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The directionality of quantum confinement on strain-induced quantum-wire lasers

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Optical properties of Ga$_{0.47}In_{0.53}$As $(x \sim 0.14)$ multiple-quantum-wire (MQWR) lasers prepared by the strain-induced lateral-layer ordering process were studied. A typical ratio of threshold current density, $\sim 10$, was observed from the GaInAs MQWR lasers with contact stripes aligned to the [110] ([[110] MQWR laser) and the [110] ([110] MQWR laser) directions. The threshold current density of the [110] MQWR laser is $\sim 30\%$ lower than that of a Ga$_{0.47}In_{0.53}$As multiple-quantum-well (MQW) reference laser. The 77 K lasing wavelengths were 1.46, 1.57, and 1.69 $\mu$m for the MQW laser, the [110] and [110] MQWR lasers, respectively. This strong anisotropy of threshold current densities and lasing wavelengths is the first direct evidence of the directionality of two-dimensional quantum confinement in the MQWR structure. © 1998 American Institute of Physics. [S0021-8979(98)08706-4]

I. INTRODUCTION

In the optical gain calculation of quantum well lasers, the transition probability is proportional to the square of the scalar product of the dipole moment in the well and the electrical field of the optical wave. Due to the difference between the conduction band to heavy-hole band transition and the conduction band to light-hole band transition, a weak contact-stripe orientation dependence of optical properties was predicted and observed in quantum well lasers. In quantum wire (QWR) structures with the two-dimensional (2D) quantum confinement in the wire region, a strong anisotropic property is expected to be observed in the QWR lasers due to the directionality of the electronic dipole moment. However, no such strong anisotropy was observed in the QWR structures fabricated by the conventional etch and regrowth methods. It is reasoned that due to the limitation of the resolution of photolithography, the wire dimension fabricated by the etch and regrowth method is in the submicron-meter range, which is too large to see strong quantization effects. Additionally, due to the process-induced interface defects and nonuniformity in these methods, the quantum size effect may have been smeared out. Although, an optical anisotropy of photoluminescence was observed on a quantum-well-wire array grown on tilted substrates, no direct evidence of the anisotropic property was experimentally confirmed on the lasing characteristics. Recently, a strain-induced lateral-layer ordering (SIL0) process has been developed to grow multiple-quantum-wire (MQWR) structures with the processing-damage free inter-

faces and a smaller physical dimension. Consequently, a better optical property is expected in the SILO process prepared MQWR lasers.

In this study, we report the optical characteristics of the GaInAs MQWR lasers grown by this SILO process. A dependence of threshold current densities and lasing wavelengths on contact-stripe orientations was observed and discussed in terms of the anisotropic effect of the electronic dipole moment and the SILO process induced material composition modulation. This optical anisotropy is a first direct evidence of the existence of 2D quantum confinement in the MQWR lasers.

II. EXPERIMENT

The Ga$_xIn_{1-x}$As MQWR separate-confinement-heterostructure (SCH) lasers were grown on S-doped ($n^+ \sim 3\times10^{18}$ cm$^{-3}$) (100) on-axis InP substrates by molecular beam epitaxy. A schematic diagram of the MQWR laser structure is shown in Fig. 1. The separate confinement regions and the active region were surrounded by two 1 $\mu$m thick Al$_{0.48}In_{0.52}$As cladding layers with a 0.12 $\mu$m Be-doped ($p^+ > 1\times10^{19}$ cm$^{-3}$) Ga$_{0.47}In_{0.53}$As cap layer on the top. The bottom cladding layer is Si doped with an electron concentration of $\sim 5\times10^{17}$ cm$^{-3}$ and the top cladding layer is Be doped with a hole concentration of $\sim 7\times10^{17}$ cm$^{-3}$. The SCH waveguide regions are made of the unintentionally doped bulk Al$_{0.2}Ga_{0.2}In_{0.52}$As of 0.13 $\mu$m in thickness on each side of the active region. The active region consists of five quantum wells separated by four barriers. Each quantum well contains eight pairs of (GaAs)$_2$/(InAs)$_2$ short-period superlattices (SPL) with a total thickness of 100 Å. The barrier is the bulk Al$_{0.2}Ga_{0.2}In_{0.52}$As with a thickness of 75 Å. The SPL layers effectively have an average bulk composition.
of Ga$_{0.47}$In$_{0.53}$As. A conventional multiple-quantum-well (MQW) SCH laser of similar structural configuration except with a lattice-matched Ga$_{0.47}$In$_{0.53}$As well region was also grown for comparison. Stripe-geometry lasers with a 60 μm wide stripe and 500 μm long Fabry–Perot cavity were fabricated. Contact stripes were aligned either parallel to the [110] direction, which is perpendicular to the QWR arrays ([110] MQWR laser), or perpendicular to the [110] direction, which is parallel to the QWR arrays ([110] MQWR laser).

In the growth of Ga$_x$In$_{1-x}$As MQWR lasers, at a fixed Ga/In ratio, the SILO process generates a strong Ga/In lateral composition modulation and creates In-rich Ga$_x$In$_{1-x}$As lateral quantum wells in the [110] direction. With the In-rich Ga$_x$In$_{1-x}$As regions surrounded by the greater band-gap Ga-rich Ga$_x$In$_{1-x}$As regions on both sides in the growth plane, combined with the Al$_{0.24}$Ga$_{0.24}$In$_{0.52}$As barriers on the top and bottom in the growth direction, a MQWR heterostructure is formed in situ. Details of the growth conditions have been described elsewhere. The formation of the MQWR structure has been previously verified using the transmission electron microscopy and the polarized photoluminescence spectroscopy. The average cross-sectional area of the In-rich Ga$_x$In$_{1-x}$As region is ~150 Å × 100 Å with a lateral periodicity of ~300 Å. The In composition in the In-rich Ga$_x$In$_{1-x}$As region has been estimated to be ~67%, while it is ~33% in the Ga-rich regions. Details of these measurements can also be found in Ref. 9.

### III. RESULTS AND DISCUSSION

In this report, we will discuss the optical characteristics measured on our lasers samples from light-output versus current (L–I) curves, and electroluminescence (EL) spectroscopy. For low temperature (77 K) EL measurements, the laser diodes were mounted on a liquid-nitrogen-cooled cold-finger-type cryostat. Pulsed conditions were utilized to measure the lasing characteristics. The pulse width is 1 μs and the repetition rate is 1 kHz. Due to its extremely high threshold current, the [110] MQWR laser did not lase at room temperature. Therefore, only the 77 K data were compared at this stage.

The L–I curves measured at 77 K from the GaInAs MQWR lasers and the Ga$_{0.47}$In$_{0.53}$As MQW reference laser are shown in Fig. 2. The [110] MQWR laser reveals a threshold current density ($J_{th}$) of ~2 kA/cm$^2$, which is about 10 times higher than that of the [110] MQWR laser, which has a $J_{th}$ of ~200 A/cm$^2$. The lower $J_{th}$ was consistently measured from the MQWR lasers with contact stripes aligned to the [110] direction. The MQW laser has a $J_{th}$ of ~260 A/cm$^2$ and no such anisotropic $J_{th}$ was observed.

The corresponding 77 K EL spectra measured from all three laser diodes were shown in Fig. 3. While a lasing wavelength of 1.46 μm was observed in the Ga$_{0.47}$In$_{0.53}$As MQW laser, the 77 K lasing wavelengths were 1.57 and 1.69 μm for the [110] and [110] MQWR lasers, respectively. Such strong anisotropic properties of $J_{th}$ and lasing wavelengths have never been observed in any other laser structures. This strong anisotropy of optical properties in our strain-induced quantum-wire lasers is proposed to be resulting from the directionality of two-dimensional quantum confinement in the MQWR structures.

As shown in Fig. 4(a), in a MQW laser structure, because of the one-dimensional (1D) quantum confinement, if neglecting the conduction band to light-hole band transition, the injected carriers will form dipoles with only two components, $e_x$ and $e_y$. Assuming the conduction band to heavy-hole band transition is dominant, ideally, only the laser emission mode with the electric field parallel to either of these two dipole components (which is the transverse electrical field mode, or TE mode) will interact with injected carriers and gain contribution from the dipoles. Only when the conduction band to light-hole band transition is involved, an $e_z$
component of the dipoles will exist and lead to the possibility of a transverse magnetic field mode, or TM mode. However, the peak emission gain of the TE mode is significantly larger than that of the TM mode. Therefore, assuming the laser cavity of the MQW laser is made along the $x$ direction and neglecting the conduction band to light-hole band transition, only the $e_y$ component will contribute to the gain since it overlaps with the $E_y$ field of the TE mode emission. The same argument applies to the MQW laser with the laser cavity aligned to the $y$ direction, where only the $e_x$ component will contribute to the gain. Consequently, in a MQW laser, only half of the injected carriers can contribute to the gain of the TE mode emission if $e_x$ and $e_y$ have an equal strength. In other words, there will be no contact-stripe orientation dependency of $J_{th}$ in MQW lasers.

In the MQWR laser, as illustrated in Fig. 4(b), because of the 2D quantum confinement, the injected carriers can form dipoles with only one component, for example, the $e_y$ component. Assuming that the laser cavity is in the $x$ direction, only the $e_y$ component will contribute to the gain. Consequently, in a MQW laser, only half of the injected carriers can contribute to the gain of the TE mode emission if $e_x$ and $e_y$ have an equal strength. In other words, there will be no contact-stripe orientation dependency of $J_{th}$ in MQW lasers.

50% reduction is mainly due to the imperfect QWR structure in our MQWR lasers.

As for the lasing wavelength, since most of the injected carriers are confined in the QWR active regions, the energy band gap in those regions will determine the lasing wavelength. The active region in the $[110]$ MQWR laser is the In-rich Ga$_x$In$_{1-x}$As region formed by the SILO process. According to a previous estimation,$^9$ the In composition in the In-rich region is $67\%$, which is much higher than the In composition ($53\%$) in the lattice matched MQW laser. Therefore, although the SPS layers have an average composition equal to Ga$_{0.47}$In$_{0.53}$As, and the quantum well width is the same, the lasing wavelength of the $[110]$ MQWR laser is much longer ($\Delta \lambda \approx 2300$ Å) than that of the MQW laser with a Ga$_{0.47}$In$_{0.53}$As active region.

Conversely, the $[\bar{1}10]$ MQWR laser did not benefit from the 2D quantum confinement. In the $[110]$ MQWR laser, the direction of optical wave propagation is parallel to the $y$ direction (its $E$ field is perpendicular to the $e_y$ component), ideally, none of the injected carriers will contribute to the gain. However, due to the imperfect QWR structure, the injected carriers are not completely confined in one direction but can be scattered into other directions, consequently the $[\bar{1}10]$ MQWR laser still can lase at a very high current injection level due to the gain contribution is from the scattered carriers. This explains why the $J_{th}$ of the $[\bar{1}10]$ MQWR laser is about 10 times higher than that of the $[100]$ MQWR laser.

![FIG. 3. 77 K $E$–$L$ spectra of MQW, $[110]$ and $[\bar{1}10]$ MQWR lasers.](image1)

![FIG. 4. The directionality of quantum confinement effect in (a) quantum well (QW) structure, (b) quantum-wire (QWR) structure.](image2)
laser. As for the lasing wavelength, since the [110] MQWR laser is operating with the scattered carriers, as shown in Fig. 4(b), both TE mode and TM mode emissions can be involved. If the conduction band to light-hole band transition becomes dominant, the TM mode emission will occur at a higher emission energy due to the larger subband energy separation. A TM mode emission was observed from a GaInP MQWR laser grown by the SILO process.11 However, in this study, both the [110] and [1¯ 10] MQWR lasers showed the TE mode emission. Therefore, in our case, another factor should be considered. Due to the carriers contributing to the gain were not completely confined in the wire regions of the [110] MQWR laser, this [110] MQWR laser should act as a quantum well laser, and the average composition of the areas containing these carriers is reflected in the lasing wavelength. The observed 1.57 μm lasing wavelength of the [110] MQWR laser is in agreement with an average In composition between 53% and 70%. Additionally, since the $J_{th}$ is so high in the [110] MQWR laser, the bandfilling effect can also be a factor for the shorter lasing wavelength.

IV. CONCLUSION

In summary, due to the small wire dimensions and the process damage-free interfaces, we have been able to observe the directional effects of the 2D quantum confinement in the GaIn$_{1-x}$As MQWR lasers grown by the SILO process. The MQWR lasers showed a strong dependence of the threshold current density and lasing wavelength on the contact stripe orientation. The dependence of threshold current density on contact-stripe orientation has been explained in terms of the interactions of dipole orientations in the laser cavity and the $E$-field components of the optical field. On the other hand, the difference of lasing wavelengths is mainly a reflection of the effective material composition in the active regions of [110] and [1¯ 10] MQWR lasers where the radiative recombination occurs.

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