Quarter-wave Bragg reflector stack of InP-$In_{0.53}Ga_{0.47}As$ for 1.65 μm wavelength

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Quarter-wave semiconductor mirrors of InP-$In_{0.53}Ga_{0.47}As$ for high reflectivity at 1.65 μm wavelength are epitaxially grown using metalorganic chemical vapor deposition. Doping of the $In_{0.53}Ga_{0.47}As$ layers is found to be critical for high reflectivity at wavelengths corresponding to the $In_{0.53}Ga_{0.47}As$ band gap. n-type doping reduces the band-to-band absorption resulting in high reflectivity while p-type doped mirrors show reduced reflectivity.

The quarter-wave semiconductor Bragg reflector[1,2] (BR) is becoming an important component in optoelectronic devices because of its ease of monolithic integration. The mirror structure is used in surface-emitting lasers,[3–6] optical switches,[7] and other devices.[8–10] In general, use of the quarter-wave semiconductor BR has been studied primarily in the $Al_xGa_{1-x}As$ crystal system because the relatively large refractive index difference along with the good lattice match between AlAs and GaAs contribute to the high performance and quality with which these mirror structures can be epitaxially grown.

For optoelectronic devices and integrated optoelectronics, however, the InP-$In_xGa_{1-x}As_yP_{1-y}$ lattice-matched crystal system is also technologically important. To date, this has been the material system of choice for high-speed optical devices operating in the 1.3 and 1.55 μm wavelength range for optical communication applications. Low surface recombination velocities also favor InP-$In_xGa_{1-x}As_yP_{1-y}$ for electronic devices as well.[11] The transparency of the InP substrate for wavelengths characteristic of lattice-matched $In_xGa_{1-x}As_yP_{1-y}$ alloys, along with a technique for the fabrication of high quality monolithic optical lenses,[12] makes the quarter-wave semiconductor BR in the InP-$In_xGa_{1-x}As_yP_{1-y}$ crystal system a desirable component. However, because of the inherently smaller index difference between InP and $In_xGa_{1-x}As_yP_{1-y}$ lattice-matched alloys as compared to the AlAs-GaAs crystal system, InP-InGaAsP BRs require a greater number of quarter-wave layers for high reflectivity. This, when coupled with the longer wavelengths of interest in these materials, requires a much thicker structure for the InP-InGaAsP mirror. Although a few attempts of quarter-wave stack BR structures have been made in the InP-$In_xGa_{1-x}As_yP_{1-y}$ system,[5,13] the reflectivities obtained are much lower than that readily achieved in the $Al_xGa_{1-x}As$ crystal system.[1,2] The interesting question arises, then, as to how large the index step can be made between InP and a lattice-matched alloy for a quarter-wave stack with high reflectivity in the wavelength range of interest. In this letter we describe the growth and characterization of InP-$In_{0.53}Ga_{0.47}As$ BR structures for high reflectivity at a wavelength of ~1.65 μm corresponding to the $In_{0.53}Ga_{0.47}As$ band edge. We further show that the doping of the BR mirror structure, either n or p type, has a significant effect on mirror reflectivity for these wavelengths.

In this study, we have used metalorganic chemical vapor deposition[14] (MOCVD) to grow the InP-$In_{0.53}Ga_{0.47}As$ mirrors. The epitaxial layers were grown at atmospheric pressure using trimethylindium (TMIn), trimethylgallium (TMGa), arsine (AsH_3), and phosphine (PH_3). The dopant sources used for n-type doping were tetraethyltin (TESn)[15] and hydrogen sulfide (H_2S). p-type doping was accomplished by using diethylzinc (DEZn). The growth temperature was 660 °C and InP substrates with (100) orientation were used for all the epitaxial growth experiments in this study. The MOCVD growth technique has a sufficiently high growth rate that a reasonable growth time can be maintained for the required epitaxial crystal thickness, while very good control over layer uniformity and alloy composition can also be achieved. Three different mirror structures have been investigated. The first structure is a nine-period stack of $In_{0.53}Ga_{0.47}As$-InP layers with a final $In_{0.53}Ga_{0.47}As$ layer (19 layers). The ternary layers are doped n type, using S with $n_s \sim 4 \times 10^{18}$ cm^{-3}, while the binary layers are n type, $n_s \sim 9 \times 10^{18}$ cm^{-3}. The second structure is identical to the first but with the InP layers left unintentionally doped while the $In_{0.53}Ga_{0.47}As$ layers are doped p type, with Zn at a level of $p_{Zn} \sim 4 \times 10^{18}$ cm^{-3}. The third structure consists of 25 periods of $In_{0.53}Ga_{0.47}As$-InP alternating layers, again with a final layer of $In_{0.53}Ga_{0.47}As$ (51 layers) and all layers S doped with the ternary n type, $n_s \sim 4 \times 10^{18}$ cm^{-3}, and the binary n type, $n_s \sim 9 \times 10^{18}$ cm^{-3}. The surfaces of all the BR structures after crystal growth have been found to be specularly smooth with no evidence of crosshatch when examined under a phase-contrast optical microscope. A transmission electron microscope (TEM) cross section (not shown) of the alternating InP-$In_{0.53}Ga_{0.47}As$ nineteen-layered mirror in which the $In_{0.53}Ga_{0.47}As$ is doped $n_s \sim 4 \times 10^{18}$ cm^{-3} shows good layer uniformity.

Figure 1(a) shows reflectivity measurements made on the nineteen-layered n-type mirror structure and on the similar structure of 19 alternating InP-$In_{0.53}Ga_{0.47}As$ layers but with the $In_{0.53}Ga_{0.47}As$ doped p type, $p_{Zn} \sim 5 \times 10^{18}$ cm^{-3}, Fig. 1(b). As stated earlier, doping of the mirror structures has a significant effect on reflectivity, with the maximum reflectivity achieved in the n-type structure being 89% at a wavelength of 1.64 μm, Fig. 1(a). At the same wavelength, the p-type mirror has a reflectivity of 82%, Fig. 1(b). If absorption losses are ignored, the calculated reflectivity for

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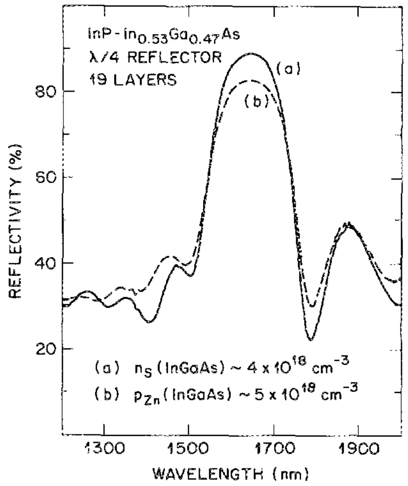

FIG. 1. Reflectivity vs wavelength for DBR of 19 layers with the $In_{0.53}Ga_{0.47}As$ layers doped (a) n type, $n_s \sim 4\times 10^{18}$ cm^{-3} and (b) p type, $p_{Zn} \sim 4\times 10^{18}$ cm^{-3}.

the 19-layer BR, using refractive indices of $n(\mathrm{InP}) = 3.17$ and $n(In_{0.53}Ga_{0.47}As) = 3.60$,[16] is 90.6%, in good agreement with the measured value of the n-type mirror structure, Fig. 1(a).

Figure 2 shows reflectivity measurements made on a 51-layer mirror structure of InP-$In_{0.53}Ga_{0.47}As$ doped n type, $n_s \sim 4\times 10^{18}$ cm^{-3}. The total thickness of this mirror structure is >6 μm, while the growth time for the 51 epitaxial layers was 2.3 h. Two reflectivity curves measured on this same wafer but at different spots on the wafer are shown. The symmetry of the reflectivity curve centered at the wavelength of 1.7 μm (solid curve) suggests that layer thicknesses of this InP-$In_{0.53}Ga_{0.47}As$ BR are close to optimum for high reflectivity at 1.7 μm. The measured reflectivity at this wavelength, which is just below the $In_{0.53}Ga_{0.47}As$ band edge, is 0.978. The calculated reflectivity for the 51-layer BR is 0.998. At a different spot on the wafer, where layer thickness change has shifted the reflectivity to a shorter wavelength of 1.63 μm (dashed curve of Fig. 2), the reflectivity is measured to be 0.963. This decrease in reflectivity of 0.015 may be due in part to increased absorption for the shorter wavelengths, but is also expected because of the shift in the BR layer thicknesses away from the optimum quarter-wave values. Note that the shape of the dashed curve of Fig. 2 also suggests that the InP-$In_{0.53}Ga_{0.47}As$ layers are not changing proportionally in layer thickness across the wafer. This is not too surprising considering that gas flow conditions change considerably from InP to $In_{0.53}Ga_{0.47}As$ epitaxial growth.

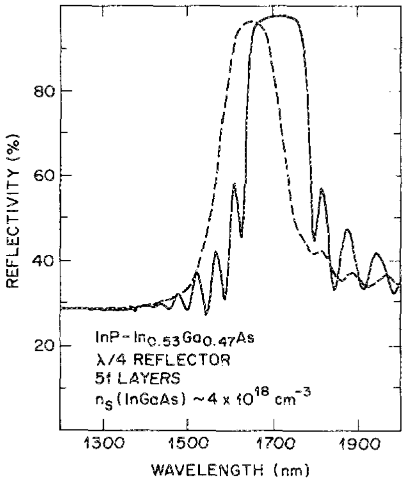

FIG. 2. Reflectivity vs wavelength for DBR of 51 layers with the $In_{0.53}Ga_{0.47}As$ layers doped n type, $n_s \sim 4\times 10^{18}$ cm^{-3}. Solid and dashed curves show reflectivity measured at two different locations on the wafer.

Doping of semiconductors is known to have a significant effect on band-edge absorption. For III-V semiconductors in which the free-carrier effective mass is small,[17] n-type doping can significantly decrease the near-band-edge absorption due to the Burstein shift.[18,19] p-type doping, however, tends to increase near-band-edge absorption due to the impurity bands which form around the acceptor levels in the crystal.[19] Figure 3 shows transmission measurements made on $In_{0.53}Ga_{0.47}As$ epitaxial layers grown on InP demonstrating the effect of doping level on band-edge absorption. For the highest n-type doping (using Sn), Fig. 3(c), $n_{Sn} \sim 7\times 10^{18}$ cm^{-3}, band-to-band absorption is greatly decreased even at wavelengths as short as ~ 1.55 μm. With the InP-$In_{0.53}Ga_{0.47}As$ quarter-wave mirror, therefore, the increased reflectivity seen for n-type doping versus p-type doping can be attributed to this reduction in band-to-band absorption.

Specific to the n-type mirrors studied here, as we increase the electron concentration in the $In_{0.53}Ga_{0.47}As$ the band-to-band absorption decreases but the free-carrier absorption increases. At high enough free-carrier (electron) concentrations, this free-carrier absorption may dominate the band-to-band absorption for wavelengths of ~ 1.65 μm and limit reflectivity. Unfortunately, little experimental data exist on the effects of free-carrier absorption in $In_{0.53}Ga_{0.47}As$. If we consider the available data for GaAs, we find that for an electron concentration of $\sim 7\times 10^{18}$ cm^{-3} the free-carrier absorption is $\alpha \sim 20$ cm^{-1}.[20] Using this value for a similar doping level in $In_{0.53}Ga_{0.47}As$, the effect of such absorption on both mirror reflectivity and transmission can be calculated using the matrix formalism presented in Born and Wolf.[21] For the imaginary part of the refractive index, $n + ik$, we have used $k = (\alpha/4\pi)\lambda_0 \sim 2.6\times 10^{-4}$. Neglecting absorption the mirror reflec-

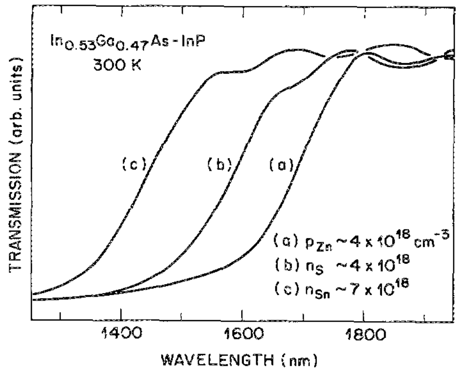

FIG. 3. Transmission vs wavelength for $In_{0.53}Ga_{0.47}As$ epitaxial layers grown on InP doped with various levels of p- and n-type doping. Near-band-edge absorption decreases as n-type doping level increases.

tivity for 25 periods of InP-$In_{0.53}Ga_{0.47}As$, with InP layers on either side of the BR, has a calculated value of 0.9931. Absorption loss of 20 cm^{-1} in the $In_{0.53}Ga_{0.47}As$ decreases this reflectivity to 0.9913 with a transmission of 0.0069. More analysis is required to determine the dominant loss mechanism in the mirror structures studied here. However, the measured reflectivities are much higher than in previous studies in the InP-$In_xGa_{1-x}As_yP_{1-y}$ crystal system.[5,13]

From the data of Fig. 3 it also appears that the InP-$In_{0.53}Ga_{0.47}As$ quarter-wave stack may be suitable for reflectors operating in the 1.55 μm range, if the net donor concentrations are $\gtrsim 7\times10^{18}$ cm^{-3}. Higher doping levels than this ($>7\times10^{18}$ cm^{-3}) have not yet been investigated in terms of their effect on the $In_{0.53}Ga_{0.47}As$ optical characteristics, although higher levels are certainly achievable.[15]

In summary, data have been presented on InP-$In_{0.53}Ga_{0.47}As$ BR mirror structures grown by MOCVD. The mirror structures are found to be of high reflectivity, with also good quality crystal obtained for the thick (>6 μm) epitaxial layers. High reflectivity for the InP-$In_{0.53}Ga_{0.47}As$ BR is demonstrated even at wavelengths corresponding to the $In_{0.53}Ga_{0.47}As$ band edge when n-type doping is used in the mirrors, which may simplify the growth of device structures using $In_{0.53}Ga_{0.47}As$ as the active material.

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