Observation of temperature-insensitive emission wavelength in GaInAs strained multiple quantum wire heterostructures


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Band gaps of semiconductors vary with temperature and, consequently, the output wavelengths of semiconductor lasers vary with operating temperatures. In long wavelength GaInAs/InP lasers, the typical temperature sensitivity of the lasing wavelength is ~5 Å/°C. This problem can be alleviated by using a distributed-feedback (DFB) structure, which uses artificially created gratings to select and maintain the output wavelength near the band gap of the semiconductor. The temperature dependence of the lasing wavelength in DFB lasers is about 1 Å/°C.1 In this study, we report on a temperature insensitive GaIn1-xAs as heterostructure with a strained multiple-quantum-wire (MQWR) active region which could potentially be made into a laser with temperature invariant stimulated emission output.

The GaIn1-xAs strained MQWR heterostructures were grown on semiinsulating Fe-doped (100) on-axis InP substrates by solid source molecular beam epitaxy. The schematic diagram of a typical strained MQWR heterostructure has already been presented in a previous publication.2 The samples studied here have active regions that contain one to five quantum wells (QWs) separated by Al0.24Ga0.24In0.52As barriers. For samples with five QWs the barrier thickness is usually 75 Å, whereas samples that only have two or three wells have barriers that are 150 Å thick. Each QW contains eight pairs of (GaAs)2/(InAs)2 short-period-superlattices (SPS) grown at a fixed Ga/In ratio with a total thickness of 100 Å. The SPS effectively has an average bulk composition of Ga0.47In0.53As.

During the growth of GaIn1-xAs strained MQWR heterostructures, the quantum wire (QWR) active region is created in situ by the strain-induced lateral-layer ordering (SILO) process within the (GaAs)2/(InAs)2 SPS regions.3 The SILO process generates a strong Ga/In lateral composition modulation and creates In-rich GaIn1-xAs lateral QWs in the [110] direction. With the In-rich GaIn1-xAs regions surrounded by the higher band gap Ga-rich GaIn1-xAs regions on both sides in the growth plane, combined with the Al0.24Ga0.24In0.52As barriers on top and bottom in the growth direction, a strained MQWR heterostructure is formed in situ. Details of the growth conditions have been described elsewhere.4 A conventional multiple-quantum-well (MQW) heterostructure of similar structural configuration except with a lattice-matched Ga0.47In0.53As multiple QW active region has been grown for comparison.

The samples were examined by photoluminescence (PL) spectroscopy in the 77 to 300 K temperature range with an excitation intensity of about 130 W/cm2. The PL samples were mounted on a cold-finger type cryostat. The luminescence was excited using an Ar+ laser tuned to 5145 Å, dispersed in a 0.5 m focal length grating spectrometer, and detected with a liquid-nitrogen cooled Ge detector using the lock-in technique.

Figure 1 summarizes the net PL peak wavelength shifts of various GaIn1-xAs MQWR and MQW heterostructures by examining the variation of PL peaks from 77 to 300 K.

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**FIG. 1.** The 77 K photoluminescence peak wavelength of GaIn1-xAs strained MQWR heterostructures, and a MQW reference sample, plotted against the net peak wavelength shift between 77 and 300 K. The dashed line represents the best linear fit to the data. It is shown to illustrate the general trend in wavelength shift with temperature.
The structures that contain five wells have 77 K PL wavelengths that vary from 1.65 to 1.69 μm. MQWR heterostructures with three or less wells have 77 K PL wavelengths that range from 1.6 to 1.62 μm. Distinct variances in wavelength such as this result from the composition modulation created during the SILO process which is directly related to the induced strain. The induced strain is not the same for samples with differing numbers of QWs in the growth direction, thus the composition modulation and consequently the PL wavelength are different. Additionally, the data for the MQWR heterostructures in Fig. 1 shows unexpected temperature-dependent wavelength shifts from 77 to 300 K. In contrast to the normal redshift observed in the MQW reference sample, the strained MQWR heterostructures with five QWs exhibit a blueshift when warming from 77 to 300 K. However, MQWR heterostructures with three or less QWs display a negligible net shift in the same temperature range.

The PL spectra of SILO process prepared MQWR samples are compared with a MQW reference sample in Fig. 2. The 77 K linewidth in Fig. 2(a) is smaller than the 77 K linewidths shown in Figs. 2(b) and 2(c). This is due to nonuniformities in wire dimensions. The MQW reference sample has a 77 K PL peak at 1.43 μm and a 300 K PL peak at 1.53 μm, which gives a redshift in wavelength of 1000 Å at 300 K. The PL peaks originating from the Al0.24Ga0.24In0.52As waveguide regions show a wavelength shift of ~800 Å. The temperature-dependent PL spectra of two strained MQWR samples with two and five QWs are shown in Figs. 2(b) and 2(c), respectively. The PL peaks from the Al0.24Ga0.24In0.52As waveguide regions of the strained MQWR samples also show a similar wavelength shift of ~800 Å. In contrast, as can be seen in Fig. 2(b), the PL peaks at 1.6126 and 1.6112 μm, corresponding to the Ga0.5In0.5As strained QWR regions at 77 and 300 K, respectively, are relatively insensitive to temperature variation and demonstrate a net shift of only 14 Å. Thus, the net temperature dependence of the wavelength in this particular SILO process induced Ga0.5In0.5As strained MQWR active region is smaller than 0.1 Å/°C between 77 and 300 K. Furthermore, Fig. 2(c) indicates a blueshift from 77 to 300 K of 615 Å in a MQWR sample with five QWs.

To further investigate this unexpected behavior, the temperature dependence between 77 and 300 K of the MQWR heterostructures, along with that of the MQW reference sample, is examined in Fig. 3. Neither the MQWR sample that blueshifts when warming to 300 K, nor the sample with negligible net shift in the 77 to 300 K range is comparable to the near linear temperature-dependent redshift in PL peak wavelength of the MQW reference sample. Moreover, the MQWR heterostructures seem to converge to a common wavelength range at roughly 300 K despite their drastic differences in wavelength dependence on temperature from 77 up until 300 K.

In order to identify the origin of this interesting temperature dependence of PL wavelength, the various factors influencing the band-gap energy of the strained Ga0.5In0.5As MQWR heterostructures must be considered. The redshift of the band-gap energy of a semiconductor with increasing temperature is known to be mainly due to thermal expansion of the lattice constant and electron–phonon scattering. Another possibility is that under high excitation conditions, the band filling in k space will contribute a blueshift to the band-gap energy. Also, in an ideal QWR structure, due to the sharp density of states (DOS) function, it will show a weaker temperature dependence in emission wavelength. However, due to slight nonuniformities in wire size, as limited by the current fabrication technology, the sharp DOS function will be broadened and show a more quantum well-like temperature dependency. Furthermore, the magnitude of temperature effects on the band-gap energies of a biaxially strained Ga0.5In0.5As QW laser heterostructure, with a QWR active region, formed by the etch-and-regrowth process was recently investigated by Miyake et al. They observed no significant difference in temperature dependence between the QWR and the QW material. Therefore, we believe the temperature effects observed in this study do not originate from the theoretically sharp one-dimensional DOS function.
To evaluate the possible band filling effect under strong excitation, PL spectra were compared with excitation levels varied over three orders of magnitude between 1.5 and >150 W/cm². The observed weak blueshift is less than 10 meV. This result is similar to that of a dry-etched GaInAs/InP QWR structure measured at 5 K. Thus, the band filling effect does not significantly alter the band structure, and hence the emitted wavelength, of our strained GaIn₁₋ₓAs MQWR samples.

This leaves the thermal expansion effect as the most likely explanation for the temperature invariant PL spectra. At the same time, however, we must not overlook the associated multiaxial strain in the MQWR regions. As shown in Fig. 4, the strained MQWR heterostructure prepared by the SILO process possesses In-rich GaIn₁₋ₓAs wirelike regions, which not only have biaxial strain (εₓₓ and εᵧᵧ) at the [(GaAs)₁₂/(InAs)₁₂] SPS/Al₀₂₅Ga₀₂₅In₀₅₂As interfaces in the (100) planes, but also have additional biaxial strains (εₓₓ and εᵧᵧ) between the In-rich and Ga-rich GaInAs lateral QW regions in the (110) planes. Thus, as the structure is heated, the In-rich GaIn₁₋ₓAs active region tries to expand, but the surrounding Al₀₂₅Ga₀₂₅In₀₅₂As and Ga-rich GaIn₁₋ₓAs wire barriers alter this process. However, the energy shift strictly due to differences in thermal expansion coefficients using a biaxial strain model is not enough to account for temperature insensitive emission wavelengths or wavelengths that blueshift with increasing temperature. This is where the multiaxial strain in the MQWR regions must be considered. For samples with a temperature invariant PL wavelength, the changes in band gap due to each strain component must cancel out at all temperatures. This requires a strain field that is not constant, but is a function of temperature itself.

Furthermore, the strain, regardless of temperature, will modify the valence band depending on the exact strain distribution in the structure. The data presented by Miyake et al. indicate that the dependence of PL peak wavelength on temperature of a biaxially strained GaIn₁₋ₓAs QW structure is no different than what we found for our unstrained Ga₀₄₇In₀₅₃As MQW sample. This implies that the valence band deformation caused by the strain does not change the temperature dependence of biaxially strained GaIn₁₋ₓAs heterostructures.

For samples with no shift or a blueshift in PL wavelength with temperature, the amount of strain that exists in the QWR region is an important factor. A MQWR structure with five QWs that was grown at a high substrate temperature of 540 °C also shows no shift in PL wavelength from 77 to 300 K. It is known that MQWR samples grown at relatively high temperatures have less of a composition modulation. Thus, MQWR structures with one to three wells, or five wells but grown at a higher temperature, have a moderate lateral composition modulation which contributes to a band gap insensitive to temperature. This further indicates that the lateral Ga-rich GaIn₁₋ₓAs barriers are the dominant factor in determining whether or not a sample has a band gap that displays no net shift with temperature from 77 to 300 K.

In summary, photoluminescence measurements show that the emission wavelengths of some of the strained GaIn₁₋ₓAs MQWR structures formed in situ by the SILO process are relatively insensitive to temperature changes from 77 to 300 K. Additionally, there are structures which blueshift unexpectedly. Overall, this unusual but promising trend in peak PL wavelength shift is a result of the complex strain that exists in the QWR regions, which counteracts, to varying degrees, the temperature induced band-gap shift. The lateral QWR barriers are the decisive factor in determining the temperature dependence of the emitted PL spectra.

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