturated vapor pressure of the liquid TEB source can be calculated by the following equation:

$$Log\,P = 8.343 - \frac{1977}{T} \quad (1)$$

where T is Kelvin temperature and P is vapor pressure in Torr.

The boron concentration in the gas phase can be quantified by the mole fraction X_v:

$$X_v = \frac{[\text{TEB}]}{[\text{TEB}] + [\text{TMGa}]} \quad (2)$$

where [TEB] and [TMGa] represented the input mole flow rate of TEB and TMGa, respectively.

The layer structure of the $B_xGa_{1-x}As$ samples is shown in Fig. 1. Firstly, a 150 nm-thick GaAs buffer layer is deposited on a (0 0 1)GaAs substrate. Then, approximately a 100 nm-thick $B_xGa_{1-x}As$ epilayer is grown. On the top of the BGaAs layer, a 10-nm-thick GaAs cap layer was deposited to form the GaAs/$B_xGa_{1-x}As$/GaAs sandwich structures. All the layers were grown at the same temperature, which ranged from 550 to 650 °C. The mole flow rate of TMGa and AsH_3 were set to 1.4×10^{-5}, 2.7×10^{-3} mol/min, respectively, for all the epilayers from run to run. The mole flow rate of TEB varied in the range of 1×10^{-5} to 8.2×10^{-5} mol/min, which caused the input V/III ratio to be varied from 28 to 112 for $B_xGa_{1-x}As$ layers growth.

A series of $B_xGa_{1-x}As$ samples with various boron compositions (x) had been grown at the growth conditions described above. The boron incorporation behavior has been intensively studied as a function of gas phase TEB mole fraction (X_v) and growth temperature (T_g).

High-resolution double-crystal X-ray diffraction (DCXRD) $\omega/2\theta$ scan was used to estimate the boron composition (x) by the separation angle between the (0 0 4) diffraction peak of the BGaAs epilayer and that of the GaAs substrate. DCXRD measurement was also used to evaluate the crystalline quality of BGaAs layers. Depth profiles of B, Ga and As elements in the epilayers were measured by secondary ion mass spectrometry (SIMS). The surface morphologies were observed by atomic force microscopy (AFM).

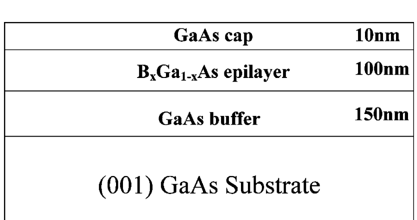

Fig. 1. Layer structure of $B_xGa_{1-x}As$ samples.

3. Results and discussion

If the lattice constant of zinc-blende BAs is assumed to be 4.777 Å [8], the lattice constant of $B_xGa_{1-x}As$ can be expressed as the following equation by Vegard's law:

$$a_{\text{BGaAs}}(x) = 5.6533 - 0.8763x \quad (3)$$

Assuming the complete relaxation of the $B_xGa_{1-x}As$ layer and a BAs Poisson ratio of 0.3, the B composition (x) could be easily calculated from the DCXRD patterns.

Fig. 2 shows the boron incorporation behavior as a function of X_v at four different growth temperatures. It can be observed that boron incorporation into BGaAs strongly depends on the growth temperature (T_g) and gas phase TEB mole fraction (X_v). Although the boron incorporation efficiency (x/X_v) was quite low, solid boron composition (x) increased with the increment of X_v value at the given growth temperature. However, there existed a critical value for X_v, beyond which the polycrystalline or amorphous BGaAs with hazy surfaces were formed. Furthermore, the crystalline quality and surface morphology of single-crystal BGaAs samples will deteriorate rapidly with the increasing value of X_v (this section will be shown and discussed later).

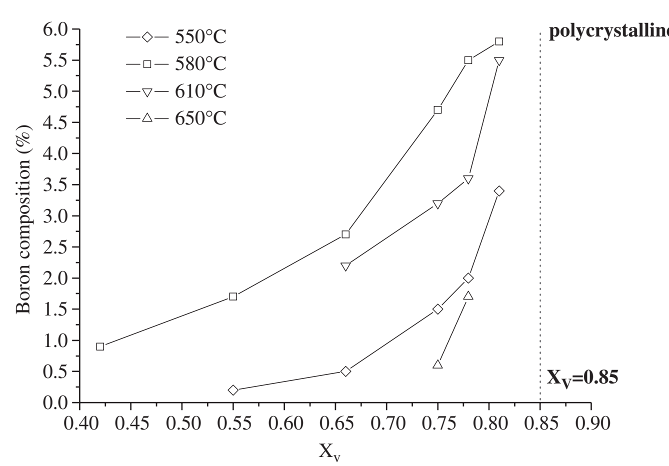

Fig. 2. Boron composition of $B_xGa_{1-x}As$ alloys measured by DCXRD as a function of X_v at (a) $T_g = 550$ °C (diamond); (b) $T_g = 580$ °C (square); (c) $T_g = 610$ °C (down triangle); (d) $T_g = 650$ °C (up triangle).