Compensation of Internal Thermal Stresses in InGaAsP/InP Lasers for Polarization Stabilization

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Abstract—Internal thermal stresses in the active layer of a conventional InGaAsP/InP laser may cause polarization instabilities which normally do not exist in conventional AlGaAs/GaAs lasers. We analyze a structure with a buffer layer for polarization stabilization by compensation of the internal thermal stresses in InGaAsP/InP lasers. Stress analyses are carried out for various structures to obtain the conditions for optimal stress-free structures. The effects of stresses from external sources are also discussed.

I. Introduction

Conventional InGaAsP/InP laser structures, including the planar buried heterostructure and the buried crescent heterostructure, consist of a thin InGaAsP active layer sandwiched between InP cladding layers on a thick InP substrate. In these structures, the internal stress caused by lattice mismatch and the differential thermal expansion exists mostly in the thin InGaAsP active layer. The stress is larger for lasers operating at longer wavelengths because of a larger compositional mismatch between the active layer and the surrounding InP layers which results in a larger difference in the thermal expansion coefficients. Under usual LPE growth conditions, this stress tends to be tensile along the junction plane ($\sigma_{xx} > 0$) at room temperature. For lasers operating in the wavelength range from 1.3 to 1.55 μm for optical communications, the tensile stress σ_{xx} is usually on the order of 10^8 dyne/cm^2.

Semiconductor lasers normally operate in the TE mode (electric field parallel to the junction) because of the higher mirror reflectivity of the TE mode compared to that of the TM mode (electric field normal to the junction). It has been shown that the TM mode can be induced by applying on the active layer an *uniaxial compressive pressure normal to the junction* [1], [2] which lifts the degeneracy of the valence bands and thereby changes the relative contribution of the light and heavy hole interband transitions [2]. The same effect can be caused by an *internal tensile stress along the junction plane* in the active layer of a double heterostructure laser [3]-[6].

Our analysis shows that [7] a net tensile stress on the order of 10^8 dyne/cm^2 in the active layer will induce sufficient lattice deformation to promote the TM mode gain large enough to compete with the normal operating TE mode. This results in some undesirable characteristics of InGaAsP lasers. First,

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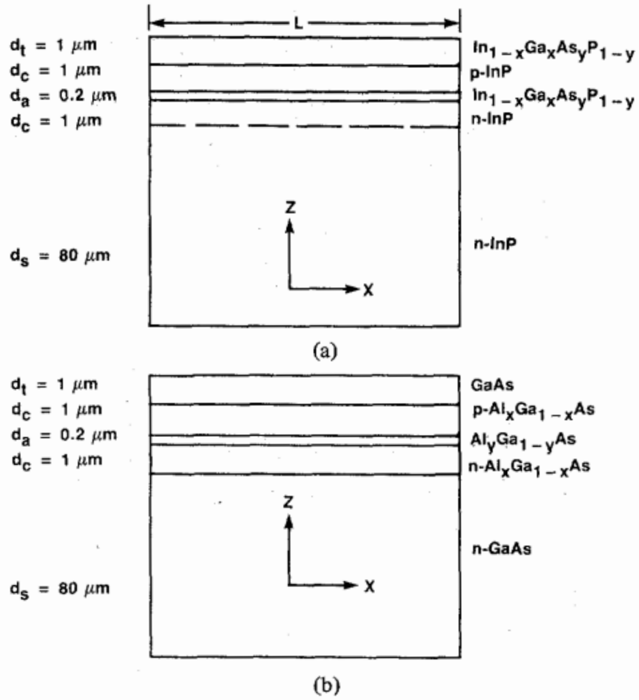

Fig. 1. Schematic structure of (a) a typical conventional InGaAsP/InP laser and (b) a typical conventional AlGaAs/GaAs laser.

an InGaAsP/InP laser may change polarization with the temperature due to thermal stress in the active layer. In fact, some InGaAsP/InP lasers are observed to operate in a mixture of TE and TM modes even at room temperature under normal operating conditions. Furthermore, at high injection currents, kinks in the power-current characteristics associated with the appearance of higher order TM modes are observed in some InGaAsP/InP lasers [6]. These kinks are caused by a combination of several effects. However, the stress in the active layer worsens the problem. These problems do not exist in conventional AlGaAs/GaAs lasers with thin active layers because of their structural differences, as can be seen in Fig. 1(a) and (b). The thermal stress in the active layer of an AlGaAs/GaAs laser induced by the thin cladding layers is compressive in the wavelength range from 8000 to 8500 Å. Such compressive stress enhances the gain of the TE mode. In the longer wavelength range, the stress becomes tensile. However, the stress in the active layer of an AlGaAs/GaAs laser is always largely offset by the thick GaAs substrate whose composition is similar to that of the active layer.

We propose in this paper an improved InGaAsP laser structure with an InGaAs buffer layer which drastically reduces the tensile stress in the active layer and thus eliminates the possibility of the TM emission. When the thickness of the buffer layer and the substrate are optimized, the active layer can be stress-free at *all temperatures.* This is a very significant improvement as the laser will no longer exhibit polarization instabilities caused by environmental temperature changes and/or injection current changes. Release of the stress in the active layer will also increase the life expectancy [8] and lower the threshold current of the laser [2]. Furthermore, our new structure allows fine tuning, after growth of the entire wafer, to achieve the stress-free condition by thinning the substrate to an optimal thickness.

II. Stress Analysis

It is generally true for conventional buried heterostructure lasers that the laser cavity length L is much (about 50–100 times) larger than the active region stripe width W. Therefore, the stress problem in this structure can be reduced to a one-dimensional one. Fig. 1(a) shows the schematic multilayer structure of a typical conventional InGaAsP/InP laser. The stress in the active layer caused by thermal strain in the multilayer structure is calculated using the generalized formula in [9]. Throughout our analysis, we take the growth temperature to be 650°C and the difference between the growth temperature and room temperature to be -630°C. The thermal expansion coefficients of $In_{1-x}Ga_xAs_yP_{1-y}$ lattice-matched to InP have been measured [10] for $y = 0, 0.6$, and 1 only. They are $\alpha = 4.56 \times 10^{-6}/°C$ for InP ($y = 0$), $\alpha = 5.42 \times 10^{-6}/°C$ for $In_{0.74}Ga_{0.26}As_{0.60}P_{0.40}$ ($y = 0.6$, $\lambda = 1.30$ μm), and $\alpha = 5.66 \times 10^{-6}/°C$ for $In_{0.53}Ga_{0.47}As$ ($y = 1$). For other compositions, we assume $\alpha(y) = (4.56 + 1.266y) \times 10^{-6}/°C$, varying linearly with y [11]. The Young's modulus, E, does not vary much with y. Throughout the calculations, we assume a (100) substrate and take a constant effective [12] $(E/1 - \nu)_{(100)} = 9.487 \times 10^{11}$ dyne/cm^2, where ν is the Poisson's ratio. The positive values of the stress σ_{xx} in the active layer are tensile along the junction plane, which corresponds to a negative lattice mismatch ($\sigma_{xx} = 10^8$ dyne/cm^2 corresponds to $\Delta a/a \simeq -10^{-4}$) and a lattice deformation in the active layer with a lattice constant normal to the junction smaller than that along the junction.

In order to grow good expitaxial layered structures for laser devices, it is crucial to control the LPE growth conditions so that the layers are close to perfect lattice-matching at the growth temperature (typically 600 to 650°C). However, because the $In_{1-x}Ga_xAs_yP_{1-y}$ material has a larger thermal expansion coefficient than that of InP, it is possible to have perfect lattice-match and stress-free conditions at only one temperature in the temperature range from the growth temperature to the device operation temperature. The upper part of Fig. 2 shows the stress σ_{xx} at room temperature for the structure in Fig. 1(a) as a function of the As content, y, in the active layer, assuming perfect lattice-matching at the growth temperature 650°C. If a lower temperature between the growth and the device operation temperatures is chosen for perfect lattice-match, as is usually done to compromise the

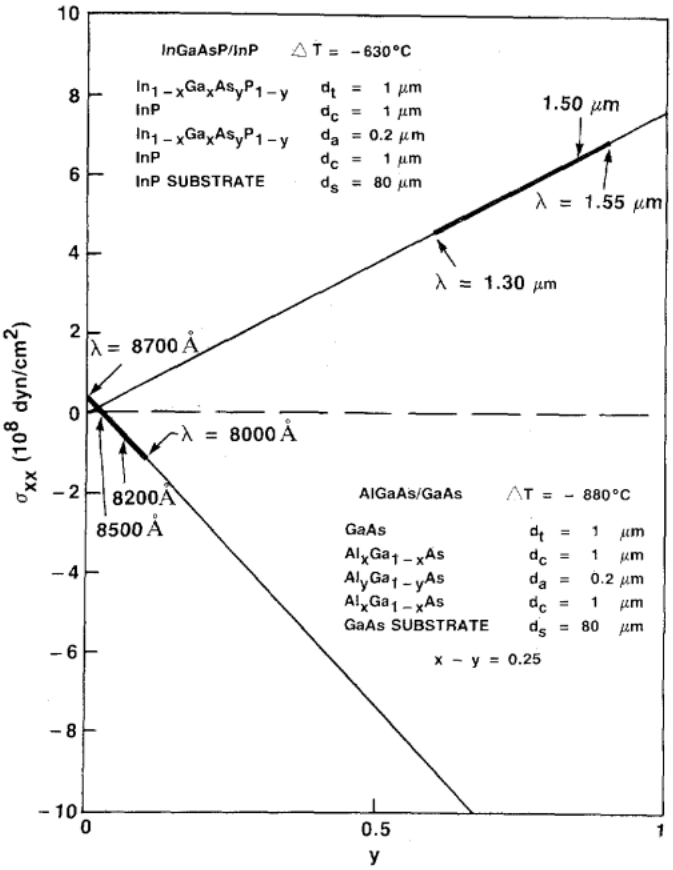

Fig. 2. Active layer stress at room temperature for the structures of Fig. 1, grown under perfect lattice-matching conditions at 650°C and 900°C for InGaAsP/InP and AlGaAs/GaAs, respectively. y refers to the As content in the cladding layers of the InGaAsP/InP structure and the Al content in the active layer of the AlGaAs structure, respectively.

matching requirements at the two extreme temperatures, the tensile stress in the active layer can be reduced linearly. However, under usual LPE growth conditions, the stress σ_{xx} in lasers in the wavelength range from 1.3 to 1.55 μm for optical communications is usually tensile and on the order of 10^8 dyne/cm^2.

In order to show the difference between an InGaAsP/InP laser and an AlGaAs/GaAs laser, we also perform a stress analysis for a typical conventional AlGaAs/GaAs laser structure in Fig. 1(b), which has the same corresponding layer thicknesses as the InGaAsP/InP structure in Fig. 1(a). We take the growth temperature to be 900°C and the difference between the growth temperature and room temperature to be -880°C. Because GaAs and AlAs have a perfect lattice-match at 900°C [13], [14], the AlGaAs/GaAs structure is always grown perfectly lattice-matched at the growth temperature. The thermal expansion coefficients are $\alpha = 6.78 \times 10^{-6}/°C$ [13], [14] for GaAs and $\alpha = 5.2 \times 10^{-6}/°C$ [13] for AlAs. For the ternary compositions, $Al_yGa_{1-y}As$, we assume a linear function $\alpha(y) = (6.78 - 1.58y) \times 10^{-6}/°C$. We also assume a (100) GaAs substrate and take a constant effective [12] $(E/1 - \nu)_{(100)} = 12.39 \times 10^{11}$ dyne/cm^2 throughout the calculations. The composition difference between the cladding layers ($Al_xGa_{1-x}As$) and the active layer ($Al_yGa_{1-y}As$) is kept at $x - y = 0.25$. The calculated stress σ_{xx} at room tem-

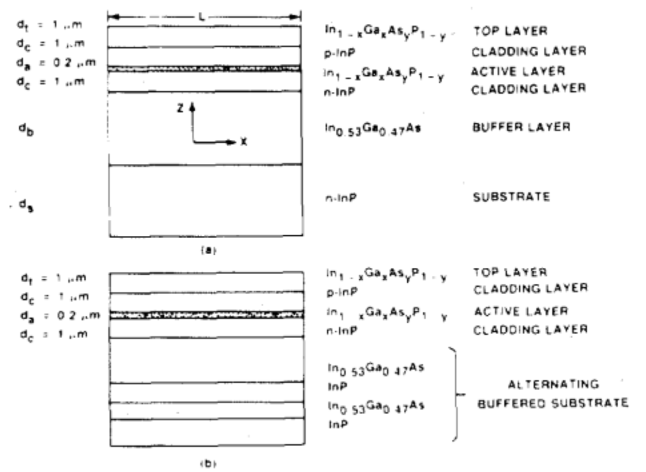

Fig. 3. (a) Improved InGaAsP/InP laser structure with an InGaAs buffer layer. (b) Buffered InGaAsP/InP laser structure with alternating InGaAs and InP layers.

perature for the AlGaAs/GaAs structure in Fig. 1(b) is shown in the lower part of Fig. 2 as a function of the Al content y, in the active layer. Substantial differences between the InGaAsP/InP and the AlGaAs/GaAs structures can be seen in the active-layer stresses in Fig. 2. This is because the relationship among the layers in an AlGaAs/GaAs structure is completely different from that in an InGaAsP/InP structure. Unlike the case of the InGaAsP/InP structure, most of the stress in the AlGaAs/GaAs structure exists in the cladding layers rather than in the active layer. Therefore, a typical AlGaAs/GaAs laser is not subject to the problem of stress-induced polarization instabilities. To our knowledge, internal-stress-induced TM emission was found only in AlGaAs/GaAs lasers with very thick (>10 μm) cladding layers [3].

III. Stress Compensation

We propose a buffered DH InGaAsP/InP structure, shown in Fig. 3(a), for compensation of the tensile stress in the active layer. $In_{0.53}Ga_{0.47}As$ is suggested as the material for the buffer layer for two practical reasons: 1) it has the largest thermal expansion coefficient among $In_{1-x}Ga_xAs_yP_{1-y}$ materials; and 2) by controlling lattice-matching conditions at growth temperature, a thicker misfit dislocation-free $In_{0.53}Ga_{0.47}As$ layer can be grown on (100) InP substrate than other $In_{1-x}Ga_xAs_yP_{1-y}$ layers [15]. The stress σ_{xx} at room temperature for a laser at 1.3 μm ($y = 0.6$) grown under perfect lattice-matching conditions at 650°C is shown in Fig. 4 as a function of the substrate thickness, d_s, for several thicknesses, d_b, of the buffer layer. Without the buffer layer, the structure reduces to the conventional structure shown in Fig. 1(a). In this case, Fig. 4 shows that if the structure is grown stress-free at the growth temperature, a large tensile stress, almost independent of the substrate thickness, always exists in the active layer. When a buffer layer of reasonable thickness is introduced, it is obvious from Fig. 4 that it is always possible to optimize the substrate thickness, by thinning, for example, so that the active layer is stress-free both at the growth temperature and at room temperature. As a matter of fact, the active layer is stress-free at all temperatures in this optimized

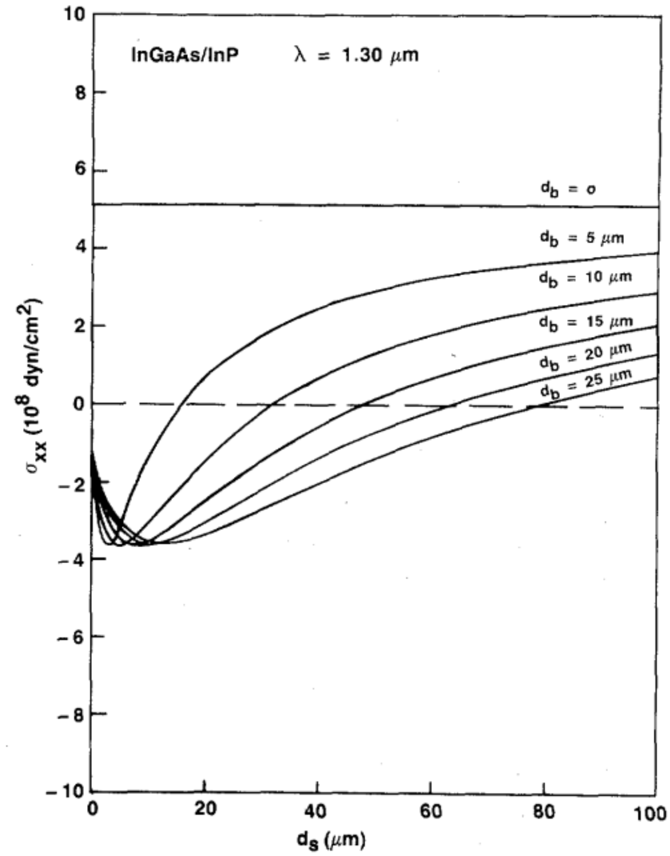

Fig. 4. Active layer stress at room temperature for a laser at 1.3 μm ($y = 0.6$) with the structure of Fig. 3, grown perfectly lattice-matched at 650°C, as a function of the substrate thickness for several thicknesses of the buffer layer.

condition, which is never possible for the structure without the buffer layer, as illustrated in Fig. 5.

The thickness of the buffer layer required to achieve the stress-free condition in the active layer depends on the composition of the InGaAsP material in the active layer and the thickness of the substrate. However, it does not change appreciably when the thicknesses of other layers, including the top layer, the active layer, and the cladding layers, are changed within a reasonable range. Therefore, the results obtained from calculations for the structure in Fig. 3 can be used as general guidelines for the optimal design of stress-free structures. The active layer stress σ_{xx} for the buffered laser structure at $\lambda = 1.30$ μm ($y = 0.6$) is shown in Fig. 6 as a function of the thickness d_b of the buffer layer for various substrate thicknesses. Figs. 7 and 8 show similar plots for lasers at two other wavelengths, $\lambda = 1.08$ μm ($y = 0.3$) and $\lambda = 1.55$ μm ($y = 0.9$), respectively. It is possible to deduce from these plots the relationship of the optimal buffer layer thickness d_b and substrate thickness d_s for stress-free structures at various intermediate laser wavelengths. Fig. 9 shows these optimal d_b - d_s relationships with a tolerance of $\sigma_{xx} = \pm 10^7$ dyne/cm^2. It is clear from Fig. 9 that it is quite easy to control σ_{xx} within $\pm 10^7$ dyne/cm^2 since the tolerances for d_b and d_s to meet this condition are quite large. Notice that a stress of 10^7 dyne/cm^2 corresponds to a negligible lattice deformation of $\Delta a/a = -10^{-5}$ which is far from being able to promote the TM

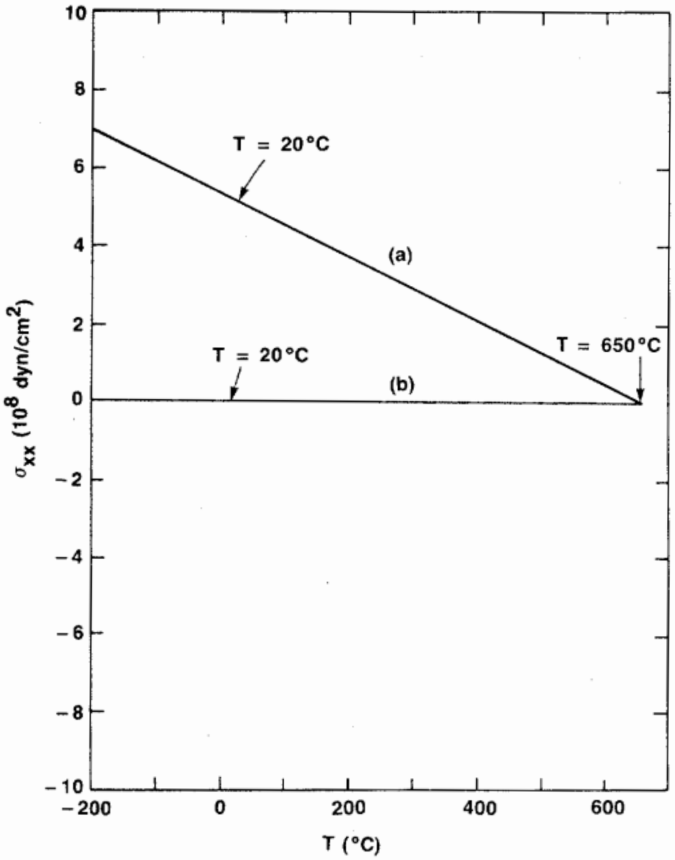

Fig. 5. Temperature dependence of the active layer stress of lasers at 1.3 μm which have (a) a structure of Fig. 1(a) with any substrate thickness and (b) a structure of Fig. 3(a) with optimal d_b and d_s for the stress-free condition, both grown under perfect lattice-matching conditions at 650°C.

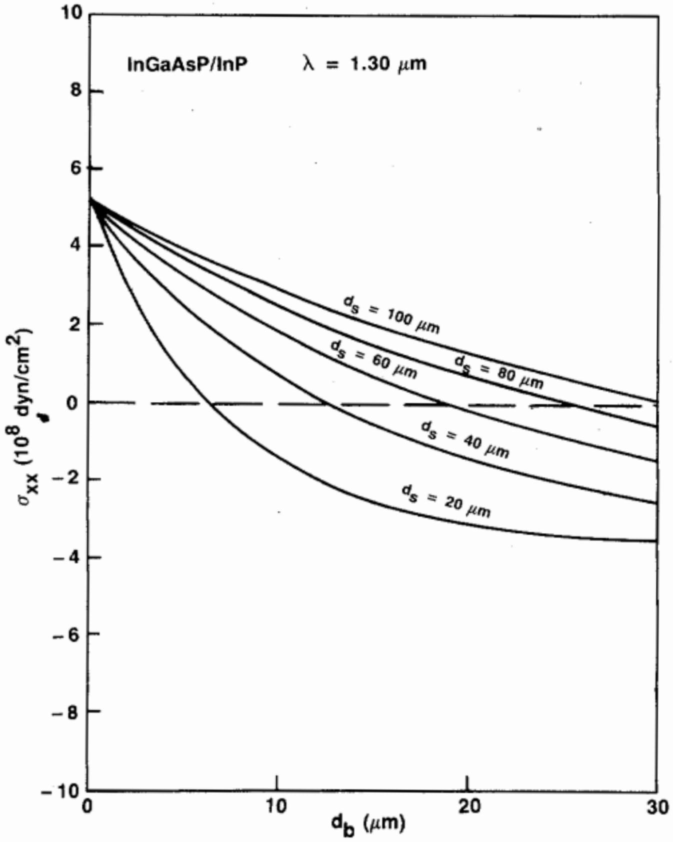

Fig. 6. Active layer stress at room temperature for a laser at 1.3 μm (y = 0.6) with the structure of Fig. 3(a), grown perfectly lattice-matched at 650°C, as a function of the buffer layer thickness for various substrate thicknesses.

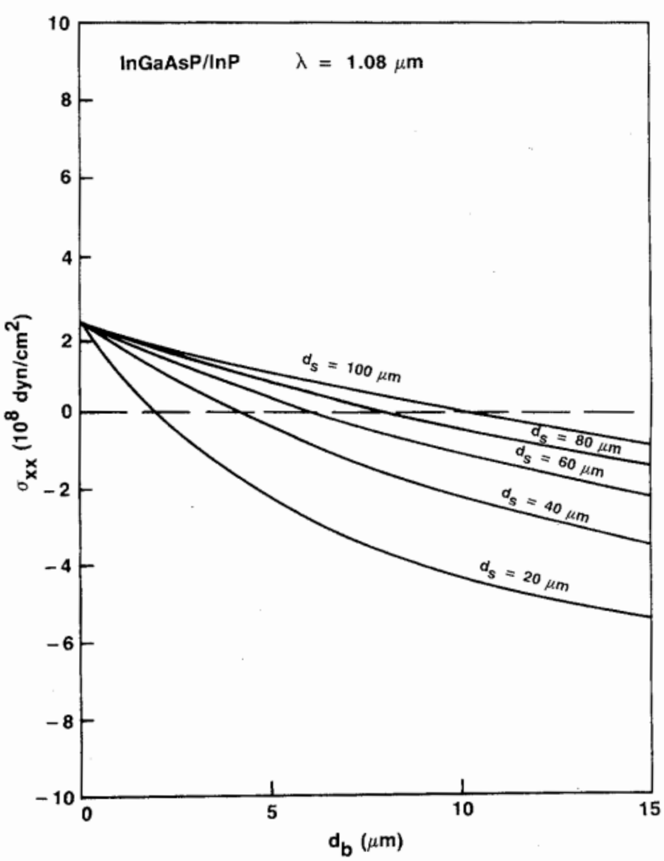

Fig. 7. Same plot as Fig. 6 for a laser at 1.08 μm (y = 0.3).

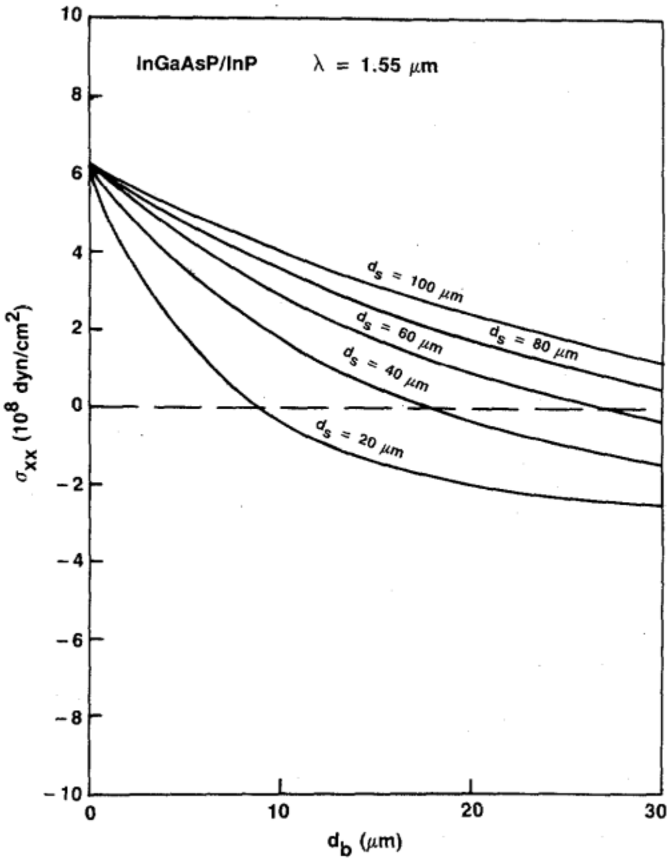

Fig. 8. Same plot as Fig. 6 for a laser at 1.55 μm (y = 0.9).

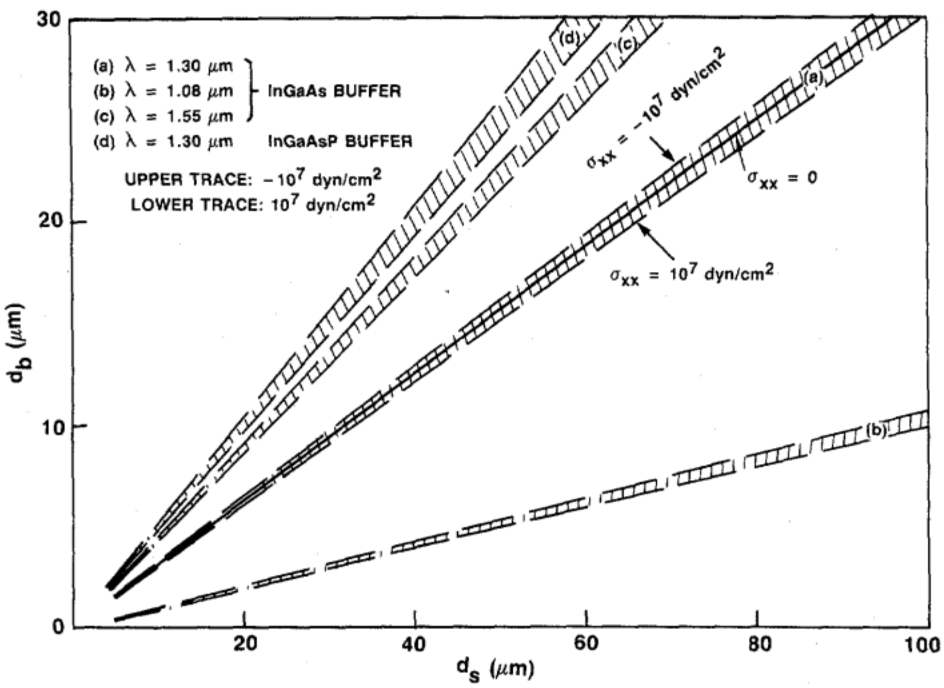

Fig. 9. Optimal relationships between the thicknesses of the buffer layer and the substrate for the stress-free condition for (a) 1.3 μm, (b) 1.08-μm, (c) 1.55-μm structures with an InGaAs buffer layer, and (d) a 1.3-μm structure with an $In_{0.74}Ga_{0.26}As_{0.60}P_{0.40}$ buffer layer. Each pair of traces shows a stress tolerance of $\pm 10^7$ dyne/cm^2.

emission. Also shown in Fig. 9(d) is the d_b - d_s relationship for a stress-free laser structure at λ = 1.30 μm, but with the buffer layer consisting of the same material ($In_{0.74}Ga_{0.26}$-$As_{0.60}P_{0.40}$) as the active layer. Comparison of Fig. 9(a) and (d) indicates that for a given substrate thickness, a thinner $In_{0.53}Ga_{0.47}As$ buffer layer is needed than an $In_xGa_{1-x}As_y$-P_{1-y} with $y \neq 1$ to achieve the stress-free condition. This leads us to the suggestion of the use of $In_{0.53}Ga_{0.47}As$ as the buffer layer material since the growth of a very thick misfit dislocation-free $In_xGa_{1-x}As_yP_{1-y}$ layer on the InP substrate may encounter some practical difficulties [15].

We also find from Fig. 9 that for lasers operating at longer wavelengths a thicker buffer layer is needed for a given substrate thickness. In practice, it may be difficult to grow misfit dislocation-free InGaAs layers thicker than 15 μm on an InP substrate. In this case, the substrate should be thinned down sufficiently to conform to the stress-free d_b - d_s relationship. In case a very thin substrate is not preferable, we propose an alternating-layer structure shown in Fig. 3(b) to circumvent this problem. In this structure, alternating InGaAs and InP layers of practical thicknesses can be grown and the InP substrate can be thinned afterward. For the purpose of calculating the stress in the active layer, the total thickness of the InGaAs buffer layers is equivalent to d_b and that of the InP layers is d_s. Then, Fig. 9 can be used for optimal design of the structure.

IV. Discussion

This paper mainly addresses compensation of thermal stress in the active layer caused by lattice mismatch of the epitaxial layers. In a semiconductor laser, the polarization behavior may also be affected by stresses from external sources, such as the stress caused by the mismatch of thermal expansion coefficients of the laser chip and the heat sink materials and the stress caused by the interaction between the substrate and the stripe window of the oxide film. So far, there has been no systematic study of the effects of the heat sink materials and die-bonding procedures on the polarization characteristics of semiconductor lasers. Among the commonly used heat sink materials, copper, with $\alpha_{copper} = 6.8 \times 10^{-6}/°C > \alpha_{InP}$, and solder materials are believed to enhance the TE mode because the stress along the junction plane is compressive at room temperature, while silicon, with $\alpha_{silicon} = 3.2 \times 10^{-6}/°C < \alpha_{InP}$, and diamond, with $\alpha_{diamond} = 1.65 \times 10^{-6}/°C < \alpha_{InP}$, enhance the TM mode because the stress is tensile. Since we have observed the TM stimulated emission at room temperature in lasers mounted on copper, as well as those mounted on diamonds, the stress caused by heat sink does not seem to be a dominant one.

Liu and Feng [4] reported the observation of mixed TE and TM modes in oxide-defined narrow-stripe AlGaAs/GaAs lasers with very thick (2 μm) Ga_2O_3 films formed by thermal oxidation. Their analysis showed that, for 2.5 μm stripe width, the uniaxial stress ($\sigma_{zz} - \sigma_{xx}$) in the central part beneath the stripe window and in the depth of 2 μm, where the active layer is located, is tensile along the junction plane and, therefore, promotes the TM mode. Our calculation, following the formula in [16], shows that the uniaxial stress decreases with increasing width of the oxide window and becomes compressive for widths larger than 5 μm. To stabilize the TE mode, it is important to avoid using thick oxide film and narrow oxide window for current confinement.

V. Conclusion

The internal tensile stress in the active layer of a conventional InGaAsP/InP laser structure tends to cause polarization instabilities in the laser. We have analyzed and compared the stress in the active-layers of the conventional InGaAsP/InP and AlGaAs/GaAs structures to show their differences and have proposed an improved InGaAsP/InP laser structure to reduce the tensile stress in the active layer and to eliminate the possibility of the TM emission. The active layer can be made stress-free at all temperatures when the thicknesses of the buffer layer and the substrate are optimized. The proposed structures stabilize the polarization characteristics of the laser against changes in the environmental temperature and/or the injection current level and eliminate stress-related kinks in the power versus current characteristics. Release of the active-layer stress may also increase the life expectancy of the lasers and lower the threshold current for lasing.

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