Solid State Science and Technology, Vol. 12, No. 1 (2004) 120-127

OPTICAL PROPERTIES OF GaAs/AlGaAs DBR MIRROR FOR OPTOELECTRONICS DEVICES

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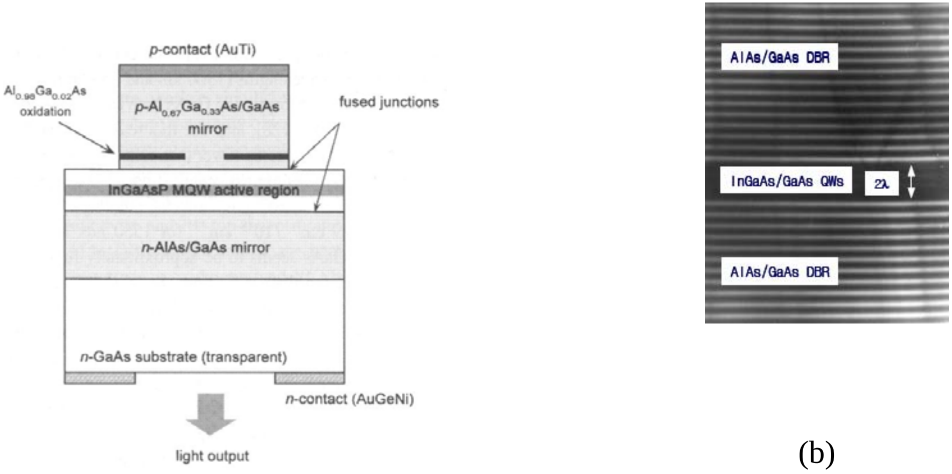
ABSTRACT

In this paper, we present a modeling analysis of Distributed Bragg Reflector (DBR) mirror comprises of alternating GaAs and AlGaAs semiconductor layers. Highly reflective mirror exceeding 99% has been obtained in this mirror, making the mirror system very promising for optoelectronics devices application. The optical properties derived from simulated reflectivity and absorption spectrums of the GaAs/AlGaAs DBR mirror are reported.

INTRODUCTION

Distributed Bragg Reflector (DBR) mirrors are used in wide range of optoelectronics devices including Vertical-Cavity Surface-Emitting Lasers (VCSELs) [1], Novalux Extended Cavity Surface-Emitting Lasers (NECSEL) [2] and Resonant-Cavity Light Emitting Diodes (RCLED) [3]. DBR is composed of alternating mirror periods with each period consisting paired layers of two different high- and low-refractive index material. The mirrors are also known as quarter-wave mirrors because each layer's thickness is equal to one-quarter of the wavelength of the light inside the material. Fig. 1 shows an example of GaAs/AlGaAs DBR used in 980 nm VCSELs device [4].



(a)

(b)

Fig. 1. (a) Schematic diagram of 980 nm VCSELs and (b) cross section of the DBR and active region of the actual device. (Ref: [4])

There are several requirements for DBR use. Firstly, it must have a very high reflectivity (>99%) due to small optical gain of the active region in the optoelectronics devices. The DBR must also exhibit a good thermal conductivity to provide heat sinking of the active region. The DBR should also be highly conductive to ease the injection of current through the mirror. Basically, there are three types of mirrors used for DBR that is dielectric, semiconductor and wafer-bonded mirror. Dielectric mirror deposited by evaporation or sputtering such as Si/SiO$_2$ [5] and Si/MgO [6] has a large refractive index ratio between layers, thus a small number of periods are necessary to achieve high reflectivity. However, disadvantages of dielectric mirror are that more complicated current confinement scheme is required due to its electrically insulating characteristic, poor thermal conductivity and high material absorption. Semiconductor mirror such as GaAs/AlGaAs [4] and InGaAsP/InP [7] can be epitaxially grown by Molecular Beam Epitaxy (MBE) or Metal-Organic Chemical Vapor Deposition (MOCVD) technique directly in one growth process and allow current injection through the mirrors by doping. Nevertheless, index ratio for semiconductor materials system that are lattice-matched is low, thus a large number of periods is needed for high reflectivity. Wafer-bonded mirror is where a semiconductor mirrors that are grown separately is bonded to a lattice-mismatch active region under specific pressure and temperature. It solved the problem of integrating active region and semiconductor mirror that are not lattice-matched. However, the electrical and thermal properties are highly dependent on the bonding process conditions, plus this bonding process is high-cost. In this paper, modeling studies of GaAs/AlGaAs DBR mirror is reported at 1.55 μm, where this is the wavelength window most optoelectronics applications will be targeting.

MODELING & SIMULATION METHOD

Fig. 2 displays DBR mirror of GaAs/AlGaAs with Table 1 listed the internal parameters.

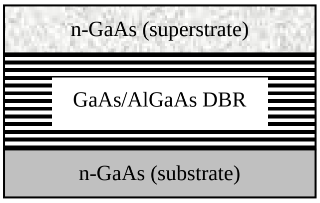


Fig. 2. Schematic GaAs/AlGaAs DBR mirror.

Table 1 Internal parameters of GaAs/AlGaAs DBR mirror

Layer type	Material	Thickness, d (μm)	Doping Concentrations, N_d ($\times10^{17}$cm^{-3})	Refractive Index (n)	Repetition
superstrate	GaAs	0.05	10	3.37	
DBR	GaAs	0.11	10	3.37	30
	Al$_{(x)}$Ga$_{(1-x)}$As	0.13	10	3.04	
	GaAs	0.11	10	3.37	
substrate	GaAs	5	50	3.37	

The DBR consisted of 30.5 periods n-type Si doped growth on n-GaAs substrate. The GaAs refractive index is 3.37 and AlGaAs is 3.04 at 1.55 µm [8]. The thickness of each layer is quarter wavelength calculated as:

$$d = \lambda/4n \tag{1}$$

where *d* is the quarter-wave layer thickness, λ is the design wavelength, and *n* is the refractive index of the material at the design wavelength.

The modeling and simulation is done by using HS_Design version 1.0 software [9] to investigate the DBR optical characteristic. Various standard methods can be use to calculate the optical characteristics of entire multi-layer device structure. The simplest and very powerful one is the Transfer Matrix Method (TMM) which is applied in the HS_Design. The calculation is done across the DBR structure, assuming it as a vertical stack. The intensity coefficients of reflection and transmission are calculated as:

$$\begin{aligned} R_{\omega,VS} &= |r_\omega|^2 \\ T_{\omega,VS} &= |t_\omega|^2 \end{aligned} \tag{2}$$

where ω is frequency, r_ω and t_ω, are the reflection and transmission amplitude coefficients, respectively, defined as:

$$r_\omega = \frac{T_{\omega,12}}{T_{\omega,22}}, t_\omega = \frac{1}{T_{\omega,22}} \tag{3}$$

The absorption coefficient of the vertical stack, which is defined as the fraction of light absorbed in the entire space between substrate and superstrate, is given by:

$$A_{\omega,VS} = 1 - T_{\omega,VS} - R_{\omega,VS} \tag{4}$$

Equations (2) to (4) are the final solutions from Maxwell equations using TMM. Details of the procedure are described in [10]. The high reflectivity or stop band of a DBR depends on the difference in refractive index of the two element materials, Δn. The spectral width of the stop band is given by [11]:

$$\Delta\lambda_{stopband} = \frac{2\lambda_{Bragg}\Delta n}{\pi n_{eff}} \tag{5}$$

where n_{eff} is the effective refractive index of the mirror calculated as:

$$n_{eff} = 2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{-1} \tag{6}$$

RESULTS & DISCUSSION

Fig. 3 shows reflectivity spectrum for the GaAs/AlGaAs DBR at various composition (x) as a function of wavelength. The spectrum are periodic, with the reflectivity peak repeats every odd multiple of the Bragg frequency. This reflectivity spectrum exhibit complicated phase and amplitude spectrum due to its distributed multi-reflection property.

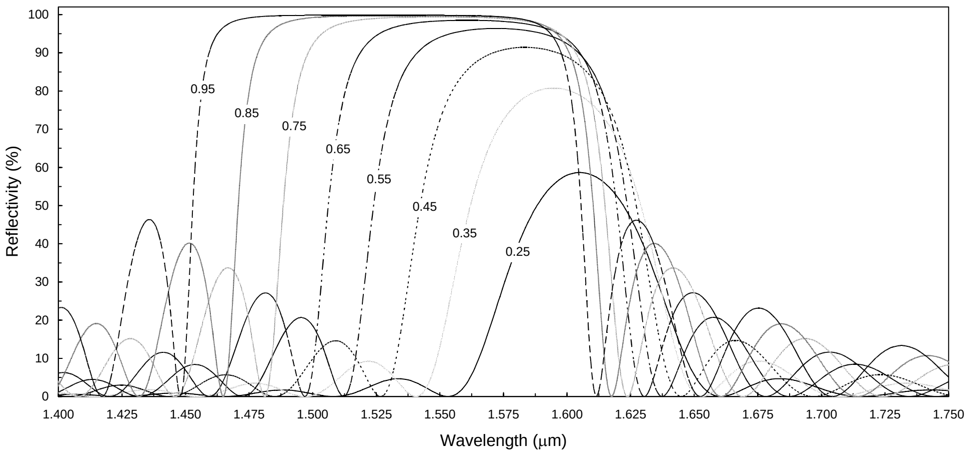


Fig. 3. Reflectivity spectrums of GaAs/AlGaAs at various compositions.

As the composition (x) increase in the AlGaAs alloy, the reflectivity spectrum shift to the shorter wavelength. Maximum reflectivity and reflectivity at 1.55 µm wavelength are also become higher as the composition (x) level increase, as shown in Fig. 4.

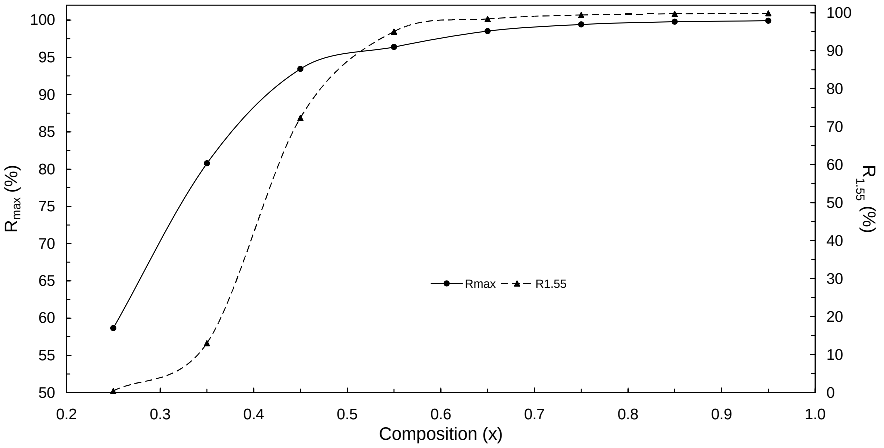


Fig. 4. Maximum reflectivity and reflectivity at 1.55 µm as function of composition.

Due to the shifting of the spectrum towards shorter wavelength, the wavelength of maximum reflectivity decreased as the composition (x) increase while the stopband declined as demonstrated in Fig. 5. This can be useful as one way of filtration control for the light to be emitted at a designed wavelength.

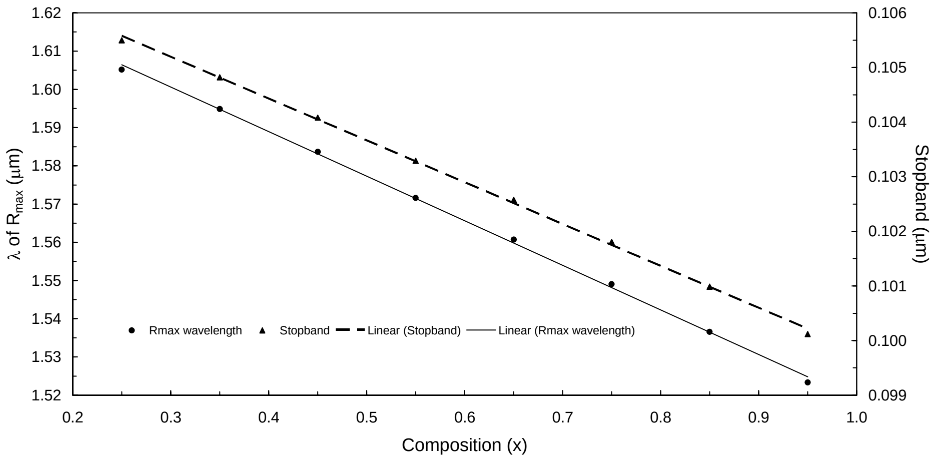


Fig. 5. Maximum reflectivity wavelength and stopband as function of composition.

Fig. 6 illustrated reflectivity spectrum of GaAs/AlGaAs DBR at various period (n) as a function of wavelength. By spacing multiple high-to-low index interfaces a distance λ/2 apart, the reflectivity of each interface adds constructively to produce mirrors with maximum reflectance of greater than 99% with a phase exactly zero or π [12]. Multiple reflections at the interfaces of the DBR and constructive interference of the multiple reflected waves increase the reflectivity with increasing number of periods as shown in Fig. 7. DBR thickness also increased linearly as the number of mirror period fabricated are increased.

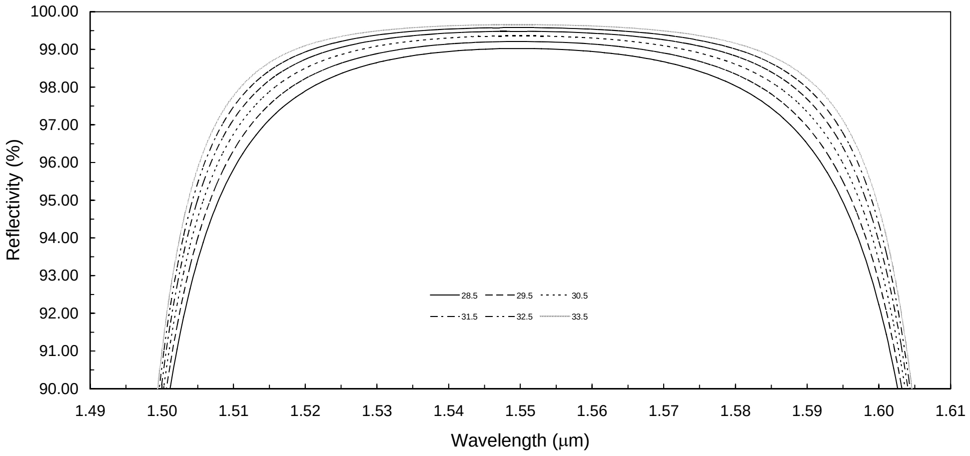


Fig. 6. Reflectivity spectrums of GaAs/AlGaAs at various periods.

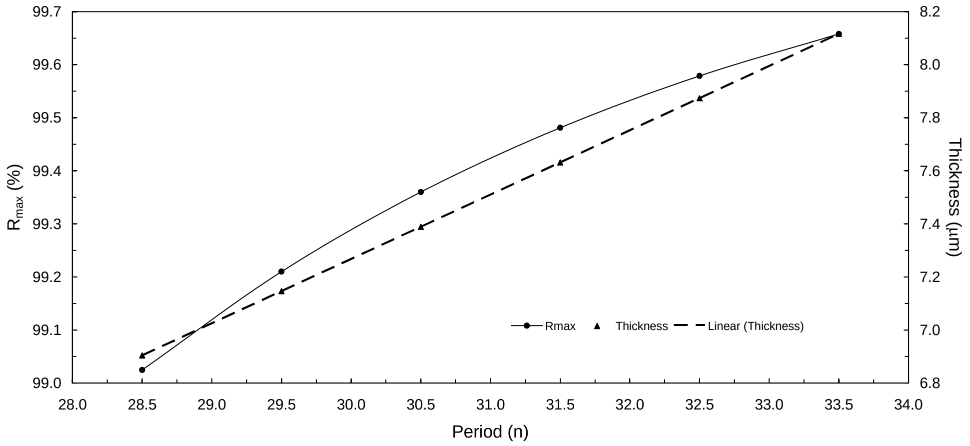


Fig. 7. Maximum reflectivity and thickness as function of period.

From the results and analysis as discussed, we proposed a GaAs/AlGaAs DBR mirror with properties as listed in Table 2. Fig. 8 shows the absorption coefficient, α for the proposed GaAs/AlGaAs DBR that is $\alpha=23.36$ cm^{-1} at 1.55 μm. In real DBR mirror systems, the reflectivity is reduced by the presence of material absorption [8] and light scattering [13]. Material absorption has typically been the dominating mechanism, due to the small roughness of state-of-the-art semiconductor fabrication.

Table 2 Properties of proposed GaAs/AlGaAs DBR

Properties	Refractive Index (n)		Period (n)	Thickness d (μm)	Doping Concentrations N_d (x10^{17}cm^{-3})		Composition (x)	R_{max} (%)	λ of R_{max} (μm)	Stopband (μm)
	GaAs	AlGaAs			GaAs	AlGaAs				
Parameter	3.37	3.04	33.5	8.12	10	10	0.74	99.66	1.55	0.10187

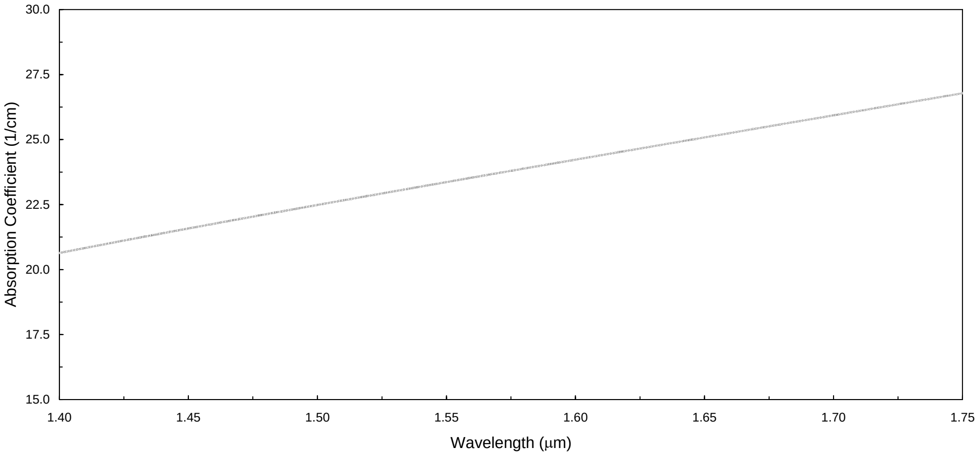


Fig. 8. Absorption coefficients for GaAs/AlGaAs DBR.

GaAs/AlGaAs DBR mirrors are widely used for below 1.0 µm optoelectronics applications. This is because most of the optoelectronics devices active region is based on GaAs material. Thus, the DBR mirror can be grown with the active region in a single epitaxial growth. GaAs/AlGaAs DBR mirror also has high reflectivity due to the high refractive index ratio (~0.33), which is among the highest for semiconductor mirror. This material system also exhibits good electrical conductivity and the highest thermal conductance for semiconductor mirror [14]. Thus, this material system would be a good choice in long-wavelength optoelectronics devices. Nevertheless, due to large lattice mismatch (~3.7%) [15], InGaAsP active region material which is normally used for long-wavelength cannot be incorporated into a GaAs/AlGaAs DBR mirror. A solution is to grow nonlattice-matched DBR and then wafer-bond to an active region as demonstrated in wafer-fusion technique [16].

CONCLUSION

Modeling and simulation of GaAs/AlGaAs DBR mirror for 1.55 µm optoelectronics devices have been studied using the HS_Design v. 1.0. High reflectivity DBR mirror about 99.66% has been obtained with composition of x=0.74 for the AlGaAs alloy and 33.5 periods for the material system. At 1.55 µm, the absorption coefficient is $\alpha=23.36\ \mathrm{cm}^{-1}$.

ACKNOWLEDGEMENT

This research work was sponsored by Telekom Malaysia Berhad under Project Number R03-0560-0. One of the authors (Mohd Sharizal Alias) thankfully acknowledges Ministry of Science, Technology and Environment of Malaysia throughout IRPA and National Scientific Fellowship for supporting the early work of this research.

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