Design of Tensile Strained InGaAsP/InGaAsP MQW for 1.55 m Polarization Independent Semiconductor Optical Amplifier

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Abstract: The theoretical optimization of tensile strained InGaAsP/InGaAsP MQW for 1.55μm windows polarization-independent semiconductor optical amplifier is reported. The valence-band structure of the MQW is calculated by using $\boldsymbol{k}\cdot\boldsymbol{p}$ method, in which 6×6 Luttinger effective-mass Hamiltonian is taken into account. The polarization dependent optical gain is calculated with various well width, strain, and carrier density.

Key words: semiconductor optical amplifier; polarization independence; MQW

EEACC: 1220

CLC number: TN722 **Document code**: A **Article ID**: 0253-4177(2003)01-0011-07

1 Introduction

There is a growing importance for the semiconductor optical amplifier (SOA) as a key component in modern optical communication systems, covering a wide window of applications for both 1300nm and 1550nm loss-free windows of silica fiber. In addition to their utility as amplifier, the SOAs can be used in realizing optical 3R regeneration (reamplifying-reshaping-retiming) wavelength switching matrix in wavelength division multiplexing (WDM) system and wavelength converters using cross gain and phase modulation and four-wave mixing[1~4]. In these applications, dependence of the SOA gain on polarization is one of the major performance-limited factors. The polarization dependent gain comes from the different quantization levels of heavy hole (HH) band, which provides the TE mode dominant gain, and light hole (LH), which provides TM mode dominant gain. Besides, the difference in the confinement factors for TE and TM modes in the waveguide influences the difference of TE and TM mode gain.

One approach to achieving polarization independent SOA is to propose the submicron width bulk active layer with the square-shaped cross section. But this type of waveguide is complicated in fabrication. For the reasons that directed e-beam writing, narrow-stripe selective area growth (NSAG) are indispensable[5]. Although it is possible to use the low tensile-strained bulk active layer to make the waveguide with sufficiently large width[6], it is preferred for many applications to use the quantum well (QW) SOA which has a larger nonlinearity than that of the bulk SOA[7]. In order to realize a polarization independent QW SOA, several types of QW have been proposed, such as low-strained QWs[8,9], QWs with tensile-strained barriers[10], alteration of tensile and compressive QWs[11~14], and delta-strained QWs[15].

In this paper, we consider the MQW with tensile strained well and compressively strained barrier, where the compressive strain of the barrier is

Received 10 June 2002, revised manuscript received 23 August 2002

proposed to compensate the mismatch of the well. The band offsets for conduction and valence bands were obtained from the model-solid theory[16]. 6×6 Luttinger-Kohn effective-mass Hamilton based on $\boldsymbol{k} \cdot \boldsymbol{p}$ method was used to calculate the valence-band structure. The polarization dependent optical gain was calculated with various well width of 6, 8, 10nm, various strain of −0.2%, −0.25%, −0.3%, and −0.35%, and various carrier density from $1.1\times10^{18}cm^{-3}$ to $2.0\times10^{18}cm^{-3}$.

2 Valence band structure of tensile strained MQW

Optical gain in bulk is insensitive to the polarization of the optical field due to the degeneracy of the heavy hole and the light hole bands in the valence band at the band edge. In quantum well structure, this degeneracy is removed and the bands are quantized in both the conduction band and the valence band. The predominant contribution to the optical gain for TE polarization comes from the stimulated transitions between the conduction band and the HH band, whereas the optical gain for TM polarization is due to the transition between the conduction band and the LH band. Introduction of the tensile strain in the quantum well shifts the HH band downwards and the LH band upwards, and also reduces the bandgap. By a suitable choice of tensile strain, optical gain of both polarizations can be equalized. Figure 1 shows the energy bands of the valence bands of three kinds of strained InGaAsP/InGaAsP MQW, where the strains of the well are 0, −0.15%, and −0.35%, respectively. The hydrostatic deformation potentials of the QW have not been taken account because they only shift the whole energy band structure and do not affect the relative positions of the subbands. In matched quantum well, the heavy hole band is brought to the top of the subband by the quantum confinement effect. The first LH subband locates much below the first HH band, as shown in Fig. 1(a). When small amount of tensile strain, such as −0.15%, is introduced in the QW, the first HH band appeared on the top of the subband, but the first LH band is close to the first HH band due to the tensile strain effect, as given in Fig. 1(b). When large amount of the tensile strain, −0.35%, is introduced in the QW, the LH band shifts to another place, even surpasses the first HH band, as indicated in Fig. 1(c).

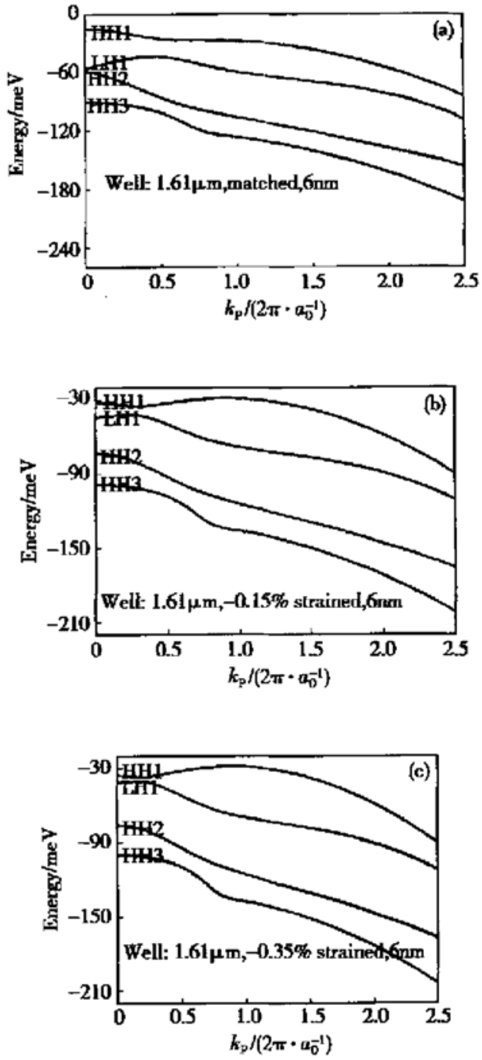


Fig. 1 Relative position of HH and LH subband in quantum well (a) Matched well; (b) −0.15% strained well; (c) −0.35% strained well

3 Structure of tensile strained MQW SOA

The tensile strained MQW investigated in this paper consisted of 6 periods InGaAsP/InGaAsP quantum wells. The bandgap wavelength of the well was 1.6μm, and the width of the well was 6, 8, 10nm. The strain was − 0.2%, − 0.25%, − 0.3%, and − 0.35%. The bandgap wavelength of the barrier was set to 1.18μm, the width was 10nm firmly, the strain of the barrier was set to 0.15% for compensation of the strain. Polarization dependent optical confinement factors for the SOA waveguide were calculated by solving 1-D 5 layers symmetric waveguide problem for TE and TM polarizations[17]. The MQW active layers were sanwitched by two InGaAsP layers with 1.20μm bandgap wavelength, the width was 100nm each. The upper and lower cladding layers were infinitely long InP. The ratio between the calculated TM and TE confinement factor was 0.66.

$$G_{TE,TM} = 10L[\Gamma_{TE,TM}\, g(\omega)_{TE,TM} - \alpha_i]\lg e \quad (1)$$

The SOA TE and TM signal gains that were used for evaluating the SOA polarization sensitivity were defined as follows[18]:

Γ: optical confinement factor;

$g(\omega)$: optical gain;

L: SOA length;

α_i: loss in the SOA.

For our anlysis, L = 1mm and α_i = 5cm^{-1}, and the SOA facet reflectivity was assumed to be zero for the type of travelling wave.

4 Mode gain of strained MQW with various parameters

Figure 2 shows the polarization sensitivity of the different tensile strained InGaAsP/InGaAsP MQW with various well widths, where the injected carrier density was firmly set at 1.6 × 10^{18}cm^{-3}. The polarization sensitivity varied with both well width and strain. There is an optimal well width for different strain. From Fig. 2(a), one could see that a 10nm well width was suitable for − 0.2% strain. The ± 1dB range of ΔG for this type of structure was from 1.42μm to 1.62μm. When the strain of the well was − 0.25%, the optimal width was 8nm. The ± 1dB range of ΔG for this type of structure was similar with that of the structure of 10nm, − 0.2% strain, which was indicated in Fig2(b). The polarization mode gain difference of − 0.35% strain was shown in Fig. 2(c). There was a wide range of polarization insensitive mode gain shown for 6nm width.

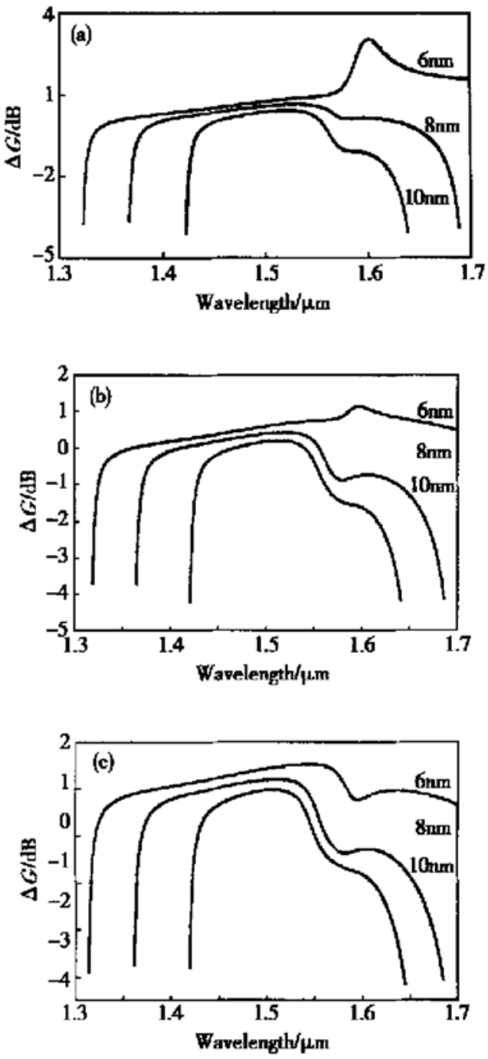


Fig. 2 Polarization sensitivity of MQW SOA with various well width and strain (a) − 0.2% strained; (b) − 0.25% strained; (c) − 0.35% strained

Figure 3 shows the TE and TM modal gain of 10, 8, 6nm well width with various strains of − 0.2%, − 0.25%, − 0.3% and − 0.35%. The modal gain spectra of different well width had same trend. With the increase of the amount of the tensile strain, the optical momentum element in $x-y$ plane, which corresponded to the TE mode optical transition, did not change much. The optical momentum along z direction, which corresponded to TM mode optical transition, increased with the increasing of the amount of the tensile strain. As a result, the intensity of the peaks of the TE modal gain spectra did not modify with the amount of strain, while the intensity of the TM modal gain spectra enhanced significantly with the increase of strain, which was indicated in Fig. 3. When tensile strain was introduced to the well, the shear deformation potential put the HH subband which dominated the TE mode transition downwards, and put the LH subband which dominated the TM mode transition upwards. When the amount of the tensile strain increased, this shift was enforced. So the peak wavelength of TE modal gain spectra shifted to the short band, and the peak wavelength of TM modal gain spectra shifted to the long band. The intensity of modal gain of TE mode and TM mode of tensile strained MQW increased with the decreasing of the well width with the same strain, as shown in Fig. 3. When the well width decreased, the quantum confinement of electron and hole enforced, the joint state density of electron and hole and optical transition strength increased. Consequently, the intensity of gain increased with the decrease of well width.

From the analysis above, 6nm, − 0.35% strained well, 10nm and 0.15% strained barrier were chosen as the optimal structure of polarization insensitive SOA materials, which well agreed with the results of Ref. [12].

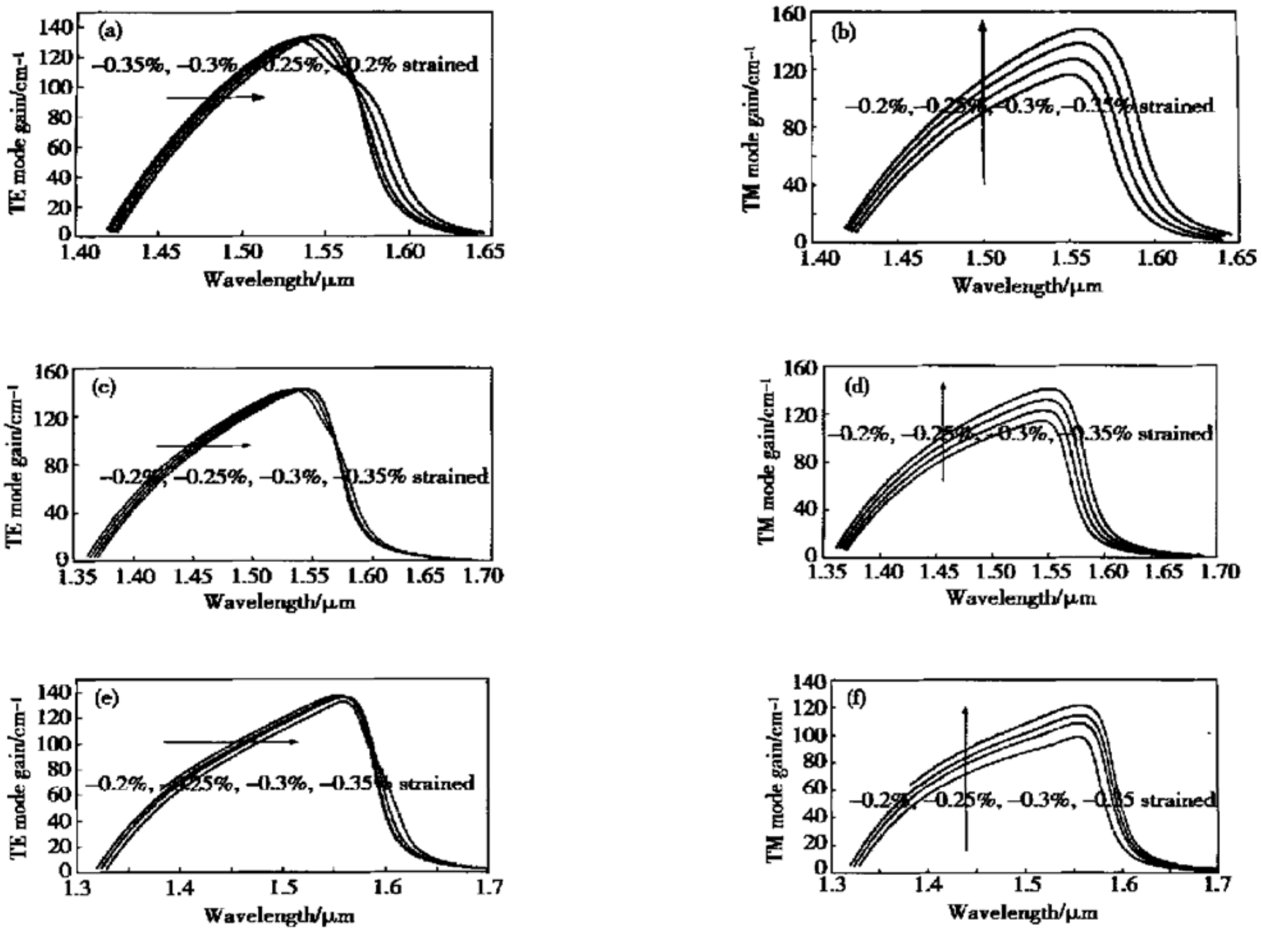
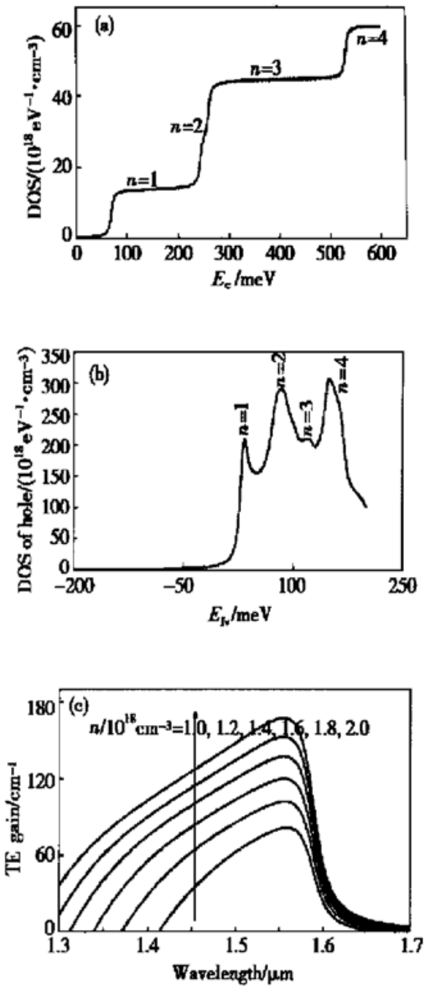
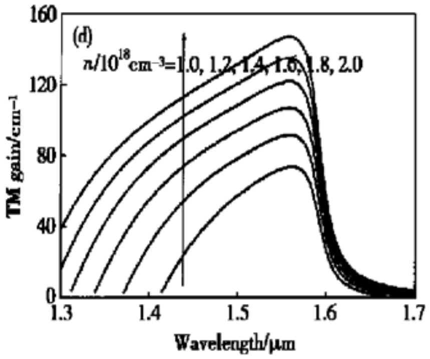


Fig. 3 TE and TM mode gain of different well width with various strain (a) TE modal gain of 10nm well width; (b) TM modal gain of 10nm well width; (c) TE modal gain of 8nm well width; (d) TM modal gain of 8nm well width; (e) TE modal gain of 6nm well width; (f) TM modal gain of 6nm well width

5 Modal gain characteristics of optimized tensile strained MQW structure for polarization insensitive 1.55 m SOA

Figure 4 shows the characteristics of optimized MQW structure with 6nm, − 0.35% strained well and 10nm, 0.15% strained barrier. Figure 4(a) shows the density of state of electron (DOS). The step-like profile of DOS was demonstrated due to quantum confinement effect. Unlike the DOS of electron, the DOS of the hole did not show step-like for the reason that there was valence band mixing effect in the strained MQW, as could be seen in Fig. 4(b). Figure 4(c), (d) and (e) shows the TE, TM modal gain, modal gain polarization sensitivity at various injected carrier densities from $1.0\times10^{18}\,cm^{-3}$ to $2.0\times10^{18}\,cm^{-3}$, respectively. A wide ±1dB range of modal gain polarization sensitivity from 1.4μm to 1.62μm at carrier density from $1.0\times10^{18}\,cm^{-3}$ to $2.0\times10^{18}\,cm^{-3}$ was demonstrated in Fig. 4(e).





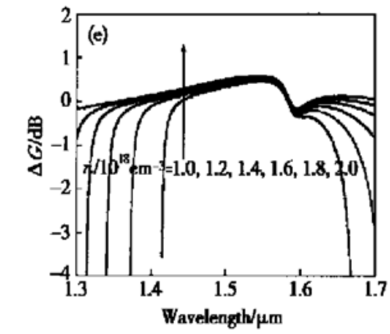


Fig. 4 Characteristics of the optimized MQW structure (a) Density of state of electron; (b) Density of state of hole; (c) TE modal gain of the optimized MQW with various carrier density; (d) TM modal gain of the optimized MQW with various carrier density; (e) Polarization sensitivity of the optimized MQW

6 Conclusion

In this paper, the valence band structures of InGaAsP/InGaAsP MQW were calculated by using ***k*·*p*** method, in which 6×6 Luttinger effective-mass Hamilton was taken into account. The polarization dependent optical gain was calculated with various well width, strain, and carrier density. The optimized MQW structure was obtained. The width, strain and bandgap wavelength of well were 6nm, − 0.35%, and 1.61μm, respectively; and the width, strain, and bandgap wavelength of barrier were 10nm, 0.15%, and 1.18μm, respectively. A wide ±1dB range of modal gain polarization sensitivity from 1.4μm to 1.62μm at carrier density from $1.0\times10^{18}cm^{-3}$ to $2.0\times10^{18}cm^{-3}$ was demonstrated of this structure of MQW.

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1.55 m 张应变 InGaAsP/InGaAsP 量子阱偏振不灵敏半导体光放大器的优化设计

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摘要: 优化设计了 1.55μm InGaAsP/InGaAsP 张应变量子阱偏振不灵敏半导体光放大器的结构. 利用 $\boldsymbol{k}\cdot\boldsymbol{p}$ 方法计算了多量子阱的价带结构, 计算中考虑了 6×6 有效质量哈密顿量. 从阱宽、应变、注入载流子密度等方面计算了量子阱模式增益的偏振相关性.

关键词: 半导体光放大器; 偏振不灵敏; 多量子阱
EEACC: 1220
中图分类号: TN722 **文献标识码**: A **文章编号**: 0253-4177(2003)01-0011-07

2002-06-10 收到, 2002-08-23 定稿