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InAsP/InGaAs composite quantum well for separate TE and TM gain

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Composite InAsP/InGaAs quantum wells are a promising candidate for realizing polarization-independent semiconductor optical amplifiers at 1.55 μm . We investigated the possibility of 8 nm tensile-strained InGaAs well surrounded by two compressively-strained InAsP layers, for achieving separate gain for TE and TM polarized light. The InAsP layers provide strain compensation while simultaneously shifting the band gap to 1.55 μm . The edge photoluminescence spectra shows that the gain for TE and TM polarized light is in the order of (3:1). © 2006 American Institute of Physics. [DOI: 10.1063/1.2172709]

Wavelength division multiplexing and time domain multiplexing applications required semiconductor optical amplifiers. The main difficulty in semiconductor optical amplifiers (SOAs) fabrication is to form a polarization insensitive structure. In recent years, there has been a great deal of interest in multiple quantum well structures based on band-filling effect for all optical devices.¹ Multiple quantum wells are potential candidates for optical amplifiers because of its high quantum efficiency, low power consumption, and compactness. In these structures stimulated transition from the conduction band to the heavy-hole band provide TE gain where as that of the light-hole band provides the TM gain. The relative orientation of heavy-hole and light-hole can be adjusted by adjusting the strain. Hence the polarization depended gain can be adjusted. Tiemeijer *et al.*² reported polarization independent quantum well SOAs which can operate at the 1.3 μm region. Newkirk *et al.*³ reported an extended design to operate the amplifier at 1.55 μm . In This design the TM gain is provided by a 1% tensile strained quantum well structure. The tensile and compressive strained layers provide strain balancing, which is an additional advantage in this structure. However, the effective confinement of electron in the 16 nm quantum well is very small, resulting in bad temperature behavior. There are reports of using strained quantum well for TE gain and a tensile strained barrier for TM gain^{4–6} or a tensile strained quaternary active layer.⁷ Both these structures lack the advantage of Tiemeijer design, which optimized the quantum wells for TE and TM gain. Later Haverkort *et al.*⁸ theoretically calculated the gain in InAsP/InGaAs composite quantum well at the 1.55 μm region. This quantum well structure has advantage of separately optimizing TE and TM gain without the disadvantages of Newkirk *et al.* The separate confinement of electron and holes in InAsP/InP/InGaAs quantum well is experimentally investigated by Aneeshkumar *et al.*⁹

In the composite quantum well structure proposed by Haverkort *et al.*, TM gain is provided by a composite InAs_{0.6}P_{0.4}/In_{0.35}Ga_{0.65}As/InGaAsP quantum well. Compressively strained In_{0.68}Ga_{0.32}As quantum well provides

the TE gain. The polarization dependence of InGaAs/InP multiple quantum well is investigated in Dorren *et al.*¹⁰ In this letter we concentrate on the InAs_{0.6}P_{0.4}/In_{0.35}Ga_{0.65}As/InGaAsP part that provides the TM gain. The quantum well structure is schematically depicted in Fig. 1. In the 8 nm 1.25% tensile strained InGaAs layer, in the composite quantum well structure, the light hole level is upper. Hence this structure provides TM gain. Due to the large conduction band offset of the InAsP, the 1.8 nm InAs_{0.6}P_{0.4} layers do not change the valence band structure too much. Hence the holes are primarily confined in the InGaAs well. The electrons are confined in a coupled three well structure consisting of two, outer compressively strained InAs_{0.6}P_{0.4} well and the central In_{0.35}Ga_{0.65}As wells. Since the polarization property depends on the relative orientation of the heavy hole and light hole position, polarization dependence in this structure can easily be tuned by adjusting the tensile strain in InGaAs quantum well. Combination of ten-

FIG. 1. Band structure of the InAs_{0.6}P_{0.4}/In_{0.35}Ga_{0.65}As/InGaAsP quantum well. Dotted lines show the light hole band. Lower solid lines represent heavy hole band and upper solid line represents the conduction band.

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FIG. 2. Theoretical (solid) and experimental (points) curves showing the band gap variation with arsenic composition in a 4 nm InAsP/InP quantum well at 4 K.

sile strained InGaAs quantum well and compressively strained InAsP quantum well produces a strain balanced structure. The purpose of our investigation is to measure ratio of TM to TE gain in the composite quantum well structure.

Theoretical investigation of the composite quantum wells shows a clear advantage of the structure over the conventional structures.⁸ The peak TM gain is high for tensile strained quantum wells with more than 1% tensile strain and rapidly decreases for smaller tensile strain. For compressively strained quantum wells, the peak TE gain also increases as a function of the strain. Also it is impossible to realize high TM gain at or above 1.55 μm with a conventional quantum well. However, composite quantum well easily allows tuning the peak TM gain wavelength above 1.55 μm .

InAs_xP_{1-x}/InP is a less investigated material for device application in the 1.55 μm region. In particular the large conduction band-offset ratio is expected to provide a novel opportunity for device design. Relatively few studies have been performed to the pseudomorphic InAs_xP_{1-x}/InP system. High quality InAsP/InP multiple quantum wells has been grown by chemical beam epitaxy. The photoluminescence (PL) measurements show a wide tunability of the band gap by changing the strain by changing the composition. All material parameters of InAsP can be approximately obtained by linear interpolation of the InAs and InP parameters.¹¹ Good agreement between the measured band gap and the interpolated values are obtained as shown in Fig. 2. The InAs interface layers which in particular appear at high arsenic concentration, greatly influence the transition energies especially in narrow quantum wells. This effect is not incorporated in our theoretical calculations that make a deviation from the experimental observation.

In this report we focused on the tensile strained quantum wells, which are used for TM gain for extending the Tiemeijer design to 1.55 μm . Our goal is to design a quantum well structure for TM gain at 1.55 μm , which does not approach the critical layer thickness. For this purpose we first investigated the 1.8 nm InAsP/InP quantum wells, which are reported to have a conduction band offset as large as 0.70 ± 0.02 for arsenic composition between 0.25 and 0.65. Even though, the band gap of InAsP/InP falls in 1.33 μm , this offset ratio is essentially helpful to shift the Tiemeijer design to 1.55 μm for TM gain as explained in the Haverkort design.⁸ The PL spectra of 1.8 nm InAsP/InP multiple quan-

FIG. 3. Photoluminescence spectra of 1.8 nm InAsP/InP for different arsenic composition at 4 K.

tum wells are for three different arsenic compositions are depicted in Fig. 3.

Since we are only interested in the relative ratio of TE and TM polarization, we used cleave side photoluminescence measurement, rather than a direct gain measurement. The multiple quantum wells of InAs_{0.6}P_{0.4}/In_{0.35}Ga_{0.65}As/InGaAsP, used for cleave side photoluminescence measurement, were grown by chemical-beam epitaxy on the InP substrate. At the Ga_xIn_{1-x}As/InP interface the conduction band to valence band offset ratio is assumed to be 40:60¹² and at the InAs_xP_{1-x}/InP interface is 70:30.¹¹ This reverse offset ratio provides a separate confinement for electron and holes in this structure. The cleave side PL measurements were done at different temperatures varying from 4 K to 225 K, in a He-flow cryostat. Samples were excited using a 532 nm second harmonic from an Nd:Yag laser and the estimated excitation density was 300 mW/cm². The front side sample is excited and the signal is collected from the cleave edge. The sample is placed as perpendicular as possible so that we can collect the signal in a small divergent angle. This will avoid the error in the variation of the Fresnel coefficient. The signal is passing through a polarizer, so that we can collect either the TM or TE. Then it is depolarized with a babinet depolarizer and detected. The circular polarization after the babinet plate is confirmed with a sec-

FIG. 4. Polarization dependent cleave side photoluminescence spectra of InAsP/InGaAs composite quantum well at different temperatures.

ond polarizer in front of the depolarizer. Figure 3 shows the cleave side PL spectra for four different temperatures. The TM:TE spectra shows an approximately 3:1 ratio for all temperatures.

In conclusion, we have demonstrated the selective TM gain in a InAsP/InGaAs composite quantum well structure. Polarization property of the structure can be easily tuned by adjusting the strain in the InGaAs well. The compressively strained the InAsP and tensile strained InGaAs make a simple strain balance structure (see Fig. 4). This is a unique advantage of the composite quantum well in addition to the 1550 nm wavelength performance. The degree of polarization of the PL from the cleave side shows that this sample demonstrated has a ground state of lh in character. The result of this measurement is in good agreement with the theoretical prediction of Haverkort *et al.*, even though the observed TM/TE ratio is only approximately 3:1. The signal shows a circularly polarized nature after the Babinet depolarizer. The difference from the expected ratio (3:1) may be because of the difference in the structure coated. The investigations of the SQWs also confirm this.

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