GaAsSb/GaAs type-II quantum well and its application on $\sim 1.3 \mu\text{m}$ laser

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Abstract

The band offset of the type-II $\text{GaAs}_{0.7}\text{Sb}_{0.3}/\text{GaAs}$ quantum well (QW) is studied. We propose an extrapolation method to remove the band-bending effect and determine the flat-band transition energy of the type-II QW from photoluminescence (PL) measurement. Then, we compare the PL peak energies of the type-II $\text{GaAs}_{0.7}\text{Sb}_{0.3}/\text{GaAs}$ QW and the type-I $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}_{0.7}\text{Sb}_{0.3}$ QW to obtain the strained band gap energy of $\text{GaAs}_{0.7}\text{Sb}_{0.3}$ and the valence-band-offset ratio of the type-II QW. The obtained band gap energy and valence-band-offset ratio are 1.01 eV and 1.15. $\text{GaAsSb}/\text{GaAs}$ double-quantum-well lasers were also grown and fabricated. The laser demonstrates a very low threshold current density of $210 \text{ A}/\text{cm}^2$ with an emission wavelength of $1.28 \mu\text{m}$.

1. Introduction

$1.3 \mu\text{m}$ semiconductor lasers grown on GaAs substrates are of great interest recently. The lasers have better performances than the traditional InP-based devices because GaAs related materials possess higher conduction band offset which results in better thermal characteristics in lasers. In addition, the high-contrast AlAs/GaAs DBR mirrors can be easily deposited on GaAs substrates to realize $1.3 \mu\text{m}$ vertical cavity surface emitting lasers (VCSELs). Currently, there are several approaches, namely InGaAsN quantum wells [1], In(Ga)As quantum dots [2], and GaAsSb quantum wells [3-5]. Among them, strained GaAsSb/GaAs quantum wells, which exhibit a staggered type-II band alignment, possess an advantage of emitting photons with transition energy lower than the fundamental band gaps of each constituent. Since the band gap versus lattice constant relation of GaAsSb is very similar to that of InGaAs, the type-II band structure allows GaAsSb/GaAs QW with less lattice mismatch to achieve the $1.3 \mu\text{m}$ optical transition. The GaAsSb QW lasers reported so far were grown mostly by metal organic vapor phase epitaxy (MOCVD) [3] and gas source molecular beam epitaxy (GSMBE) [4, 5]. Fewer results were reported for those by solid source molecular beam epitaxy (SSMBE). In this paper, we report GaAsSb/GaAs double quantum well lasers grown by SSMBE utilizing cracked Sb monomer (Sb_1) source. The high quality of the laser is manifested by the very low threshold current density measured in the broad area devices.

In the design of type-II GaAsSb/GaAs QW lasers, knowledge of the band parameters is essential. In particular, the earlier studies on the band lineup between GaAs and GaAsSb gave inconsistent results. In terms of GaAsSb/GaAs valence-band-offset ratio Q_v , the reported values range from 1.05 to 2.1 [6-7]. There are two problems responsible for these scattered results. The first is the band bending effect resulting from the spatial separation of electrons and holes in the type-II QW. This effect induces a blue shift in photoluminescence when the excitation power increases [7-8] and makes the determination of the flat-band transition energy of the GaAsSb/GaAs QW difficult. In this study, we propose a simple extrapolation method to remove the effect of band bending in the QWs. The second problem is on the band gap energy of GaAsSb. In GaAsSb/GaAs QW's, the thick GaAs layer makes the electrons at nearly free states and the heavy hole mass results in small quantum shift in valence band. In this situation, the band offset contributes only slight effect on the transition energy of the QW, and the band gap energy of GaAsSb becomes an important parameter on the determination of Q_v . In previous studies [7], the strained band-gap energy was calculated from the empirical formulas for bulk GaAsSb alloy [9]. In this report, we introduce a new method to determine the band gap experimentally. We grew GaAs/GaAsSb type-II QW's and AlGaAs/GaAsSb type-I QW's with the same GaAsSb composition. By comparing their transition energies and employing the well-known band offset data of AlGaAs/GaAs heterointerface [10-12], the band gap energy of GaAsSb and the valence-band-offset ratio can be determined. The obtained band gap energy of $\text{GaAs}_{0.7}\text{Sb}_{0.3}$ is 1.01 eV, and the valence-band- offset ratio Q_v of $\text{GaAs}/\text{GaAs}_{0.7}\text{Sb}_{0.3}$ is 1.15.

2. Experiments

All samples for band-offset study were grown on (100) GaAs semi-insulating substrates by using VG V80H solid source molecular beam epitaxy (SSMBE). Arsenic tetramer (As_4) and cracked Sb monomer (Sb_1) beams were used in the growth of GaAsSb QWs. The improvement on the optical quality of the Sb-containing compound semiconductor by using Sb_1 instead of Sb_4 has been reported in the literature [13]. After the deposition of a

GaAs buffer layer at 600°C, the GaAs_{0.7}Sb_{0.3} QW was grown at 500°C. All type-II QW samples are capped with 100-nm-thick GaAs. For type-I QWs, identical growth conditions were used for the GaAs_{0.7}Sb_{0.3} well. The barrier Al_{0.3}Ga_{0.7}As layer is 100 nm in thickness, and was grown at 580°C. The compositions of the layers were determined from a Bede QC200 high resolution X-ray diffractometer. Photoluminescence spectroscopy (PL) was used to measure the transition energies of the QWs. The measurement used a 514.5nm Ar ion laser for the excitation, and an InGaAs detector for detecting luminescence spectrum.

The lasers were grown on n⁺-GaAs (100) substrate by the SSMBE system. The active region of the separate confinement hetero-structure laser was grown at 500°C. It consists of two 7-nm-thick GaAs_{0.66}Sb_{0.34} quantum wells embedded in GaAs barriers and is sandwiched between two 0.1-μm-thick Al_{0.3}Ga_{0.7}As waveguide layers. Al_{0.6}Ga_{0.4}As layers with 1.5 μm in thickness serve as the cladding layers of the lasers. The AlGaAs layers and a 0.5-μm-thick buffer n⁺-GaAs layer were grown at 580°C. Finally, 50-μm-wide broad-area lasers with different cavity lengths were fabricated by using standard photolithography, wet-etching, and metallization processes. The as-cleaved lasers were tested under pulsed mode. The EL and lasing spectrums were taken by coupling the light output into a multimode fiber and fed into a HP70951A spectrum analyzer.

3. Results and Discussions

In PL measurement, the photon-generated electron-hole pairs are separated in the type-II GaAsSb/GaAs hetero-structure. After relaxation, holes are confined in the GaAsSb well, while electrons in the GaAs layer. The separated charges form a dipole layer, and induce an approximately triangular quantum well in the GaAs sides for electrons. An increase in the excitation intensity enhances the electric field in the GaAs sides, and consequently raises the electron states in the squeezed potential well. Since the hole has much larger effective mass and is confined in a narrow quantum well, the band bending and energy shift in GaAsSb well can be neglected, and the blue shift in the PL measurement is mainly attributed to the increase of the electron state energy. The electric field at the GaAs/GaAsSb interface can be expressed as

$$F = 2\pi en_w/\epsilon, \quad (1)$$

where n_w is the sheet density of electron in the triangular well, ϵ_0 is the dielectric constant of GaAs, and e is the

electron charge. Since the photoluminescence is mainly due to the spontaneous emission, the integrated PL intensity L is proportional to n_w^2 . Note that the state energy in a triangular well is proportional to the two-third power of the electric field. Therefore, the relation between the state energy and the integrated PL intensity is given by [14]

$$E_0 \propto F^{2/3} \propto L^{1/3}, \quad (2)$$

The electron quantization energy is thus expected to increase proportionally with the third root of the integrated PL intensity. Fig. 1 shows the PL peak energy as a function of the third root of the integrated intensity L in the power dependent PL measurement of a GaAs/GaAs_{0.7}Sb_{0.3} QW. The well thickness is 5 nm. As can be seen, the PL peak energy follows the expected behavior described in Eq. (2). The intercept corresponding to zero integrated intensity, which implies zero electric field, is the flat-band transition energy E_{T2} of the type-II QW. Fig. 2 shows the band lineups of both type-I AlGaAs/GaAsSb and type-II GaAs/GaAsSb heterojunctions. As shown in the figure, the flat-band transition energy is

$$E_{T2} = E_G^{\text{GaAs}} - Q_v (E_G^{\text{GaAs}} - E_G^{\text{GaAsSb}}) + E_{HH1} + 3kT/2, \quad (3)$$

where E_G^{GaAs} and E_G^{GaAsSb} are the energy gaps of GaAs and GaAsSb, Q_v is the valence-band-offset ratio, E_{HH1} is the heavy-hole ground-state energy, k is Boltzmann's constant, and T is absolute temperature. The addition of $3kT/2$ is due to the thermal populated electrons with higher growth-direction wavevector in GaAs [15-16]. Because of the heavy-hole effective mass, the valence band offset has slight effect on E_{HH1} . Therefore, it is difficult to find Q_v through the difference in E_{T2} measured from QW's with different well width. In this situation, the accuracy of E_G^{GaAsSb} becomes an essential factor for Q_v determination. In order to derive the strained E_G^{GaAsSb} , we analyze the band lineup of type-I Al_{0.3}Ga_{0.7}As/GaAs_{0.7}Sb_{0.3} QW whose transition energy is

$$E_{T1} = E_G^{\text{GaAsSb}} + E_{E1}' + E_{HH1}', \quad (4)$$

where E_{E1}' and E_{HH1}' are the ground-state energies of the electron and the heavy hole in the type-I Al_{0.3}Ga_{0.7}As/GaAs_{0.7}Sb_{0.3} QW, respectively. Assume the valence band offsets have slight effect on E_{HH1} and E_{HH1}' , $E_{HH1} \sim E_{HH1}'$. By comparing the band structures of AlGaAs/GaAsSb and AlGaAs/GaAs, one can obtain

$$E_{T1} \sim E_{T2} + \Delta E_{C2} - \Delta E_{C1} + E_{E1}' - 3kT/2, \quad (5)$$

where ΔE_{C1} and ΔE_{C2} are the conduction-band offsets of AlGaAs/GaAsSb and AlGaAs/GaAs heterojunctions. ΔE_{C2}

has been well studied and the widely accepted value is 0.6 times the band gap difference [10-12], which is used in this calculation to obtain ΔE_{C1} . The difference between ΔE_{C2} and ΔE_{C1} is just the conduction-band offset of GaAs/GaAsSb QW, ΔE_{C3} . With the knowledge of ΔE_{C3} , the energy gap of GaAsSb can be given by

$$E_G^{\text{GaAsSb}} = E_{T2} + \Delta E_{C3} - E_{HH1} - 3kT/2. \quad (6)$$

And the valence band offset ratio, Q_v , can also be obtained. Fig. 3 shows the PL spectrums of a type-I $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}_{0.7}\text{Sb}_{0.3}$ QW and a type-II $\text{GaAs}/\text{GaAs}_{0.7}\text{Sb}_{0.3}$ QW. The thicknesses of the $\text{GaAs}_{0.7}\text{Sb}_{0.3}$ wells in these two QW's are 50 nm. The derived Q_v values are 1.15 for GaAs/GaAs_{0.7}Sb_{0.3} QWs, and the strained band gap of GaAs_{0.7}Sb_{0.3}, E_G^{GaAsSb} , is 1.01 eV.

Fig. 4 depicts the light output power versus current characteristics of a broad-area laser with 1.54-mm-long cavity. The threshold current is 162 mA which corresponds to a threshold current density of 210 A/cm². The result is among the lowest values reported for GaAsSb lasers [3]. In fact, the infinite-cavity-length threshold current density obtained in this study is only 83 A/cm². The internal quantum efficiency and the internal loss are 62.8% and 3.45 cm⁻¹, respectively. The low threshold current density is attributed to the use of Sb₁ source in the growth of GaAsSb layers. Temperature characteristics of our laser were measured from 25°C to 85°C, and the characteristic temperature is 60K, which is among the typical value for GaAsSb laser reported in the literatures [3-5]. We also measured the electroluminescence (EL) spectrums of the lasers under various injection currents and observed the blue-shift effect as can be seen in Fig. 5. In a laser diode, the relation between the injection current and the carrier density in its active region can be found from its output power versus current density characteristics. For injection current density, an empirical formula, $J \propto n_w^2$ [17], is assumed. Inserting this relation into Eq. (1), we can obtain the following relationship,

$$E_0 \propto F^{2/3} \propto J^{2/3z}, \quad (7)$$

The z value extracted from the integrated EL versus the injection current is ~ 1.32 . The EL peak position versus the $J^{2/3z}$ plot is shown in the inset of Fig. 5. The curve can be fitted by a straight line, indicating the blue shift is mainly from the increase of the electron quantum shift in GaAs. The intercept of the line gives the flat-band transition energy of the $\text{GaAs}_{0.67}\text{Sb}_{0.33}/\text{GaAs}$ quantum well, which can be used to estimate the band gap energy of the strained $\text{GaAs}_{0.67}\text{Sb}_{0.33}$. With the assumption that $Q_v = 1.15$, the calculated band gap energy is 0.960 eV.

4. Conclusion

We analyzed the band lineup of GaAsSb/GaAs QW. Extrapolation method is used to remove the band bending effect and determine the flat-band transition energy of the type-II QW. By comparing the type-II GaAsSb/GaAs QW's with the type-I AlGaAs/GaAsSb QWs, we obtained the energy gap of GaAsSb successfully. The obtained band gap energy of $\text{GaAs}_{0.7}\text{Sb}_{0.3}$ is 1.01 eV, and the valence-band-offset ratio Q_v of GaAs/GaAs_{0.7}Sb_{0.3} is 1.15. We have successfully grown a low threshold current density GaAsSb/GaAs double QW laser by using SSMBE. The emission wavelength is 1.28 μm , which is very close to the 1.3 μm band for optical fiber communication. A very low threshold current density of 210 A/cm² is achieved, which can be attributed to the use of Sb₁ source in the growth of GaAsSb layers.

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Fig. 1 PL peak energy as a function of the third root of the integrated PL intensity. The sample is a type-II GaAs/GaAs_{0.7}Sb_{0.3} QW with 5 nm well width.

Fig.2 Flat band diagram of a type-I AlGaAs/GaAsSb QW and a type-II GaAs/GaAsSb QW. The band lineup of AlGaAs/GaAs heterojunction is also displayed.

Fig. 3 Room temperature photoluminescence spectrums of a type-I Al_{0.3}Ga_{0.7}As/ GaAs_{0.7}Sb_{0.3} QW and a type-II GaAs/GaAs_{0.7}Sb_{0.3} QW. Both well thicknesses are 5 nm.

Fig.4 L-I characteristic of the GaAsSb/GaAs laser whose emission spectrum is shown in the inset.

Fig. 5 Electroluminescence spectra of the laser under various injection currents. The inset is the plot of EL peak energy vs. $J^{2/3z}$.