

InAsSb on GaAs (001): influence of the arsenic molecules form on composition and crystalline properties of MBE layers

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Abstract. The influence of As molecular form on the composition and crystalline properties of $\text{InAs}_x\text{Sb}_{1-x}$ solid solutions with MBE has been experimentally investigated. A series of samples has been grown at different growth temperatures. The grown samples were studied with the HRXRD and TEM methods. The incorporation coefficient of As_4 and As_2 molecules were determined at different growth temperatures. It has been found that the incorporation coefficient of As_4 much more dependent on growth temperature compared to As_2 . It has been found that at a low growth temperature a step-like increase of Sb fraction in an $\text{InAs}_x\text{Sb}_{1-x}$ film leads to a decrease of threading dislocations density in a layer with a smaller x .

1. Introduction

The $\text{InAs}_x\text{Sb}_{1-x}$ solid solutions get much attention because of a possibility of creating IR-sensitive optoelectron devices on their base with a wavelength to $12.4\ \mu\text{m}$ [1-5]. However, there are a number of problems concerned with obtaining high-quality epitaxial $\text{InAs}_x\text{Sb}_{1-x}$ layers.

One of them is the absence of a substrate material for the whole range of $\text{InAs}_x\text{Sb}_{1-x}$ compositions [6]. This leads to a degradation of the grown structures quality caused by the introduction of defects conditioned by mismatch film and substrate lattice constants.

Moreover, the formation of layers with a specific composition in the group V sublattice is a nontrivial problem too. The composition of the solid solution depends on both the value of Sb and As molecule fluxes (J_{Sb} and J_{As}) and their incorporation coefficient S_{Sb} и S_{As} . Incorporation coefficient is understood as a ratio of the atoms built in a crystal to their number arrived with the corresponding molecular flux for a time unit per surface unit. According to the definition of incorporation coefficients, arsenic composition x in a $\text{InAs}_x\text{Sb}_{1-x}$ solid solution is connected with the density of group V molecular fluxes by the ratio:

$$x = \frac{1}{1 + \frac{J_{\text{Sb}}}{J_{\text{As}}} \times \frac{S_{\text{Sb}}}{S_{\text{As}}}} \quad (1)$$

Relation $J_{\text{As}}/J_{\text{Sb}}$ is easily set and controlled during MBE, whereas relation $S_{\text{Sb}}/S_{\text{As}}$ is a complex function of growth conditions. The ratio of incorporation coefficients depends on substrate temperature (T_s), value and ration of group III and V elements molecular fluxes, molecular form of



group V elements in a flux [7]. These parameters allow immediate control of the surface state and the growing $A^{III}B^V$ film properties. Therefore, studying their influence on the S_{Sb}/S_{As} ratio at MBE of solid $InAs_xSb_{1-x}$ solutions is of interest.

The purpose of this work is experimental investigation of the influence of As molecular form and growth temperature on the composition and crystalline properties of $InAs_xSb_{1-x}$ solid solutions grown on GaAs (001) substrate with the MBE method.

2. Experimental methods

The work has been carried out on the handmade MBE-machine "Shtat"-type equipped by a valve-type As source with a cracking zone to obtain As_2 and As_4 fluxes. The In and Sb₄ fluxes were formed by crucible sources with shutters. The density of atom and molecular fluxes coming up to the surface was determined by the indications of vacuum controller Granville Phillips 307 whose sensor was placed onto the substrate position [8] during the measurement. Substrate temperature control was realized by the indications of the thermocouple placed in the heating element. The flux sensor and the thermocouple indications were calibrated using the phase diagrams of GaAs (001) [9] surfaces on the methods formulated in [10].

A series of samples was grown at 320°C, 330°C, 355°C and 370°C. Each sample consisted of two layers. The first layer was grown using the As_2 molecular flux. After the end of the first layer growth, the growth manipulator with the substrate was turned to the molecular fluxes measurement position. The cracking zone temperature of the arsenic source was decreased from 950°C to 400°C for As_4 flux generation. The second solid solution layer was grown using the As_4 molecular flux equivalent to the As_2 in the atomic expression.

The In flux was equal to $5.45 \cdot 10^{14}$ atom/cm²·s, which corresponds to the growth rate of one monolayer per second. The fluxes of group V, in the atom expression, was $\sim 8.6 \cdot 10^{14}$ atom/cm²·s for Sb₄, for As_2 and $As_4 \sim 1.0 \cdot 10^{15}$ atom/cm²·s. The thickness of epitaxial layers was 500 nm when using the As_2 and 350 nm when using the As_4 .

3. Investigation methods

The grown samples were investigated by HRXRD and TEM.

3.1. Investigated by HRXRD

The grown samples were investigated by HRXRD. Registration of the X-Ray rocking curves was made on a two-crystal diffractometer using the crystal Ge (004) monochromator for line Cu $K_{\alpha 1}$.

The data on the dependence of the composition of $InAs_xSb_{1-x}$ solid solution on T_s are presented in Figure 1.

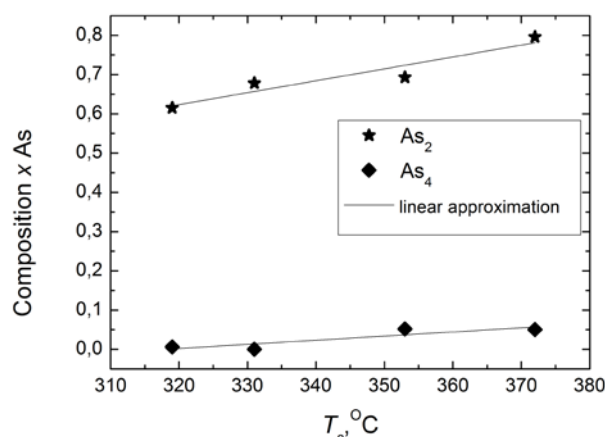


Figure 1. The arsenic fraction in the $InAs_xSb_{1-x}$ solid solution as a function of T_s . The data for the films grown with As_2 are designated with asterisks, the data for the films grown with As_4 are designated with a diamond.

The data of FWHM for X-Ray rocking curve (W), which are given in Table 1, were obtained depending on the $InAs_xSb_{1-x}$ film growth temperature. Here h_1 and h_2 are the first and second film thicknesses, respectively, R – relaxation degree, %.

Table 1. HRXRD data.

	T_s °C	h_1 nm (As_2)	h_2 nm (As_4)	W h_1	W h_2	R h_1 (%)	R h_2 (%)
st 1468	320	500	350	2486	1690	96.65	99.75
st 1469	330	500	350	2313	1678	95	100
st 1470	355	500	350	2237	1629	95	97
st 1471	370	500	350	2486	1690	91	100

It follows from the data of Table 1 that, in case of using As_2 , a decrease of $InAs_xSb_{1-x}$ film relaxation degree is observed with an increase of growth temperature.

Assisted with expression 1, the values of S_{Sb4}/S_{As2} and S_{Sb4}/S_{As4} ratios were calculated for arsenic and antimony molecules. The data about the composition of solid solution layers obtained with the HRXR method and the J_{As2} , J_{As4} и J_{Sb4} values measured during the samples growth (see black squares in Figure 2 and Figure 3) were used for the calculation. The linear approximation of experimental data was carried out for dependence of the As fraction in the solid solution on the growth temperature (see Figure 1). This procedure allowed building the model dependences of S_{Sb4}/S_{As2} and S_{Sb4}/S_{As4} ratios on T_s .

The Figure 2 and 3 show that both S_{Sb4}/S_{As2} , and S_{Sb4}/S_{As4} values decrease with increasing of T_s in temperature range $320 \div 370^\circ\text{C}$, but decreasing of S_{Sb4}/S_{As4} about 5 times more. Such a difference in the behavior of these ratios is explained by the thing that As_2 molecules interact with a surface predominantly by the exchange mechanism, and As_4 molecules – by the vacancy mechanism [11].

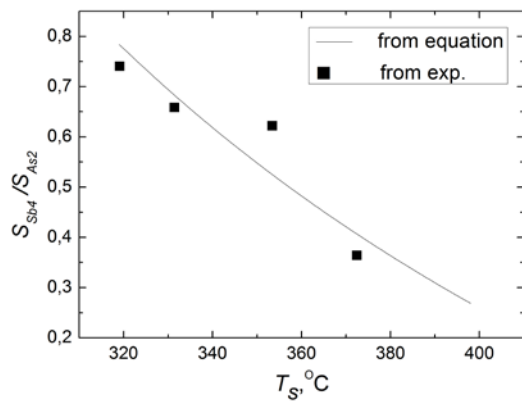


Figure 2. S_{Sb4}/S_{As2} as a function of T_s .

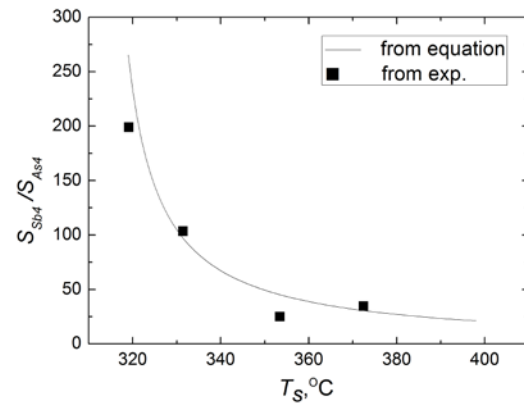


Figure 3. S_{Sb4}/S_{As4} as a function of T_s .

The data of Figure 3 are in good qualitative agreement with the results of Lee G S *et al.* [12]. It is important to note that although temperature ranges of our and G. S. Lee *et al.* investigations are analogous, the beam equivalent pressure ratios for group V elements $BEP(Sb_4)/BEP(As_4)$ is essentially different (from 0.08 to 0.38 – for ref. [12] and 0.72 – for our work).

3.2. Investigated by TEM

The structure of grown samples investigations were performed by a JEOL-4000EX electron microscope operated at 400 kV. The (110) cross sections for TEM studies were prepared in a standard manner by etching with argon ions. Bright-field / dark-field TEM and HRTEM were used.

It was found that a transition layer, that forms at the interface of $InAs_xSb_{1-x}$ films with different compositions at low T_s , decrease the threading dislocations density to the 5-6 times (see Figure 4).

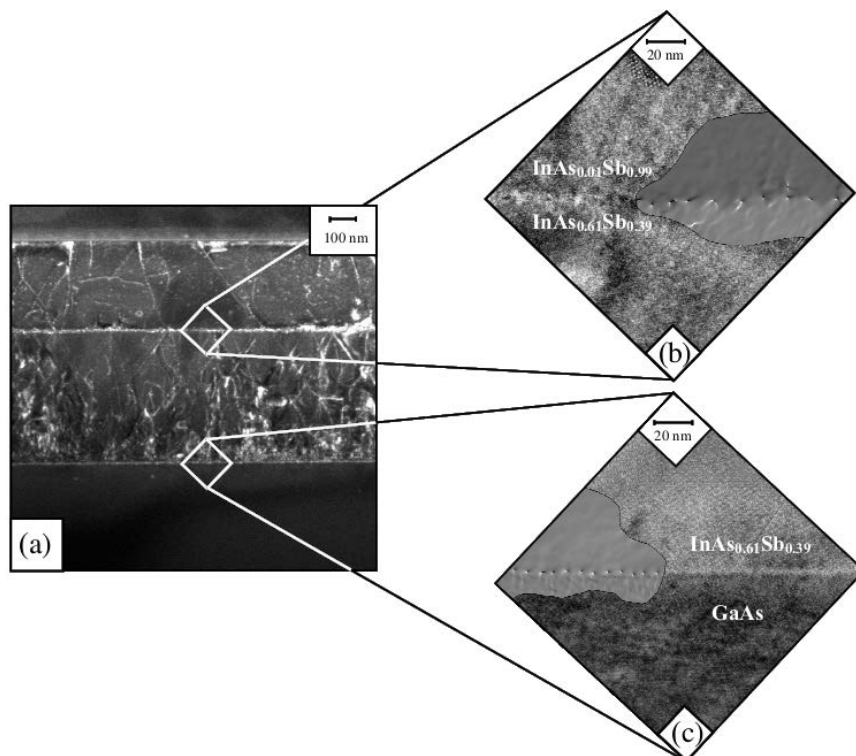


Figure 4. (a) – The (110) cross-sectional TEM image of the sample with two $\text{InAs}_x\text{Sb}_{1-x}$ epilayers. The lower layer was grown with As_2 , top – with As_4 ($T_s = 320^\circ\text{C}$); (b) – HRTEM image of the *film / film* interface; (c) – HRTEM image of the *substrate / film* interface. The arrays of misfit dislocations are shown on insets (derived by Fast Fourier Transform analysis of HRTEM images).

Such effect was not observed at high growth temperatures (see Figure 5).

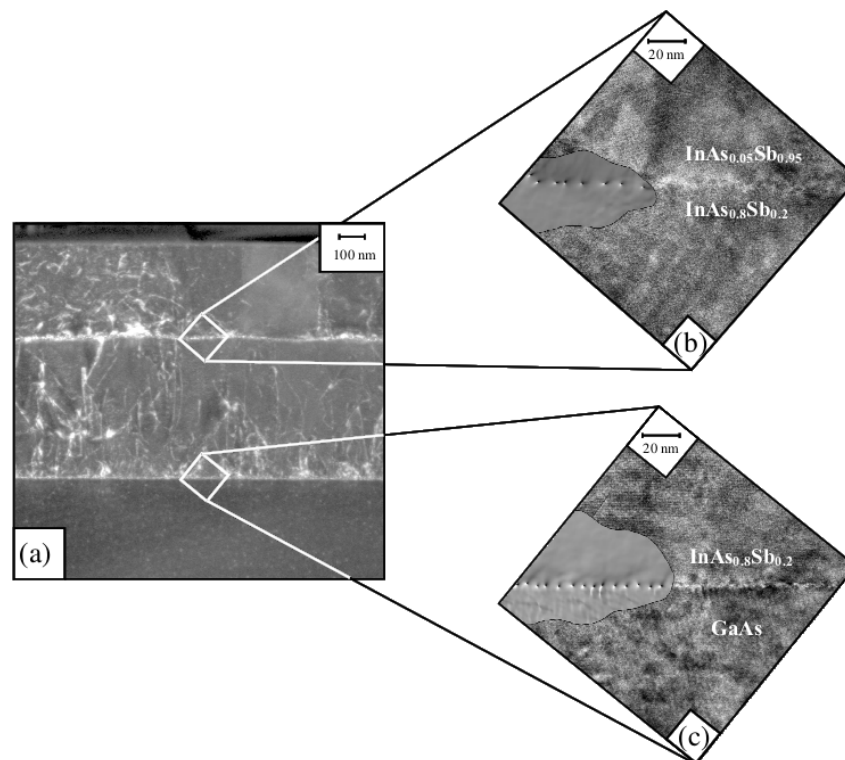


Figure 5. The same as Figure 4, but for the case of $T_s = 370^\circ\text{C}$.

4. Conclusion

It was clarified that, during $\text{InAs}_x\text{Sb}_{1-x}$ MBE, the efficiency of As_2 molecules incorporation, at other equal conditions, is considerably higher than that of As_4 molecules. It was found that the As_4 efficiency incorporation is more temperature sensitive compared to As_2 . It was found that a decrease of threading dislocations density occurs in the layer with a smaller x value at a low growth temperature in case of a step-like increase of the Sb fraction in a $\text{InAs}_x\text{Sb}_{1-x}$ film. This phenomenon can be used in the creation of dislocation filters which will provide growing high-perfection $\text{InAs}_x\text{Sb}_{1-x}$ solid solution layers on various $\text{A}^{\text{III}}\text{B}^{\text{V}}$ semiconductor substrates.

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