Determination of InSb/AlInSb quantum well energy spectrum

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Abstract. The InSb/AlInSb single quantum well energy spectrum is determined both theoretically and experimentally (from the photoluminescence spectra). The 8-band Kane model is used to take into account the dispersion law nonparabolicity. The mechanical strain is considered by the deformation potentials theory. The photoluminescence measurements were carried out in the 12-160K temperature range and at various excitation powers. All the observed features of the photoluminescence spectra are well described by the theoretical calculations.

1. Introduction

The InSb/AlInSb quantum-well nanostructures for microwave high electron mobility transistors (HEMT) have higher electron mobility than that of conventional HEMT made of other III-V materials. This is achieved due to the highest electron mobility in InSb compared to any other III-V compound. Recent active studies of InSb/AlInSb heterostructures have been conducted by QinetiQ research group [1] and Intel [2]. In [2] the first prototype of a 305 GHz transistor with an n-InSb channel was reported. Formation of a two-dimensional InSb channel with record-breaking electron mobility was also mentioned in [3]. Additionally, InSb/AlInSb quantum-well nanostructures are used to make infrared light emitting diodes [4].

2. Theory

The InSb/AlInSb quantum well energy spectrum was calculated using the 8-band Kane model [5] for different quantum well widths and temperatures. Mechanical strain due to pseudomorphic growth was considered in the effective Hamiltonian by the deformation potentials theory [6]. The bulk InSb energy dispersion law in [010] and [110] directions for both strained and unstrained cases is shown on fig. 1. The splitting of the heavy-hole and light-hole bands is clearly seen, as well as the energy shift of conduction band minimum. Energy gap for InSb pseudomorphically grown on Al0.11In0.89Sb increases from 0.234 eV to 0.245 eV (at 20K). The temperature dependence was taken into account using the Varshni law. The necessary parameters for calculations were taken from [7-9]. The effective Schrödinger equation for quantum well was solved in the momentum space considering wave vectors only within the Brillouin zone so as to eliminate spurious solutions [10]. We used periodic boundary conditions assuming a single quantum well as a superlattice with a large barrier thickness [11]. The band parameters space dependence was contained within the effective kp-Hamiltonian operator corresponding to BenDaniel-Duke boundary conditions at interfaces.
Figure 1. The bulk InSb band structure near the Γ-point with (solid lines) and without (dashed lines) mechanical strains calculated using the Kane model. The mechanical strains correspond to InSb/Al\textsubscript{0.11}In\textsubscript{0.89}Sb quantum well (T = 20 K).

3. Experiment

Structures containing InSb/AlInSb single quantum wells were grown by molecular beam epitaxy (MBE) on GaAs semi-insulating substrates with AlSb buffer layers (fig. 2). The photoluminescence (PL) experimental setup was based upon a VERTEX 80 Fourier-transform infrared spectrometer (FTIR) operating in step-scan mode, coupled with a lock-in amplifier. This allowed us to detect the modulated PL signal, while excluding constant blackbody radiation from the spectra.

The PL measurements were carried out in the 12-160K temperature range; excitation was performed with a chopped beam of an 809 nm laser diode of variable power. An example of the obtained PL spectra for various excitation densities is shown on Fig. 3. Excitation density values are shown for a constant laser beam (without the mechanical chopping).

Figure 2. A sketch of the studied samples band gap profile along the growth direction.

Figure 3. PL spectra of an InSb/Al\textsubscript{0.11}In\textsubscript{0.89}Sb single quantum well at various laser excitation densities. Arrows mark the ground-state transition energies $E_m$. 
4. Analysis

In order to eliminate the heating effect on the band gap energy we extrapolated the excitation power dependence of the PL peak energy $E_m$ to zero excitation power (fig. 4). This procedure had been made for the spectra measured at minimum temperature (12 K). Then we calculated the ground-state transition energy $\Delta E$ for different quantum well widths so as to find out the sample quantum well width (fig. 5).

![Figure 4](image1.png)

**Figure 4.** The excitation power dependence of the PL peak energy for InSb/Al$_{0.11}$In$_{0.89}$Sb quantum well.

![Figure 5](image2.png)

**Figure 5.** The theoretical dependence of the ground-state transition energy on the quantum well width for InSb/Al$_{0.11}$In$_{0.89}$Sb quantum well. Dashed lines illustrate the sample quantum well width determination.

Since the real sample temperature is supposed to be higher than the temperature inside the cryostat and there is no big difference in the PL spectra at 12 K and 25 K (fig. 8), the calculations were performed for 20 K temperature. The sample quantum well width is found to be about 30 nm, which agrees with the TEM measurements. The accuracy depends on spectral resolution and in our case it is not better than 4 nm.

In contrast to a simple quantum well with parabolic dispersion law, the sample 2D density of states is not a step-like function. This is due to the strong nonparabolicity of the dispersion law, which is caused by kp-interaction and mechanical strains (fig. 1). This fact may influence the excitation power dependence of the PL peak energy. However, we assume that the main effect on the PL peak position is due to the energy band gap temperature dependence. Thus, to estimate the sample temperature for different excitation powers we calculated the quantum well energy spectrum temperature dependence taking into account the Varshni law (fig. 6). An example of the quantum well energy spectrum is shown on fig. 7.

![Figure 6](image3.png)

**Figure 6.** The theoretical temperature dependence of the ground-state transition energy for InSb/Al$_{0.11}$In$_{0.89}$Sb quantum well (W=30 nm). Dashed lines mark the PL peak position for various excitation powers.
We compared the theoretical results with the PL spectra at different temperatures (fig. 8) taking into account that the real sample temperature is higher than the temperature inside the cryostat. Thus, to mark transitions at 12 K, calculations for 55 K were made, as follows from fig. 6.

**Figure 7.** The energy spectrum of a InSb/Al_{0.11}In_{0.89}Sb quantum well calculated using the 8-band Kane model ($k_x=k_y=0$). (Solid lines represent electron and heavy-hole energy levels. Dashed lines represent light-hole energy levels. The light-hole band is shown by the thick dashed line.)

**Figure 8.** PL spectra of an InSb/Al_{0.11}In_{0.89}Sb single quantum well at various temperatures. Arrows mark transition energies shown on fig. 8 for the 30 nm-thick quantum well at 55K (grey) and 120 K (black).

The theoretical calculations are in a good agreement with the transition energies observed on the PL spectra. However, within the performed measurements it is not possible to experimentally establish the transition energies within the CO$_2$ absorption region. Unlike the parabolic approximation, the Kane model allowed us to explain all the observed features on the PL spectra.

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