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The features of the layers growth in stressed InAs/GaSb superlattices

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Received July 20, 2021
Revised October 4, 2021
Accepted October 18, 2021

The paper presents the results of a study of factors affecting the thickness of transition (interface) layers in stressed InAs/GaSb superlattices during growth by MOCVD method. It is shown that the thicknesses of the interface layers between InAs and GaSb are practically independent of the growth temperature. The thickness of the interface layers is influenced by the direction of switching the layer growth. The smallest thickness of 1.2−1.4 nm of the interface layer InAs/GaSb was obtained for the direction of growth switching from GaSb to InAs.

Keywords: MOCVD, stressed superlattice, InAs/GaSb, interface layer, transmission electron microscopy.

DOI: 10.21883/TPL.2022.02.52835.18966

Photoreceivers operating in the near and middle infrared (IR) band find various applications ranging from ecological (for the detection of hazardous substances in atmosphere) to military ones. The design and construction of such devices is a very promising task. HgCdTe is now regarded as the basic material system for IR photoreceivers. Stressed InAs/GaSb superlattices allow one to expand the class of optoelectronic instruments operating in the middle and near IR band (up to 15 μm). Their use is an alternative approach that provides an opportunity to reduce the Auger recombination rate and, consequently, raise the operating temperature [1,2].

Molecular beam epitaxy (MBE) is currently the basic method for production of InAs/GaSb superlattices [3–5]. It follows from literature data [6] that the minimum thickness of interface (i.e., transition) InAs/GaSb layers for MBE is approximately 1 monolayer (0.3 nm). However, the metalorganic chemical vapor deposition (MOCVD) technology is better suited for mass production of instruments, since it is more cost-effective. MOCVD is currently used primarily for the production of thick (more than 3 μm) A^3B^5 layers (specifically, InAs and GaSb). However, the requirements as to the sharpness and the quality of the interface between layers are more stringent in the case of growth of thin-layer superlattices. Therefore, a set of studies of growth stages, which affect the sharpness of heteroboundaries and the „quality" of quantum wells and, consequently, the performance parameters of a heterostructure, need to be performed for MOCVD. For example, the dependence of the thickness of interface layers in InAs/GaSb superlattices grown by MOCVD on the direction of growth switching (from InAs to GaSb and vice versa) was examined in [7]. Their minimum thickness was 2.5−3.8 monolayers (0.75−1.14 nm).

The aim of the present study is to examine the influence of temperature, conditions and switching dynamics of growth of InAs/GaSb/InAs layers on the sharpness and the quality of heteroboundaries.

Structures were grown using an AIX-200 (AIXTRON, Germany) MOCVD system on n-GaSb (001) substrates. The reactor pressure was 100 mbar. Purified hydrogen with a dew point no worse than -100°C was the carrier gas. The total flow through the reactor was 5.5 slpm. The following compounds were the sources of elements for growth: trimethylindium (TMIn), triethylgallium (TEGa), trimethylstibine (TMSb), and arsine (AsH_3). The ratio of V/III elements (condition of complete pyrolytic decomposition of reagents) was 93 for InAs and 22.5 for GaSb. The growth rates for InAs and GaSb were kept equal.

The obtained structures were studied with a JEM-2100F (Jeol, Japan) transmission electron microscope (TEM) at an accelerating voltage of 200 kV in the diffraction contrast mode (two-beam conditions). The sample preparation procedure was standard for heterostructures: polishing with successive grit size reduction and sputtering with Ar^+ ions with an energy of 4−0.5 keV under grazing angles at the end stage.

The thickness of layers was measured using dark-field TEM images obtained under two-beam conditions with effective diffraction vector $\mathbf{g} = (002)$. The mechanism of contrast formation in this mode is as follows: GaSb layers in an image are separated from InAs layers by a thin dark-contrast band that corresponds to the transition In(GaAs)Sb layer with gradual intersubstitution of components in the sublattices of groups III and V. The boundaries of InAs/GaSb layers were identified by the minimum contrast in the intensity profile that corresponds to the center of the In(GaAs)Sb transition layer. The boundaries of the In(GaAs)Sb transition layer itself were set at half the height of the drop of intensity of In(GaAs)Sb/InAs and In(GaAs)Sb/GaSb layers.

It should also be noted that the TEM resolving power in the diffraction mode is worse than the one in the lattice resolution mode, since the objective lens aperture is smaller. However, the spatial TEM resolution with the aperture used is no worse than 0.6 nm.

Tentatively speaking, our research may be divided tentatively into two parts focused on the determination of two different characteristic relationships:

1. Relationship between the growth temperature and the thickness of In(GaAs)Sb transition layers under otherwise equal conditions.

2. Relationship between the conditions of gas feed switching and the thickness of In(GaAs)Sb transition layers at the chosen growth temperature.

A structure consisting of four groups of two InAs layers in GaSb was grown to examine the influence of the growth temperature on the thickness of interface layers. Each group was grown at constant temperature within the range from 480 to 540°C with a pitch of 20°C. The thickness of GaSb between the groups and between the InAs layers within a group was set to 30 and 15 nm, respectively. The thickness of the InAs layers themselves was also 15 nm. The flows of reagents of elements of groups V and III were kept constant; only the growth temperature was varied with the needed setting time to stabilize its probable fluctuations.

With this structure design, the growth of upper layers is naturally affected by the probable extended defects and other features of lower layers. However, we assumed (and this was confirmed by the results of TEM studies) that lower groups of layers should have a low density of threading extended defects. Defects generated at a specific layer may be determined using the differential method.

The transverse section of the structure (Fig. 1, *a*) imaged in the mode sensitive to changes in the chemical composition (dark field with effective diffraction vector $\mathbf{g} = (002)$) reveals clear boundaries of InAs and GaSb layers, allowing one to easily determine their thickness. Extended defects may be detected under different diffraction conditions (e.g., with effective diffraction vector $\mathbf{g} = (220)$; see Fig. 1, *b*).

In addition to the thickness of InAs and GaSb layers and transition In(GaAs)Sb layers, the quality of the structure and the presence of extended defects were estimated using the obtained TEM images. It is evident from Fig. 1 that the thickness of layers is nonuniform in the lateral direction in the first (lower) pair of InAs/GaSb layers grown at 480°C. The gap between the InAs layers is very small, and inclusions producing local elastic stress of a hemispherical shape are seen. The layer thickness is more uniform in the second pair (the growth temperature here is 500°C), and the number of defects decreases. The third pair of layers (the growth temperature is 520°C) features the most uniform thickness in the entire sample, but a certain number of extended defects can be found. The fourth (uppermost) pair of layers (the growth temperature is 540°C) has the same lateral thickness uniformity as the third pair, but the density of extended defects here is 1–2 orders of magnitude higher than the corresponding density in any lower layer. Fig. 1, *b* shows clearly that the fourth pair features the greatest number of defects. In view of the above, the optimum growth temperature at AIX-200 was determined to be 500–520°C. Layers grown at this

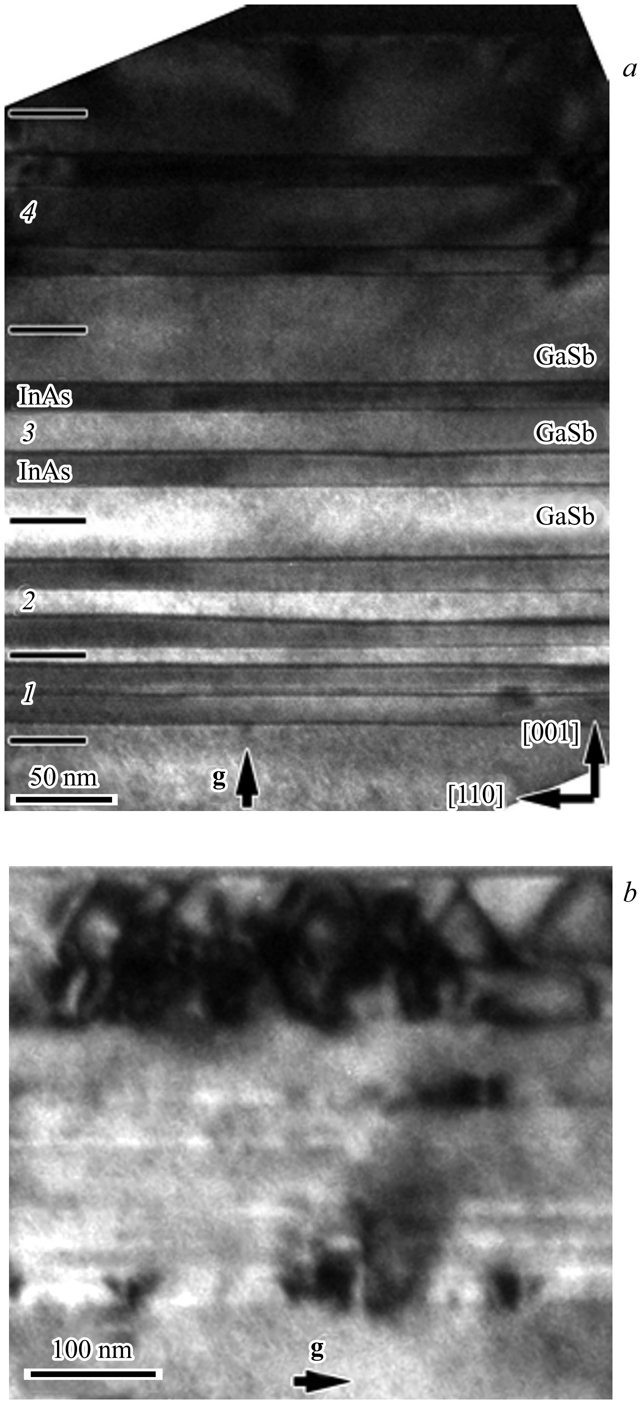

Figure 1. TEM image of the transverse section $(1\bar{1}0)$ of the sample with InAs/GaSb layers, which were grown at temperatures of 480–540°C, under different diffraction conditions. *a* — dark-field image with effective diffraction vector $\mathbf{g} = (002)$. Numbers *1–4* denote the groups of layers, and horizontal bars between the numbers indicate the tentative boundaries between groups of two pairs of InAs/GaSb layers. *b* — light-field image with effective diffraction vector $\mathbf{g} = (220)$.

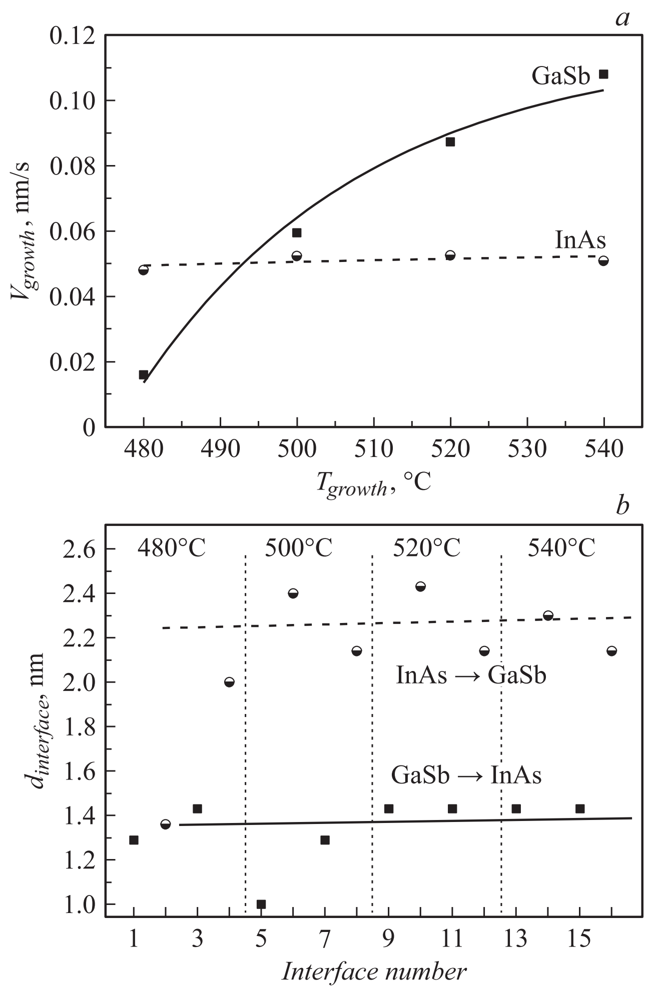

Figure 2. Dependences of the growth rate of binary InAs and GaSb layers on the growth temperature (a) and of the thickness of the transition layer between InAs/GaSb on its number and the corresponding growth temperature (b).

temperature have the minimum number of defects and an acceptable thickness uniformity. Therefore, a temperature of 500°C was chosen for the experiments aimed at identifying the influence of the conditions of gas feed switching on the thickness of transition In(GaAs)Sb layers at a constant growth temperature.

In addition to estimating the density of defects, we used the obtained TEM data to measure the thickness of individual InAs, GaSb layers and the thickness of interface In(GaAs)Sb layers between InAs/GaSb (Fig. 2, b). The growth rates of InAs, GaSb layers (Fig. 2, a) were estimated based on their thickness.

it can be seen from Fig. 2, a that the growth rate of InAs layers remains constant within the 480–540°C temperature range. However, the growth rate of GaSb layers depends on the growth temperature and increases by a factor of 6 as the temperature goes up. This behavior of the growth rate is likely attributable to the increase in efficiency of pyrolytic decomposition of TMSb from 13% at 480°C to 90% at 540°C [8], which, in turn, alters the TMSb/TEGa ratio: it increases from 2.9 to 20.3.

It follows from the dependence in Fig. 2, b that the thickness of interface layers between InAs/GaSb is almost independent of the growth temperature. Even with synchronized feed of both reagents, the thickness of interface layers is affected by the direction of growth switching. A smaller thickness of the interface layer between InAs/GaSb in our experiment was obtained for the direction of growth switching from GaSb to InAs. The measured value (1.2–1.4 nm) is close to the interface layer thickness reported in [7]. Presumably, interface In(GaAs)Sb layers forming under the InAs→GaSb direction of growth switching are thicker due to the fact that the growth rate of binary GaSb layers is higher.

A structure of a similar design (four groups of two InAs layers in GaSb) was grown at a temperature of 500°C to reveal the patterns of influence of the conditions of gas feed switching on the thickness of In(GaAs)Sb transition layers. Different reagent switching delays were used in the process of growth of different groups of layers. As above, the thickness of transition In(GaAs)Sb layers was measured, the thickness uniformity of InAs and GaSb layers was estimated, and the density of extended defects was considered.

Fig. 3 presents the dependence of the interface layer thickness on the reagent feed sequence and the growth switching direction. Open squares represent the GaSb→InAs sequence: following the growth of GaSb, stabilizing TMSb was fed into the reactor for 2–10 s; this was followed by a hydrogen purge (30 s), and then the growth of InAs was initiated by feeding AsH_3 into the reactor for 2–10 s with subsequent introduction of TMIn. Filled squares correspond to the InAs→GaSb sequence: following the growth of InAs, stabilizing AsH_3 was fed into the reactor for 2–10 s; this was followed by a hydrogen purge (30 s), and then the growth of GaSb was initiated by feeding TMSb into the reactor for 2–10 s with subsequent introduction of TEGa.

The interface layer thickness was minimized when AsH_3 was introduced 2 s earlier than TMIn in the GaSb→InAs sequence. It can be seen from Fig. 3 that the interface layer thickness in both sequences increased with time delay between the introduction of elements of groups V and III. It should be noted that the InAs→GaSb growth switching direction is more sensitive to the time delay between the introduction of elements of groups V and III. This is manifested in the interface layer thickness that increases from 2.1 nm (when the element of group V in introduced 2 s earlier than the element of group III) to 2.4 nm (when the time delay is 10 s).

The obtained results suggest that the thickness of In(GaAs)Sb interface layers at the boundary of binary InAs/GaSb layers is almost independent of the growth temperature. However, the optimum temperature of growth at AIX-200 falls within the 500–520°C range, since the density of extended defects in layers is minimized at such temperatures. The direction of switching of gases (sources of reagents) exerts the primary influence on the thickness

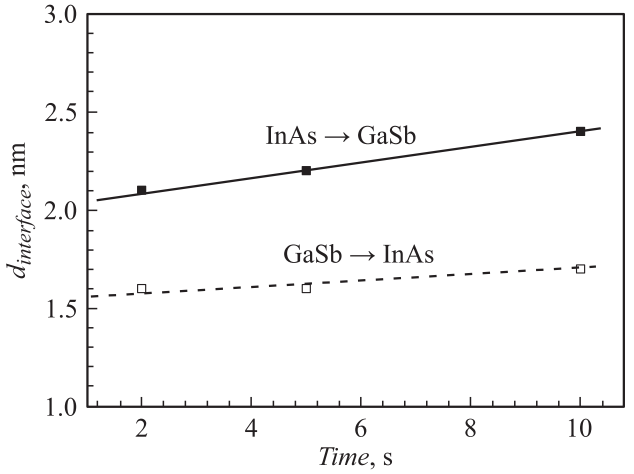

Figure 3. Dependence of the interface layer thickness on the growth switching direction and the feed time delay between the reagents.

of In(GaAs)Sb interface layers. The smallest thickness (1.2−1.4 nm) was measured in the experiment with the direction of growth switching from GaSb to InAs with AsH_3 introduced just 2 s earlier than TMIn.

Conflict of interest

The authors declare that they have no conflict of interest.

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