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Ultrahigh-Reflectivity (99.8%) InGaP/GaAs Multilayer Reflector Grown by MOCVD for Highly Reliable 0.98-μm VCSELs

K. Shinoda, K. Hiramoto, K. Uomi, and T. Tsuchiya

Central Research Laboratory, Hitachi Ltd.
1-280 Higashi-Koigakubo, Kokubunji, Tokyo 185, Japan

We report a 45-period InGaP/GaAs multilayer grown by low-pressure MOCVD for highly reliable 0.98-μm InGaAs vertical-cavity surface-emitting lasers (VCSELs). Reflectivity of 99.8% is obtained which is the highest ever reported for Al-free semiconductor multilayers. In addition, the stability of the layer thickness in the entire multilayer is discussed from the viewpoint of the asymmetrical reflectivity spectrum. This indicates that the layer thickness slightly decreases (1.5%) during the epitaxial growth.

1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) are attractive light sources for use in optical interconnections and optical signal processing. So far, there have been numerous reports on low-threshold operation of 0.98-μm VCSELs with strained InGaAs quantum well active layers[1,2]. One key requirement for low-threshold 0.98-μm VCSELs is high-reflectivity (>99.5%) semiconductor mirrors, which are transparent at the lasing wavelength. So far, GaAs/AlAs mirrors have usually been used for 0.98-μm VCSELs due to their large difference in refractive index. Recently, Numai et al. have demonstrated 0.98-μm VCSELs with a record low-threshold current of 190 μA in a 5-μm-diameter airpost with a dry-etched smooth sidewall[3]. Since AlAs tends to be oxidized in such multilayers and may therefore reduce the reliability of these devices, Al-free multilayers should be used to achieve highly reliable 0.98-μm VCSELs. The first fabrication of a multilayer consisting of GaAs and $In_{0.49}Ga_{0.51}P$ lattice-matched to GaAs has recently been reported using chemical beam epitaxy (CBE)[4].

In this paper, we report on a 45-period InGaP/GaAs multilayer with high reflectivity of 99.8%, successfully grown by metal-organic chemical vapor deposition (MOCVD). This value is the highest ever reported for Al-free semiconductor multilayers. We also discuss the variation of the layer thickness during the epitaxial growth from the viewpoint of the asymmetrical reflectivity spectrum.

2. EXPERIMENTAL PROCEDURE

A 45-period undoped InGaP/GaAs (74.6/69.5 nm) reflector with quarter-wavelength-thick layers was grown on a GaAs substrate by low-pressure MOCVD[5]. The growth temperature was 650°C and the pressure was 40 Torr. The growth rates for InGaP and GaAs were 17 nm/min and 14 nm/min, respectively.

Mirror reflectivity was measured, as follows. The output light from a white light source through a monochromator was vertically focused onto the sample, and the reflected light was detected with a Si pin photodiode. The absolute value of the reflectivity was calibrated using a standard gold mirror. The cross-sectional structure of the reflector was observed with a scanning electron microscope (SEM) and with a thickness fringe transmission electron microscope (CAT-TEM)[6].

3. RESULTS AND DISCUSSION

Figure 1 shows a cross-sectional SEM image of the 45-period InGaP/GaAs multilayer reflector. The mean period of the multilayer was measured and found to be

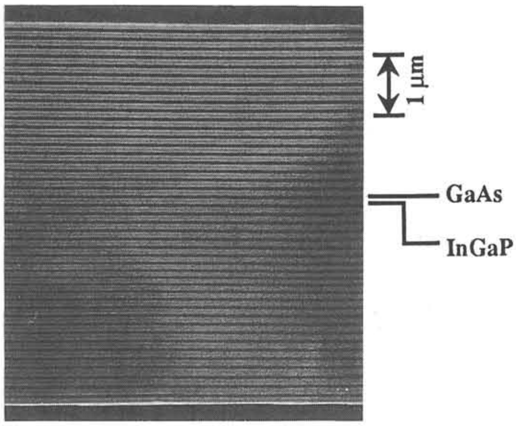

Fig. 1 Cross-sectional SEM image of the 45-period InGaP/GaAs reflector.

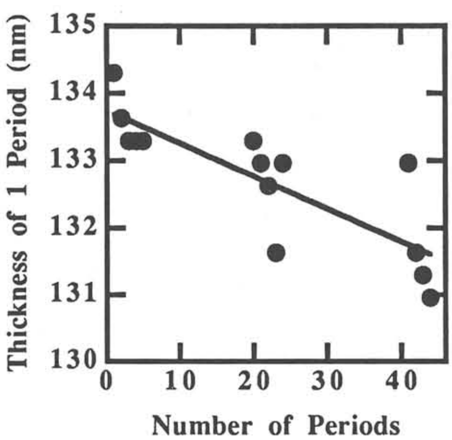

Fig. 2 Variation of the 1-period thickness of the InGaP/GaAs multilayer.

143±1 nm, which is in good agreement with the designed value of 144 nm. Figure 2 shows the variation of 1-period thickness of the multilayer measured using CAT-TEM. It was found that the layer thickness variation was only 1.5%.

Figure 3 shows the peak reflectivity of the multilayer as a function of the number of periods. This dependence on the number of periods was measured after selectively etching each layer in turn from the 45-period multilayer. This figure also shows the theoretical curve. Note that the measured values are in good agreement with the calculated values. Extremely high reflectivity of 99.8% was obtained for the 45-period multilayer. Moreover, even at 30 periods, reflectivity is as high as 99.4%. This result implies highly stable

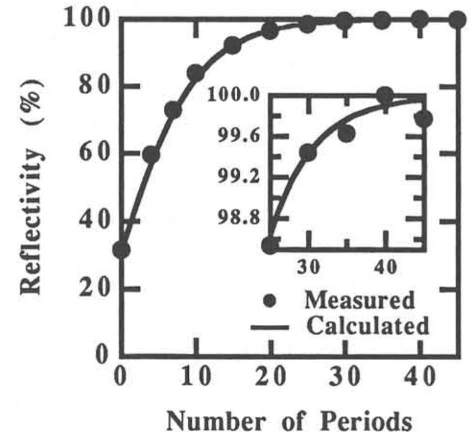

Fig. 3 Measured and calculated peak reflectivity of InGaP/GaAs multilayer as a function of the number of periods.

growth conditions throughout the 7-hour epitaxial growth.

Next, we discuss in more detail the layer thickness variation during epitaxial growth. Figure 4 shows the measured reflectivity spectra at various numbers of periods. As can be seen in Fig. 4, the reflectivity of the short-wavelength side of the stopband becomes larger than that of the long-wavelength side as the numbers of periods increases. In addition, the center wavelength of the stopband decreases with increase in the number of periods, as shown in Fig. 5. From this investigation, we conclude that the layer thickness gradually decreases during the growth. The dotted curves in Fig. 4 show the calculated values assuming that the layer thickness decreases linearly by 1.5% of the designed value during the 45-period epitaxial growth. In the calculation, the refractive index dispersion of the material was taken into account[7)]. The calculated spectra agree closely with the experimental data. The agreement between the measured and calculated center wavelength is good. For periods less than 10, the center wavelength shifts toward shorter wavelength with decrease in the number of periods. This is due to the refractive index dispersion of the materials. A slight decrease (1.5%) in the layer thickness was consistent with the above-mentioned CAT-TEM results. The measured center wavelength of the stopband is 966 nm, which is 14 nm shorter than the target value (980 nm). However, this can be easily adjusted by the growth time of the epitaxial layer.

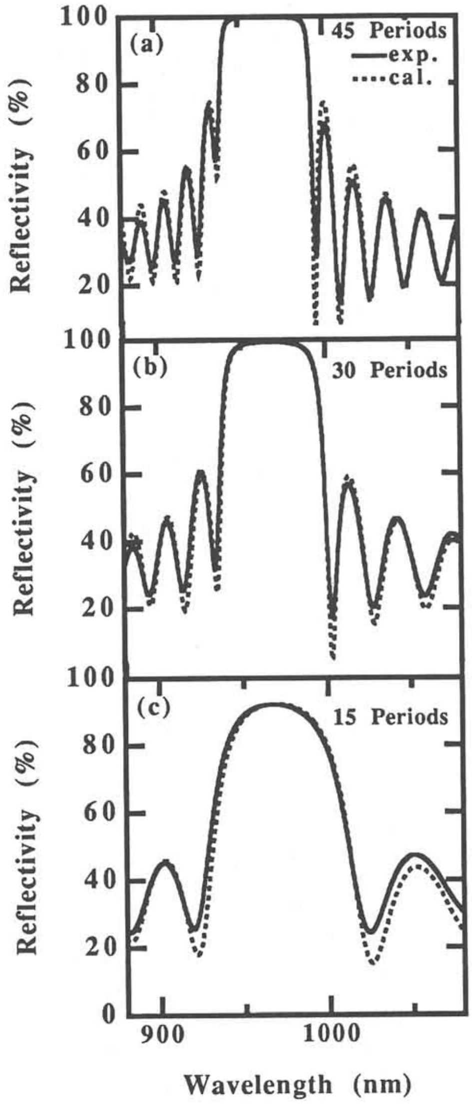

Fig. 4 Measured and calculated reflectivity spectra at various numbers of periods. (a) 45 periods, (b) 30 periods, (c) 15 periods. In the calculation, the 1.5% decrease in the layer thickness during the growth is taken into account.

4. SUMMARY

We have fabricated an InGaP/GaAs multilayer reflector by low-pressure MOCVD. High reflectivity of 99.4% and 99.8% was obtained for 30 and 45 period multilayers, respectively. Systematic investigation of the measured asymmetry of the reflectivity spectra showed a slight decrease (1.5%) in layer thickness during the epitaxial growth. From these results, we conclude that the InGaP/GaAs multilayer reflector has potential for low-threshold, highly-reliable 0.98-μm VCSELs.

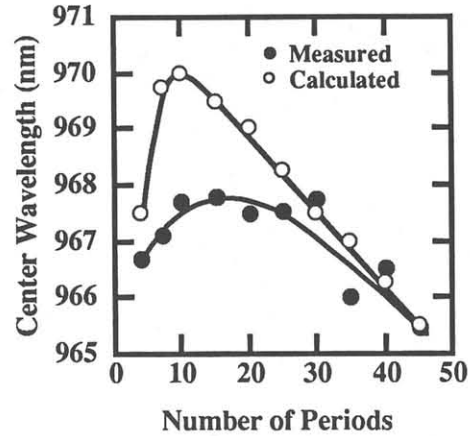

Fig. 5 Measured and calculated center wavelength of the stopband as a function of the number of periods.

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