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子計畫一：砷銻化鎵第二型量子井的成長與元件技術

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行政院國家科學委員會專題研究計畫成果報告

前瞻性量子元件技術-子計畫一：砷銻化鎵第二型量子井的成長與元件技術

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中文摘要

本計畫研究以固態源分子束磊晶法在砷化鎵基板上成長銻砷化鎵/砷化鎵第二型量子井以及雷射二極體。在第二型量子井的部分我們達到波長1300nm、半寬80meV的室溫光激螢光譜。單量子井雷射的室溫振盪波長達1292nm，起振電流密度達300 A/cm^2。此外，我們也研究銻砷化鎵/砷化鎵第二型異質結構的能帶接合。我們首先提出一個外插法來去除這種量子井結構中因載子分離電場所造成的光激螢光譜的藍位移，以獲取平能帶狀況下的光子遷移能量。然後再藉由比較不同井寬量子井的平能帶遷移能量以獲取異質結構價電帶不連續佔能隙差的比例，Qv。我們所獲得的Qv值為1.32。

關鍵詞: 分子束磊晶，含銻化合物半導體，銻砷化鎵量子井，能帶接合，價電帶不連續。

Abstract

In this study, GaAsSb/GaAs type-II quantum wells and laser devices have been successfully grown and fabricated. The photoluminescence emission wavelength of the type-II quantum well reaches 1300m with a FWHM of 80 meV. On the results of the type II GaAsSb/GaAs single quantum-well laser diode, an emission wavelength of 1292nm and a low threshold current density of 300A/cm^2 are demonstrated at room temperature. The band offset of the type-II $GaAs_{0.7}Sb_{0.3}$/GaAs quantum well is also studied. We propose an extrapolation method to remove the band-bending effect and determine the flat-band transition energy of the type-II quantum well from photo-luminescence (PL) measurement. Then, we compare the flat-band transition energy of type-II $GaAs_{0.7}Sb_{0.3}$/GaAs QW with different quantum well thickness to extract the valence-band-offset ratio of the hetero-structure. The obtained valence-band-offset ratio is 1.32.

Keywords: molecular beam epitaxy, Sb-based compound semiconductor, GaAsSb quantum well, band-lineup, valence band discontinuity.

Introduction

Recently, GaAs based long-wavelength lasers have attracted great attentions and are recognized as the key light sources for the optical communication in the near future. Besides the mature and low-cost fabrication technologies inherited from the GaAs based materials, the most important advantage of the lasers is the compatibility with the high-index-contract GaAs/AlAs distributed Bragg reflectors (DBRs), which is essential for the high-performance long-wavelength vertical-cavity surface-emitting lasers (VCSELs). Currently, the approaches to GaAs based long-wavelength lasers includes diluted nitrides InGaAsN quantum well lasers [1], InAs quantum dot lasers [2], GaAsSb/GaAs type-II quantum well lasers

[3-6], and the traditional InGaAs/GaAs quantum well lasers [7-8].

GaAsSb/GaAs type-II semiconductor heterostructure with the capability of emitting photons with energy less than fundamental band gaps of each layer is an important candidate for GaAs-based long wavelength laser diodes. Recently we have successfully grown a low threshold current GaAsSb/GaAs double quantum-well (QW) laser that emits at 1280 nm [6]. In this study, we further increase the Sb-content in the GaAsSb QW and further push the wavelength to 1292 nm. Besides the device fabrication, the characteristics especially the band structure of the GaAs/GaAsSb QW were also investigated. For the design of GaAs/GaAsSb type-II laser devices, the band alignment is an essential parameter. However, the earlier studies on the band lineup of GaAs/GaAsSb system gave scattered results. In terms of valence band offset ratio $Q_v = \Delta E_v/\Delta E_g$, the reported data ranges from 1.05 to 2.1 [9-10]. Most of these studies used photoluminescence (PL) to determine the transition energy of the QW with different well width. However, the band bending induced by spatially separated electrons and holes may cause significant blue shift on the PL peak wavelength as excitation level increases, [10-11] and makes the determination of flat band transition energy rather difficult. We propose a simple method to derive the flat-band transition energies in these type-II QWs. And by fitting the transition energy versus the quantum well width, the GaAsSb/GaAs valence band offset ratio can be derived.

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 [12]. After the deposition of a GaAs buffer layer at 600^{o}C, the $GaAs_{0.7}Sb_{0.3}$ QW was grown at 500^{o}C. All type-II QW samples are capped with 100-nm-thick GaAs. The compositions of the layers were determined from a Bede QC200 high resolution X-ray diffractometer. Photo- luminescence 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 the luminescence spectrum detection.

The lasers were grown on n^+-GaAs (100) substrate by the SSMBE system. The active region of the laser was grown at 500^{o}C. It consists of one 7-nm-thick $GaAs_{0.64}Sb_{0.36}$ quantum well and two 80-nm-thick GaAs barrier layers. The active layer was enclosed within two 100-nm-thick AlGaAs graded index (GRIN) layers. $Al_{0.6}Ga_{0.4}As$ layers with 1.5 μm in thickness were used as the cladding layers of the laser and the growth temperature was 580^{o}C. By increasing Sb content in the GaAsSb well, the PL emission wavelength can be extended to 1300 nm.

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 electroluminescence and lasing spectrums were taken by coupling the light output into a multimode fiber and fed into a HP70951A spectrum analyzer.

Results and Discussion

Fig. 1 shows the PL spectrum of the GaAsSb/GaAs single quantum well laser after the top p-cladding layer being removed. The peak position is at 1300 nm, and the FWHM is about 80 meV. The relatively broad FWHM is not unusual in GaAs/GaAsSb QWs [10, 13-14], and can be attributed to two origins. The first one is from the nearly free electrons which are weakly confined in the GaAs layer. Electrons with larger wavevector along the growth direction have higher probability to penetrate into the GaAsSb layer. The resulted larger electron-hole wavefunction overlap of these high energy electrons prolongs the high energy tail of PL spectrum and broadens the FWHM. The second reason is the compositional grading or fluctuation in GaAsSb layer as have been reported in literatures [14-16]. 50-µm-wide broad stripe lasers with different cavity lengths were fabricated. Fig. 2 displays the L-I characteristic of the grown laser under pulsed mode operation. The threshold current density is ~300 A/cm^2. Fig. 3 shows the spectrum of a laser with a cavity length of 2.2 mm. The lasing wavelength is 1292 nm.

For the band alignment determination, type-II GaAs/$GaAs_{0.7}Sb_{0.3}$ single and multiple QWs with different well thickness ranging from 3 nm to 9 nm were grown. Fig. 4 shows the excitation power dependence on the PL peak energy shift of a $GaAs_{0.7}Sb_{0.3}$/GaAs MQW. As can be seen, the QW exhibits a very significant blue shift as the excitation power is increased. In order to extract the flat-band transition energy of the type-II GaAs/GaAsSb QW, we derived a simple one-third root relation between the electron quantization energy and the integrated PL intensity [17-18].

In PL measurement, the photon-generated electron-hole pairs are separated in the type-II GaAsSb/GaAs heterostructure. 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

$$F = 2\pi e n_W/\varepsilon_0, \qquad (1)$$

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 ground state energy in a triangular well is proportional to the two-third power of the electric field. Therefore, the relation between the ground state energy and the integrated PL intensity is given by [16]

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

The electron quantization energy is thus expected to increase proportionally with the third root of the integrated PL intensity. Fig. 5 shows the PL peak energy as a function of the third root of the integrated intensity in the power dependent PL measurement of a GaAs/GaAsSb QW. As can be seen, the PL peak energy follows the expected behavior. The intercept of the plot corresponding to zero integrated intensity, which implies zero electric field, is the flat-band transition energy of the type-II QW. Fig. 6 shows the flat-band energy of $GaAs_{0.7}Sb_{0.3}$ as a function of QW width. The valence band offset ratio Q_v. can be derived from the flat-band transition energy of QW's with different well width. The band gap energy of the $GaAs_{0.7}Sb_{0.3}$ and the strain induced shift on its heavy-hole band gap were calculated. By using Q_v as the fitting parameter, the flat-band transition energies of different well widths were then calculated to fit the experiment data. The best fitted Q_v of GaAs/ $GaAs_{0.7}Sb_{0.3}$ heterostructure is 1.32.

Conclusion

We have extended the lasing wavelength

of the GaAsSb/GaAs quantum well laser to 1292 nm successfully. The threshold current density is 300A/cm^2. The GaAsSb/GaAs band alignment was also studied by measuring the PL of the $GaAs_{0.7}Sb_{0.3}$/GaAs quantum wells. By proposing a simple method to exclude the band bending induced blue shift in power dependent photoluminescence, we derived the valence band offset ratio Q_v of GaAsSb/GaAs QW. The result is 1.32.

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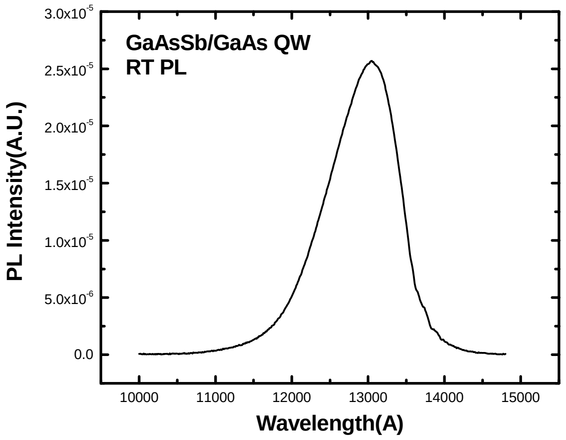

Fig.1 Room temperature PL spectrum of the grown GaAsSb/GaAs single quantum well laser. The top p-cladding has been removed.

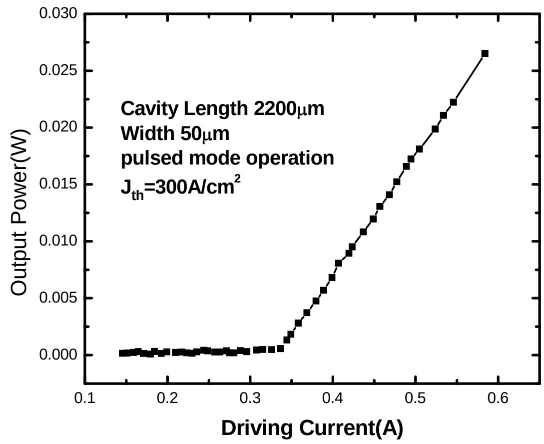

Fig.2 Light output versus injection current characteristics of GaAsSb/GaAs SQW laser.

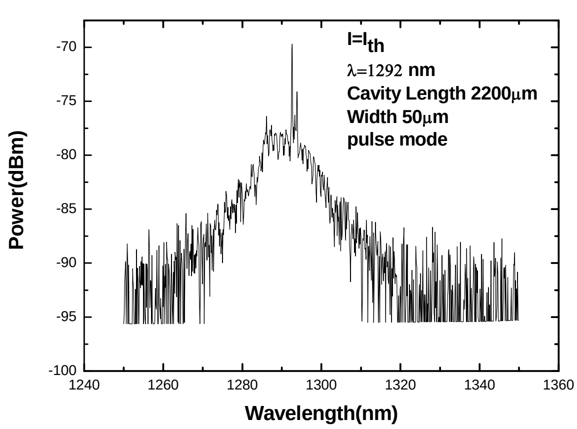

Fig. 3 Lasing spectrum of GaAsSb/GaAs SQW laser.

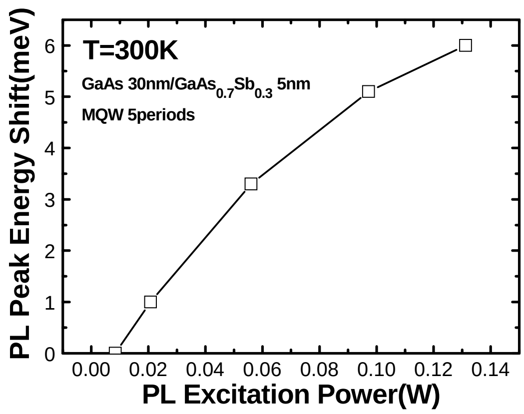

Fig. 4 Excitation power dependence of a GaAs/ $GaAs_{0.7}Sb_{0.3}$ QW PL peak energy.

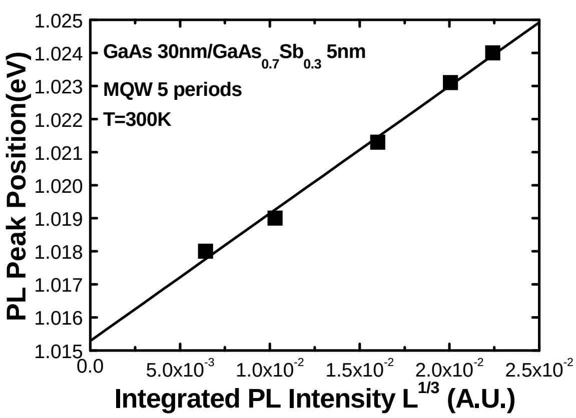

Fig. 5 $GaAs_{0.7}Sb_{0.3}$/GaAs QW PL peak position as a function of the cubic root of the integrated PL intensity.

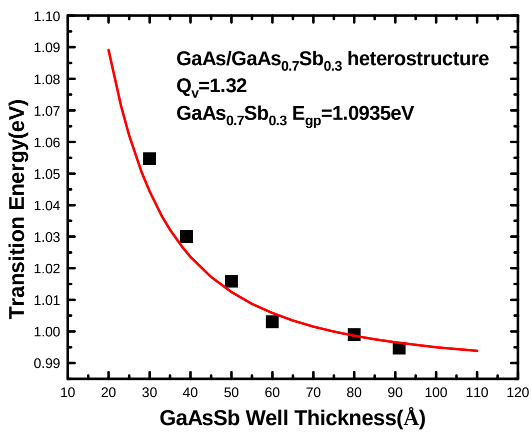

Fig.6 PL transition energy versus well thickness plot of $GaAs/GaAs_{0.7}Sb_{0.3}$ heterostructures. The fitted Q_v is 1.32.