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Long wavelength (1.3 and 1.5 μm) photoluminescence from InGaAs/GaPAsSb quantum wells grown on GaAs

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Room temperature photoluminescence at wavelengths between 1.2 and 1.5 μm has been observed in samples consisting of InGaAs/GaPAsSb quantum well structures grown on GaAs. The emission wavelength is varied primarily by changing the composition within the GaPAsSb layer. It is proposed that such long wavelength emission results from a spatially indirect interband transition in the type-II quantum wells where the electron and hole wave functions have large spatial overlap. © *1999 American Institute of Physics.* [S0003-6951(99)00235-1]

Vertical-cavity surface-emitting lasers (VCSELs) operating at 1.3 μm are desirable for low cost optical telecommunication systems and data links. Realization of these devices may enable applications such as ''fiber to the home'', which operate over distances of only a few kilometers. Due to the potentially large market for 1.3 μm VCSELs, much research has been carried out to develop devices using different approaches based primarily on two substrates, InP and GaAs. When grown using InP/InGaAsP, VCSELs have poor performance due to the high thermal sensitivity and refractive index properties of the materials.[1] One of the most promising, albeit complex, approaches has been to use wafer fusion, in which the active region grown on an InP substrate and the distributed Bragg reflectors grown on GaAs are bonded together to form the VCSEL.[2]

In order to ensure reliability and reproducibility, and to overcome the limitations of the InP/InGaAsP material system, there is interest in developing alternative structures based on GaAs, especially since GaAs-based technology is generally more advanced than that of InP. However, it is not straightforward to find materials that can be grown on GaAs with band gaps that are suitable for 1.3 μm emission. In one approach, quantum dot (QD) structures have been developed. InGaAs QDs have shown photoluminescence (PL) at 1.3 μm,[3] and a resonant cavity photodiode operating at 1.27 μm has been realized.[4] More recently, an edge-emitting QD laser operating close to 1.3 μm has also been demonstrated.[5] Room temperature (RT) PL at 1.3 μm has been observed using strained GaAsSb quantum wells (QWs) and lasing has been reported in an edge-emitting device at 1.27 μm.[6] PL wavelengths of up to 1.33 μm have also been observed in GaAsSb/InGaAs bi-layer QW samples, with a type-II band-edge alignment.[7] The approach that was able to achieve the longest emission wavelength so far in a GaAs-based VCSEL structure used a single GaInNAs QW, and RT pulsed operation was achieved with an emission wavelength of 1.18 μm.[8]

In order to avoid the limitation of the lasing wavelength being determined by the band gap of a single material, we have developed InGaAs/GaPAsSb QWs grown on GaAs. This letter describes the optical and structural characteristics of the QWs, in particular demonstrating that the peak of the PL emission spectrum can be shifted from 1.2 to 1.5 μm, depending on the composition of the GaPAsSb layer. Theoretical modeling shows that the proposed QW structure has a type-II band-edge alignment, in which the electron and hole wave functions have large spatial overlap.

A schematic of the band-edge alignment of the type-II QWs is shown in Fig. 1. The proposed structure consists of thin QWs of InGaAs and GaPAsSb for the electrons and holes, respectively, embedded in GaAs. A theoretical two-band model based on the envelope wave function approximation has been used to calculate the transition energies and overlaps between electron and hole wave functions for the type-II QW structures. The wave functions of the lowest electron energy state and the lowest hole energy state are also shown schematically in Fig. 1. The band offsets have

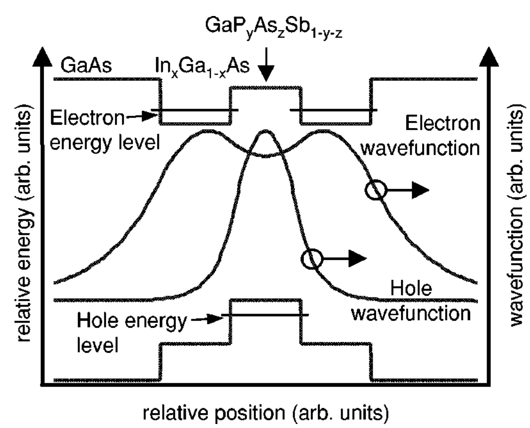

FIG. 1. Schematic band-edge diagram of InGaAs/GaPAsSb/InGaAs type-II QW embedded in GaAs. Schematic electron and hole wave functions are also shown.

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TABLE I. Room temperature transition wavelengths between electron-heavy hole and the wave function overlaps as a function of the layer thickness of the type-II QW.

	Thickness of each layer		
	15 Å	30 Å	60 Å
Transition wavelength (e-hh) (μm)	1.154	1.265	1.357
Wave function overlap (%)	75.5	63.8	37.6

been calculated using the model-solid theory[9] and the effects of strain on the band structure have also been included. Nonparabolicities for both the conduction band and the valence band have been taken into account. Table I summarizes the results obtained for different thicknesses of an $In_{0.4}Ga_{0.6}As/GaP_{0.15}As_{0.4}Sb_{0.45}/In_{0.4}Ga_{0.6}As$QW structure embedded in GaAs. For 3.0-nm-thick layers, the calculated transition wavelength is close to 1.3 μm and there is a large overlap of the electron and hole wave functions. Such a large electron-hole wave function overlap is the foundation of this structure design.

Based on these calculations, samples with QW thicknesses of approximately 3.0 nm have been grown and characterized. All samples have been grown by molecular beam epitaxy (MBE) on GaAs substrates at a growth temperature of 505 °C. The samples for PL measurements were grown on a 20-period AlAs–GaAs superlattice followed by a 220 nm GaAs buffer layer, and they were capped by a 10-nm-thick GaAs layer. The InGaAs layers of the active region were nominally 3.0 nm thick, with ~40% In composition, while the GaPAsSb layer was also nominally 3.0 nm thick. The maximum strain per layer was calculated to be less than 3%. Two samples (labeled here as A and B) with different compositions for the middle layer were chosen for further investigation. Samples containing only the GaPAsSb layer or only the two InGaAs layers separated by a 3 nm GaAs layer were also grown for comparison.

Reflection high-energy electron diffraction (RHEED) measurements were carried out during growth. These showed that both InGaAs layers displayed a transition to a faceted surface morphology, very close to the completion of the layer. It is thus expected that the first InGaAs layer has formed a rough uneven surface for deposition of the GaPAsSb layer. Deposition of the GaPAsSb layer appeared to smoothen out the growth surface, resulting in a relatively smooth surface at the end of the 3.0 nm growth on which the second InGaAs layer was then deposited.

Transmission electron microscopy observations of cross-sectional samples have been carried out to characterize the layer structure of the samples. Figure 2 shows a dark field transmission electron micrograph obtained for sample A. This image clearly shows two well defined interfaces with a separation of 9.0 nm, which is in excellent agreement with the total thickness determined from the growth rate for the InGaAs/GaPAsSb QW structure. This finding demonstrates that the as-grown sample has indeed a QW structure. The top InGaAs/GaAs interface shows a certain degree of roughness, which is consistent with the RHEED observation. However, this roughness does not provide substantial additional lateral

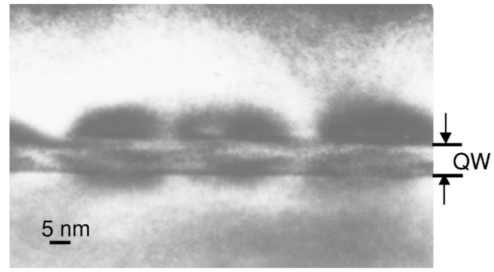

FIG. 2. Dark field electron micrograph showing cross section of an InGaAs/GaPAsSb/InGaAs QW structure. The total well region layer thickness is 9.0 nm.

quantum confinement as is the case for conventional quantum dots, in which electrons are confined in a three-dimensional dot. The interfaces between the InGaAs layers and the GaPAsSb layer are not very well defined in the electron micrographs. This is due at least partially to the lack of contrast between the different group-V element atoms. Inhomogeneous strain contrast is also visible extending into the GaAs cladding layers on either side of the QW. The strain field variations are believed to result from thickness and compositional variations within the QW itself. Electron micrographs of sample B showed undulating contrast within the QW structure, confirming these variations. High resolution lattice imaging showed no visible sign of structural defects. Chemical composition within this QW cannot be determined easily and further experiments using other characterization tools are currently under way.

Room temperature PL measurements have been performed using the 514 nm line of an argon-ion laser at excitation densities between about 40 and 1000 W/cm^2. Samples with different compositions for the GaPAsSb layer show PL emission wavelength varying over a broad range up to 1.5

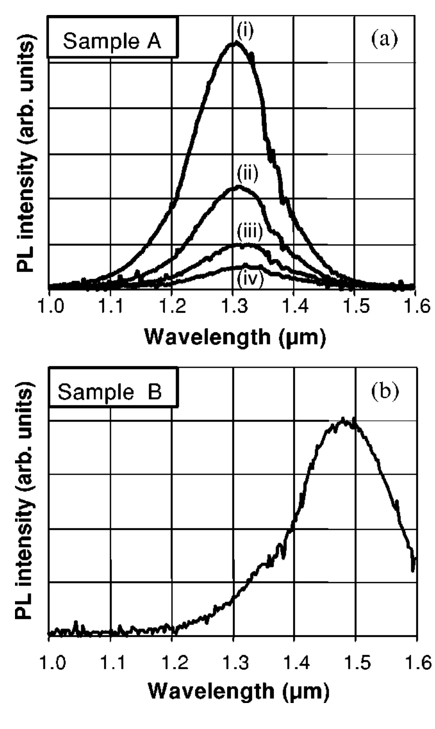

FIG. 3. Room temperature PL spectra of two different InGaAs/GaPAsSb/InGaAs QW structures embedded in GaAs. (a) Sample A at excitation densities of (i) 1000 W/cm^2, (ii) 250 W/cm^2, (iii) 100 W/cm^2, and (iv) 50 W/cm^2. (b) Sample B at an excitation density of 1000 W/cm^2.

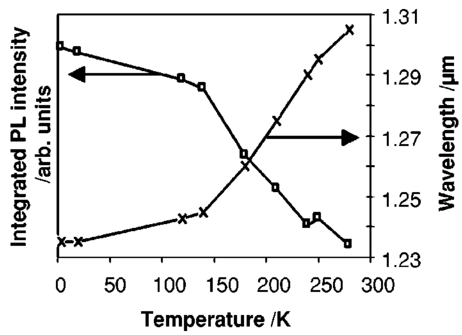

FIG. 4. Temperature dependency of the integrated PL intensity and the peak PL wavelength of sample A at an excitation density of 50 W/cm^2.

μm. Figure 3 shows the PL spectra obtained for the two samples described in this letter. For sample A, the peak of the PL spectrum was observed at 1.3 μm and the linewidth, defined as the full width at half maximum (FWHM), was measured to be 110 meV. As the excitation intensity increased, a blueshift of the PL spectrum of 13 meV was observed. For sample B, the peak wavelength was close to 1.5 μm, with a FWHM of 130 meV. These samples also displayed a long wavelength spectral tail, which is believed to be caused by compositional variations within the GaPAsSb layer. For the samples without any GaPAsSb layer, PL emission between 1.07 and 1.15 μm was observed, with no long wavelength spectral tail. No blueshift of the spectrum with increasing excitation density was seen. These results indicate that the long wavelength emission arises from a spatially indirect transition between the InGaAs and the GaPAsSb layer. At low temperature (2 K), a larger blueshift of 30 meV was observed as the excitation density was increased from 5 to 250 W/cm^2. This is primarily attributed to the band filling of lower energy states which arise from the compositional fluctuations within the GaPAsSb layer. The observed blueshift has also been seen in type-II structures.[10,11]

Temperature-dependent measurements have shown that the integrated PL intensity increases by a factor of 15 on cooling from 300 to 2 K, which is shown in Fig. 4 for sample A. This occurs primarily as the temperature is cooled to about 120 K, after which the intensity increase becomes much smaller. The spectral peak wavelength was also found to vary much less below 120 K, and increased at a rate of approximately 3.7 Å/K above 120 K. The wavelength change, together with the absolute wavelength, are best modeled by considering the temperature dependency of the electron and hole energy level shifts in a type-II band-edge aligned QW. The spectral linewidth also decreased to a minimum value of 74 meV below 120 K. The broad linewidths are believed to be dominated by the fluctuations in composition of the GaPAsSb layer and the widths of the QW layers.[12] Additional broadening mechanisms could include the strong band-filling effect in type-II structures,[13] as well as InGaAs QW asymmetry resulting from segregation in the growth direction.

In conclusion, we have demonstrated a material system grown on GaAs that is suitable for optoelectronic devices operating at long wavelength. PL emission at wavelengths between 1.2 and 1.5 μm has been achieved. Theoretical modeling has suggested that this emission is due to a type-II transition, where there is a large spatial overlap of the electron and hole wave functions.

Electron microscopy was carried out at the Center for High Resolution Electron Microscopy at Arizona State University.

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