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Interface effect on structural and optical properties of type II InAs/GaSb superlattices

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ABSTRACT

For type II InAs/GaSb superlattice (SL) structure, we reveal that, if the overall strain of the SLs is balanced to be zero, there exists a quantitative relationship between the interface (IF) materials and the SL constituent layers, which can serve as guidance on how to design the specific IF structure and on how to tune the strain. Controlled growth of a series of samples was performed to vary the strain by the IF engineering. It is found that while the photoluminescence (PL) peak position changes insignificantly with the changing strain, the PL intensity is intimately related to the strain.

1. Introduction

The short-period InAs/GaSb superlattice (SL) structure has a unique type II bandgap alignment and thus may exhibit properties like the reduced Auger recombination rate, relatively long carrier lifetime [1,2], and large effective mass. These features make the SL structure a favorable material for infrared photodetector applications. Recently, type II InAs/GaSb SL photodetectors have been investigated intensively and the detection wavelength covers the mid, long and very long wavelength (MW, LW, and VLW) ranges [3–13]. For the growth of the SL structure, since there are no common cations and anions, how to switch from one constituent material to the other is a challenge. The switch or the transition can be and has to be done by the interface (IF) design and control. Two types of IFs,the InSb-like IF for InAs-on-GaSb and the GaAs-like one for GaSb-on-InAs, are regarded as natural [14]. However, different IF combinations can actually be realized by engineering the IFs. For molecular beam epitaxy (MBE), this IF engineering can be done by controlling the shutter open/close sequences of different sources. On the other hand, due to the varying difference of the lattice constant among InAs, GaSb, InSb and GaAs, the overall strain of the SL material can also be controlled by the IF engineering. It is possible to make the strain close to zero even for a VLW SL structure [13]. Thanks to the extreme importance of the IFs, there have been investigations like IF effect on the surface roughness [15], strain [16–21], and the transport property [22] of the SL material.

In this paper, we first reveal that there exists a quantitative relationship between the IF materials and the SL constituent layers if the overall strain of the structure is balanced to be zero. This quantitative relationship can serve as guidance on how to design the specific IF structure and on how to adjust the strain. It is found that the strain is actually determined by the IF structure and the InAs layer thickness and has nothing to do with the GaSb epilayer thickness. This is not surprising since the SLs are grown on GaSb substrate and thus the thickness of the GaSb layer is not important in terms of the overall strain. Based on this revealed relationship, we then performed controlled growth of a series of samples in which the layer thickness of the InAs and the GaSb in the SLs is designed to be the same but the strain is varied from 0 to the order of 10^{-3} magnitude by the IF engineering. To reveal how the IF structure influences the optical property, the photoluminescence (PL) measurements were done for the series of samples. It is found that while the PL peak position changes insignificantly with the changing value of the strain, the PL intensity is intimately related to the strain and the smaller the strain is, the stronger the PL signal is.

2. Strain in InAs/GaSb SL

For type II SL growth, some IF effects like intermixing, segregation of different species are actually very complicated. To simplify

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the complicated physical picture, we neglect the potential formation of ternary and quaternary materials. Thus, the materials involved during the growth are InAs, GaSb, GaAs and InSb. Here, GaAs and InSb are the IF materials. If the growth of the epilayers is pseudomorphic or coherent on the GaSb substrate, the parallel or in-plane lattice constant of each epilayer, $a_i^{\parallel}$, should be equal to that of GaSb, a_{GaSb}, where i denotes the different epilayers, i.e., InAs, GaSb, GaAs or InSb. For each epilayer, the vertical strain $\varepsilon_i^{\perp}$ is related to the parallel strain $\varepsilon_i^{\parallel}$ by the equation below:

$$\varepsilon_i^{\perp} = -\frac{2\nu}{1-\nu}\varepsilon_i^{\parallel}, \tag{1}$$

where ν is the Poisson ratio and $\nu = C_{12}/(C_{11}+C_{12})$, where C_{11} and C_{12} are the elastic moduli of the i material, which can be referred to the literature [23]. Therefore, for each material, ν is known. The vertical and parallel strains are defined as

$$\varepsilon_i^{\perp} = -\frac{a_i^{\perp}-a_i}{a_i}, \quad \varepsilon_i^{\parallel} = -\frac{a_i^{\parallel}-a_i}{a_i}, \tag{2}$$

where a_i is the lattice constant of the i material. For a pseudomorphic growth, $a_i^{\parallel}$ is equal to the lattice constant of GaSb. Therefore, combining Eqs. (1) and (2), we then get that the vertical lattice constant $a_i^{\perp}$ is 6.0173, 6.0959, 6.8970 and 5.2430 Å for InAs, GaSb, InSb and GaAs epilayers, respectively. Therefore, for the pseudomorphic growth, the InSb layer is compressively strained while InAs and GaAs materials are tensilely strained, which are illustratively drawn in Fig. 1(a). The average lattice constant of the SL structure along the growth direction, $a_{avg}^{\perp}$, should be

$$a_{avg}^{\perp} = \sum_i (a_i^{\perp} \cdot m_i) / \sum_i m_i, \tag{3}$$

where m_i denotes the layer thickness of the i material in one period in terms of monolayer (ML). If the overall strain of the SL structure is zero, $a_{avg}^{\perp} = a_{GaSb}$ and we then get

$$m_{InSb} = 1.065 m_{GaAs} + 0.098 m_{InAs}. \tag{4}$$

Eq. (4) describes a quantitative relationship between the IF materials and the SL constituent layers for the case that the overall strain is zero. This relationship can serve as guidance on how to design the specific IF structure and on how to adjust the strain of the SL structure. The IF structure should be designed to try to abide by the relationship described by Eq. (4). Any deviation from the relationship for a grown structure will result in a non-zero strain. The larger the deviation is, the larger the strain is. When the strain is large enough, the interfaces may be degraded resulting in dislocations. It is useful to discuss several features Eq. (4) revealed. First, even if the overall strain of the SLs is tuned to be zero, except for GaSb, the other epitaxial materials like InAs, InSb and GaAs are still strained. For instance, the vertical and parallel strains are 6.5% and −5.9%, respectively, for the InSb IF material. Second, when the overall strain of the SLs is balanced to be zero, the relationship has nothing to do with the GaSb epilayer thickness. This can be made sense of because the SLs are grown on the GaSb substrate. Third, Eq. (4) also indicates that the key point for a good growth is how to handle the InSb IF material. This is in particular true for a SL structure aiming at longer detection wavelength [13]. We know that the InAs constituent layer thickness in the SLs should be increased with the increasing detection wavelength. To reach a longer detection wavelength, in order to increase the electron–hole wavefunction overlap, a larger thickness ratio of InAs to GaSb is favorable. Therefore, for a longer detection wavelength, a larger amount of InAs is needed in the SL design. According to Eq. (4), this implies that thicker InSb layers are needed to compensate for the lattice mismatch between InAs and GaSb. Considering that the growth of InSb on both InAs and GaSb belongs to the Stranski–Krastanov mode [24,25], three-dimensional islanding occurs when the InSb deposition is beyond the critical thickness. This causes a problem since more InSb can degrade the structural quality due to the large lattice mismatch (>6%) between InSb and InAs/GaSb. According to our previous experimental observation, when the continuous deposition of the InSb IF layer is thicker than about

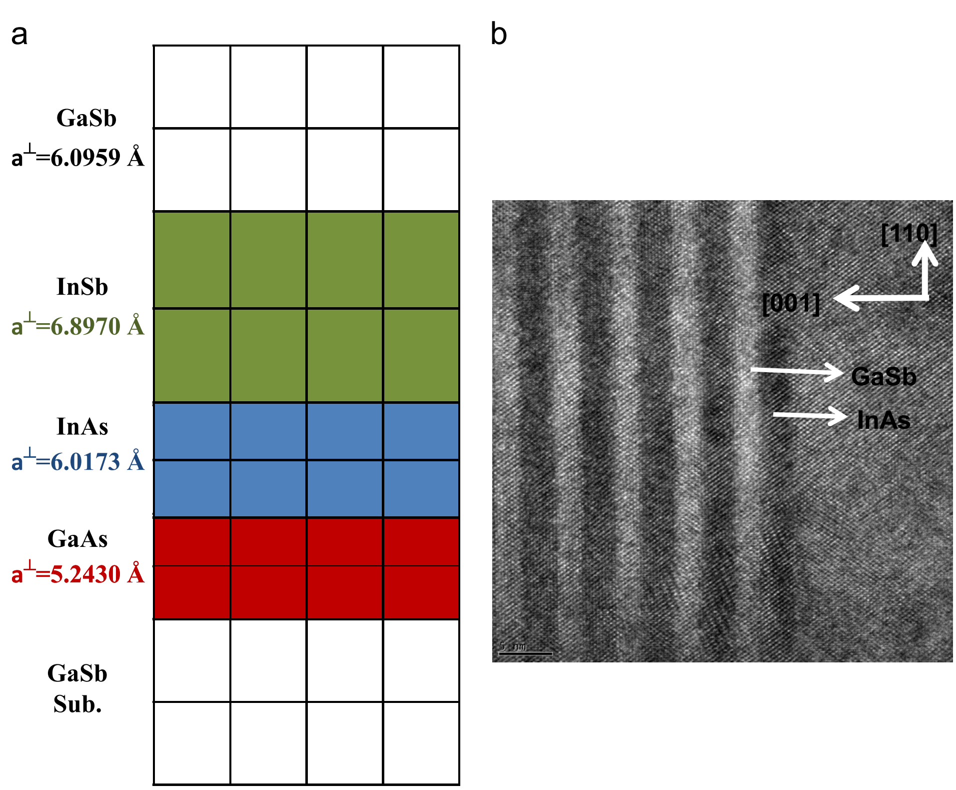

Fig. 1. (a) The schematic drawing showing the pseudomorphic growth of a type II SL structure with the vertical lattice constant denoted for GaAs, InAs, InSb and GaSb materials. (b) The cross-sectional TEM image of sample *e*.