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Sb surfactant-mediated growth of strained InGaAs multiple-quantum wells by metalorganic vapor phase epitaxy at low growth temperatures

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ABSTRACT

We report on the influence of growth temperature on the Sb surfactant-mediated growth of strained InGaAs multiple-quantum wells by metalorganic vapor phase epitaxy and propose an effective method for obtaining the surfactant effect at low growth temperatures. When reducing the growth temperature from 620 to 540 °C, the Sb supply, which is needed to improve the surface morphology and the photoluminescence intensity, decreases to one tenth because of the surface segregation of the Sb atoms. With the help of Sb segregation, the surfactant effect at a growth temperature of 540 °C is obtained simply by supplying Sb prior to well growth.

1. Introduction

Strained multiple-quantum-well (MQW) lasers have been widely used to increase emission wavelengths by increasing the strain of wells in the active regions. For example, strained InGaAs(N)/GaAs MQW lasers on GaAs can emit light in the 1.3–1.55 μm range [1,2]. Moreover, emission wavelengths longer than 2 μm have been achieved in strained In(Ga)As/InGaAs(P) MQW lasers on InP [3,4]. However, excessive strain causes three-dimensional (3D) growth, and crystalline defects occur in the MQW structure. This 3D growth has been effectively suppressed by reducing the growth temperature or using a surfactant. Surfactant-mediated growth was investigated by Copel et al. [5] for a Si/Ge system using molecular beam epitaxy (MBE), and then applied to III–V heterostructures such as an InGaAs(N) layer on a GaAs substrate [6,7]. The combination of a surfactant and low-temperature growth has been actively investigated with respect to MBE growth to further suppress 3D growth [8]. However, with metalorganic vapor phase epitaxy (MOVPE), reducing the growth temperature was the only sure way to suppress 3D growth. In contrast, we have recently reported that 3D growth can be suppressed by supplying a small amount of antimony (Sb) as a surfactant for strained InGaAs MQWs on InP substrates grown by MOVPE at a temperature as high as 620 °C [9]. When combining the use of a surfactant and low-temperature growth in MOVPE, it is necessary to clarify the surfactant effect of Sb when the growth temperature is reduced. In this article, we report the effect of the growth temperature on the crystalline quality of strained InGaAs MQWs with an Sb surfactant. Specifically, we investigated the dependence of the morphologies and the optical properties of strained MQWs grown at 540 and 620 °C on the amount of Sb surfactant supplied. In addition, we examined the Sb depth profiles of MQWs grown at different temperatures by secondary ion mass spectroscopy (SIMS), and studied the behavior of Sb on the growing surface. Based on our consideration of the Sb behavior, we also investigated an effective way of supplying the surfactant at a low growth temperature.

2. Experimental details

The samples were grown on n-type (1 0 0)-InP substrates in a horizontal MOVPE reactor at 50 Torr. We grew a 200-nm-thick InP buffer layer at a temperature (T_g) of 620 °C, followed by an MQW structure and a 100-nm-thick InP capping layer at 540 or 620 °C. The MQW structure contained three 11-nm-thick $In_{0.79}Ga_{0.21}As(Sb)$ wells with a compressive strain of 1.75% and four 18.5-nm-thick $In_{0.48}Ga_{0.52}As$ barriers with a tensile strain of 0.4% with respect to InP. The growth rate and the V/III ratio of the wells were 0.75 nm/s and 40, respectively. The precursors for In, Ga, As, and P were trimethyl-indium (TMIn), triethyl-gallium (TEGa), arsine (AsH_3), and phosphine (PH_3), respectively. The Sb precursor was tris-dimethyl-amino-antimony (TDMASb). The TDMASb flow

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rate was varied from 0 to 191 μmol/min. The solid compositions and thicknesses of the wells and the barriers were determined by X-ray diffraction (XRD) analysis. The surface morphology was studied using atomic force microscopy (AFM) in air. Room temperature photoluminescence (PL) measurements were performed using the 532 nm line of a frequency-doubled Nd:YVO_4 laser. SIMS depth profiles of the samples were measured with an ATOMIKA SIMS-4000.

3. Results and discussion

The 3D growth induced by increasing the well strain has been observed as a surface undulation for an InGaAs/GaAs MQW on a GaAs substrate [10]. In accordance with this observation, we first investigated the influence of supplying TDMASb on the surface morphologies of strained InGaAs MQWs on InP substrates. Fig. 1 shows AFM images of samples grown at 540 °C (a) without and (b) with a TDMASb flow rate of 15 μmol/min. The TDMASb was supplied only during well growth. In Fig. 1(a), hillocks can be seen on the surface of the sample grown without the TDMASb supply. On the other hand, these hillocks disappeared when TDMASb was supplied as shown in Fig. 1(b). The improvement in the surface morphology reflects the suppression of the 3D growth of the strained InGaAs wells owing to the surfactant effect of Sb. Supplying the TDMASb, the 3D growth could be suppressed both for the strained InGaAs MQWs grown at 620 °C in an earlier study [9] and for those grown at 540 °C in this study.

Next, we performed AFM and PL measurements for the samples grown at 540 and 620 °C with the TDMASb flow rate in the 0–191 μmol/min range to investigate the effect of the TDMASb supply on the structural and optical properties for each growth temperature. Figs. 2(a) and (b), respectively, show the dependences of the root mean square (RMS) surface roughness and the PL peak intensities of the samples on the TDMASb flow rate. For all the samples, the PL peak wavelength was approximately 2.1 μm. For the sample grown at 620 °C, the RMS roughness was 0.9 nm without the TDMASb supply. As the TDMASb flow rate increased, the RMS roughness gradually decreased until it reached a value of about 0.4 nm. When the growth temperature was 540 °C, the RMS roughness abruptly

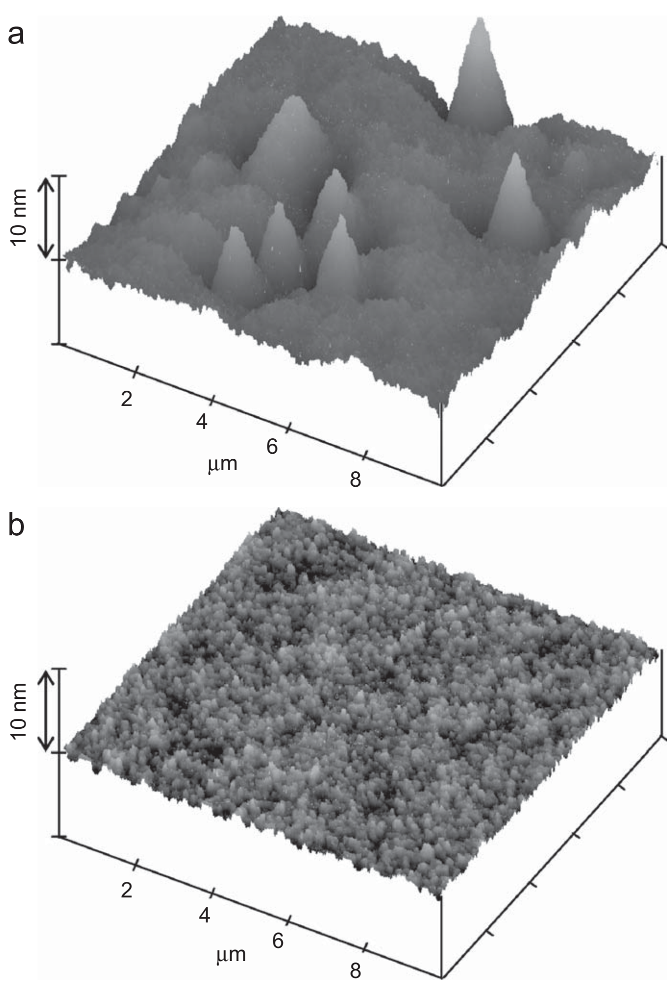

Fig. 1. AFM images of strained MQWs grown at 540 °C (a) without and (b) with the TDMASb supply. The TDMASb flow rate is 15 μmol/min.

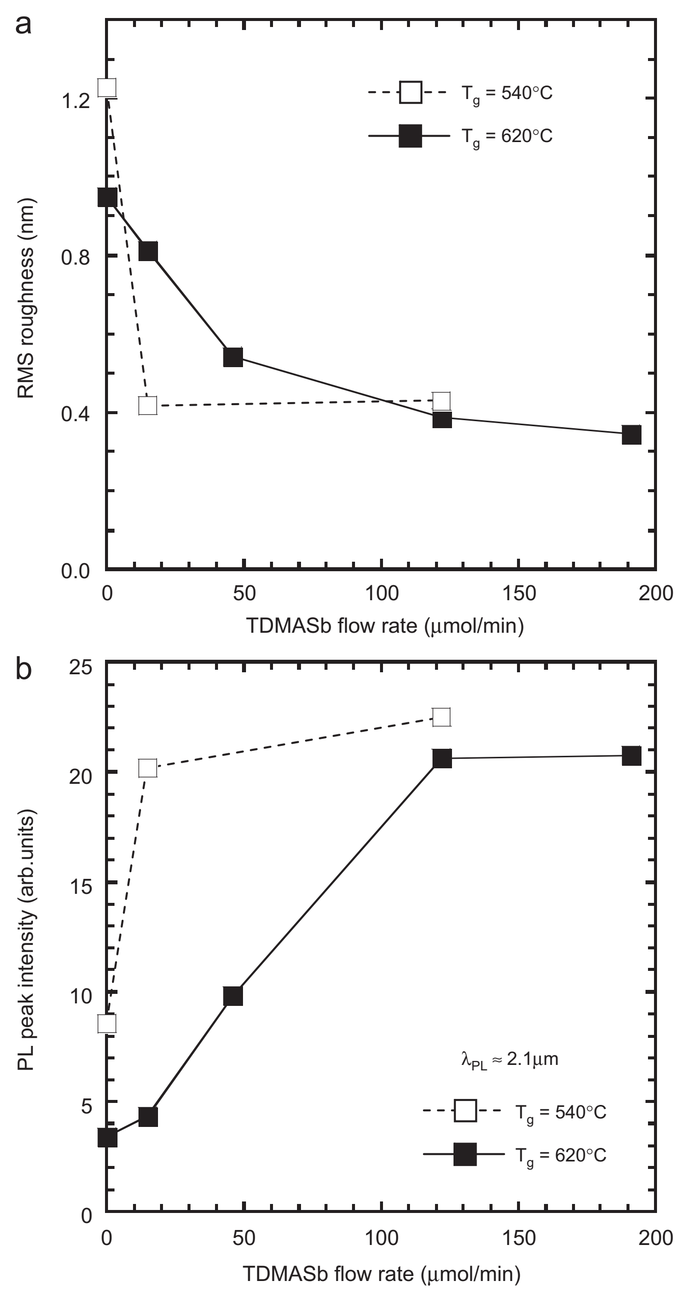

Fig. 2. Dependence of (a) the RMS roughness and (b) the PL peak intensity of strained MQWs on the TDMASb flow rate.