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EFFECTS OF Si, Al_2O_3 AND SiC SUBSTRATES ON THE CHARACTERISTICS OF DBRS STRUCTURE FOR GaN BASED LASER

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Abstract: *Films of AlGaN and GaN are used as a Distributed Bragg Reflector (DBR) mirror for light emitting diode (LED) and vertical-cavity surface-emitting laser (VCSEL) type of laser. In this paper, we report the influence of different substrates on the reflectivity of DBR structure by using three different substrates, sapphire, silicon carbide and silicon. The DBR structure and optical properties of the films have been studied using the transfer matrix method (TMM). Better characteristics are obtained when Si substrates are used as compared to conventional* Al_2O_3 *substrates. This suggests that Si is a very promising substrate for GaN-based DBR mirror for blue laser diodes.*

Keywords: DBR structure, VCSEL, TMM

1. INTRODUCTION

III-V nitride semiconductors offer a wide range of applications due to their wide direct band gap, which is not found in conventional semiconductors. The current semiconductor technology covers only the region between infrared to green [1]. The band gap of GaN at room temperature is 3.4 eV (corresponding to a wavelength of 365 nm in the ultraviolet region) and that of InN, AlN are 1.9 and 6.2 eV, respectively. Technology-based semiconductors like GaAs cannot reach such shorter wavelengths and it is this property of III-V nitrides which makes them significant for optoelectronic applications like laser diodes [2]. The group III nitrides are promising materials for optoelectronic devices, high temperature electronics and cold cathodes because of their large band gap, high thermal stability, high saturation velocity and excellent physical properties.

There are two main problems related to (In,Ga,Al)N epitaxial layer growth. First, it is difficult in achieving useful doping ranges, in particular, the p-type doping at high concentration levels. The second problem is the lack of lattice and thermal matching substrate for this material system [3]. To date, sapphire and SiC substrates are most widely used for nitrides deposition. A (0001) sapphire has a lattice mismatch as large as 22% for InN, 16% for GaN and 12% for AlN.

The lattice mismatch between the substrate and the epitaxial layer results in very large dislocation density in nitride epitaxial layers grown on sapphire influencing the GaN device quality and therefore makes commercialization for the GaN devices difficult. The lattice mismatch between 6H SiC and GaN is only 3.3% but SiC substrate has comparatively poorer quality and suffers from high cost [4]. New, alternative substrates such as ZnO and NdGaO are promising for the epitaxial growth of nitrides and have much better lattice matching (when cutting them along relevant planes) and/or closer thermal expansion coefficients. Metalorganic vapour phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) are most widely used for thin (In,Ga,Al)N layers deposition. These two techniques enable the growth of a binary: AlN, GaN, InN and ternary InGaN, AlGaN alloys suitable for device application. The MOVPE growth process occurs as a chemical reaction between pyrolyzed metalorganic sources and ammonia [5]. This process takes place in high temperatures, > 1000°C. The reaction kinetics and detailed thermodynamics depend on employed precursors, substrates and the growth process parameters such as pressure, carrier gas, temperature, and the reactor geometry. To date, none detailed theoretical MOVPE deposition process model is known to exist. Consequently, in each laboratory the optimal nitride layers growth conditions have to be determined experimentally.

In this paper, we will report on the influence of different substrates on the reflectance properties of Distributed Bragg Reflector (DBR) mirror structure. In particular, we will compare their optical properties using the transfer matrix method and photoluminescence technique.

2. SUBSTRATES USED FOR GROWTH

GaN single crystal substrates are ideal substrates because the lattice mismatch is reduced to a great extent. But there is a difficulty in growing bulk substrates and hence many other substrates have been adopted for GaN growth [6]. In this section, we first discuss the properties of various substrates to show that Si, SiC and Al_2O_3 have appropriate properties for the growth of GaN. Then, we compare Si, SiC, and Al_2O_3 with regard to their application to laser diodes and determine the best substrate in producing high reflection for LED and laser diodes.

2.1. Sapphire (Al_2O_3)

The most common substrate used is sapphire in the c-plane, i.e., Al_2O_3 (0001). Nitridation of sapphire is performed to improve the optical and structural properties. However, a long nitridation times must be avoided because it leads to formation of AlN on the surface, which degrades the properties of the epilayer [6].

2.2. Silicon Carbide (SiC)

The main advantage of this substrate is that its lattice parameter and the thermal expansion coefficients are close to GaN. There is a possibility of producing vertically working optoelectronic devices using conductive SiC. But it is not widely used because of its cost, chemical inertness and mechanical hardness. When the growth proceeds, it leads to dislocations at the island edges because GaN does not wet the SiC surface. SiC is a potential substrate because it has a lattice mismatch of only 3.3% and it is very stable at high temperatures and also has excellent thermal conductivity. But it is not commonly used because it is expensive and obtaining a clean surface is very difficult [7].

2.3 Silicon (Si)

Silicon is a promising substrate material for all devices because of its low cost and availability. Hence in most research, GaN is grown on silicon substrate. However, the problem with silicon is that it cannot withstand high temperatures. Consequently a buffer layer is used. Many buffer layers like AlN and ZnO have been suggested. Successful growth of crack-free films would be advantageous because Si is very cheap and also integration is easy for silicon devices. It has been reported that Si (111) promoted the Wurtzite phase whereas Si (001) promotes the cubic phase nitrides [6]. Moreover, GaN does not wet the silicon surface at all.

3. DBR WITH DIFFERENT SUBSTRATE

DBRs are one of the most important elements used to realize vertical-cavity surface-emitting lasers (VCSELs). Also, in the design of the integrated fluorescence sensor, DBRs are used as an effective optical filter. DBRs are typically made of two alternating materials with an optical thickness equal to $\lambda_B/4$, where λ_B is called the Bragg wavelength, (see Fig. 1). At λ_B, the reflectance from each interface of the DBR interferes constructively, which is additive, and results in a large net reflectivity.

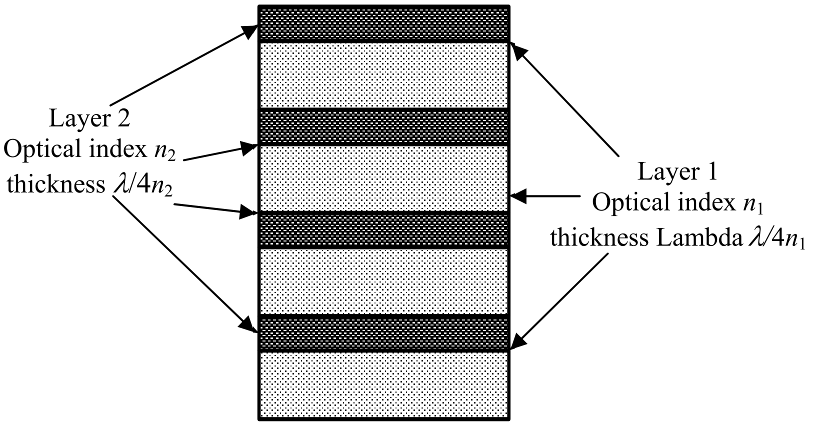

Figure 1: Diagram of DBR two alternating materials of optical thickness ($\lambda/4$) are used to form a DBR

From Fresnel's equations [8] due to matching of the tangential electric fields for a propagating electromagnetic wave at normal incidence, the reflectivity from a single optical interface is given by

$$r = \frac{n_1 - n_2}{n_1 + n_2} \tag{1}$$

where r is the reflectivity of the electric field from a single interface, and n_1 and n_2 are the optical indices of the alternating $\lambda_B/4$ material layers. As stated above, the $\lambda_B/4$ optical thickness of the DBR layers causes the reflections from each interface to interfere constructively. From Figure 2 the power reflectivity, R, of a DBR with k material pairs at λ_B is given by [9],

$$M = \begin{bmatrix} \cos(\delta_1) & i\sin(\delta_1)/n_1 \\ in_1\sin(\delta_1) & \cos(\delta_1) \end{bmatrix} * \begin{bmatrix} \cos(\delta_2) & i\sin(\delta_2)/n_2 \\ in_1\sin(\delta_2) & \cos(\delta_2) \end{bmatrix} * \begin{bmatrix} 1 \\ n_s \end{bmatrix} \tag{2}$$

with

$$\delta = n_{1,2}d_{1,2}\cos\theta \cdot \frac{2\pi}{\lambda} \tag{3}$$

$$d_{1,2} = \lambda_B / 4n_{1,2} \tag{4}$$

In Eq. (2), the first (2 × 2) matrix is associated with Layer-1, the second with Layer-2 and the column matrix is for the substrate. Where n_s and $n_{1,2}$ are the refractive indices of the substrate and the corresponding layer respectively, $d_{1,2}$ is the geometrical thickness of the corresponding quarter wave layers and λ_B is the target wavelength for the peak of the high reflectance band. The characterized matrix of multilayer films can be expressed by

$$M = M_1 * M_2 * M_3 * \cdots * M_s = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{5}$$

$M_1, M_2, M_3, \ldots, M_s$ is the characterized matrix represent the layers 1, 2, 3, …, s respectively.

The optical admittance is given by

$$Y = \frac{m_{21}}{m_{12}} \tag{6}$$

and the reflectance is defined by

$$R = \left(\frac{1-Y}{1+Y}\right) * \left(\overline{\frac{1-Y}{1+Y}}\right) \tag{7}$$

Typical power reflectance of DBRs used in VCSELs are in the range of 99.9–99.999%. This high reflectance is required to compensate for the small amount of optical gain due to the short cavity length of VCSELs. The reflectivity spectrum is generated through a thin film optical simulator based upon a transfer matrix method. The DBR design is centered on λ_B = 420 nm with 15-pairs of alternating GaN and $Al_{0.3}Ga_{0.7}N$ layers. DBRs have a limited reflectance band. The spectral width of the high reflectivity band is given by [10].

$$\Delta\lambda = \frac{2\lambda_B \Delta n}{\pi n_{eff}} \tag{8}$$

where Δn is the difference in refractive index between the two DBR layers and n_{eff} is the effective refractive index of the mirror. The effective refractive index is given by

$$n_{eff} = 2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{-1} \tag{9}$$

4. RESULT AND DISCUSSION

DBR mirror structure is chosen as the base of the simulation. The structure is shown in Figure 2. Matlab program is used for simulation and the formulas from Eq. (1) to (7) in previous section are used. The objective of this simulation is to show how the change in the DBR substrate will result in the difference of reflectivity. For the simulation, we have used the thicknesses of the $Al_{0.3}Ga_{0.7}N$ and GaN layers of 44.16 and 41.8 nm, respectively while the refractive index values of $Al_{0.3}Ga_{0.7}N$, GaN (λ = 420 nm) and sapphire used were 2.3777, 2.5067 and 1.784, respectively. Figure 3 shows that the center peak of three plots has the maximum reflectivity of 65%, 78%, 87%, for sapphire, Sic, Si, as a substrate for DBR structure respectively.

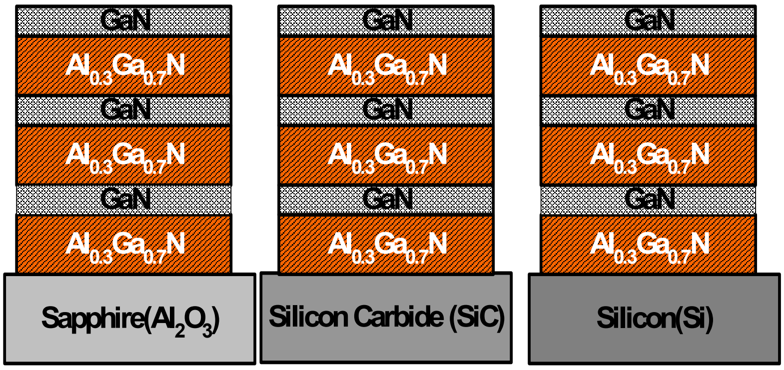

Figure 2: Design of DBR structure mirror for blue light with different substrate

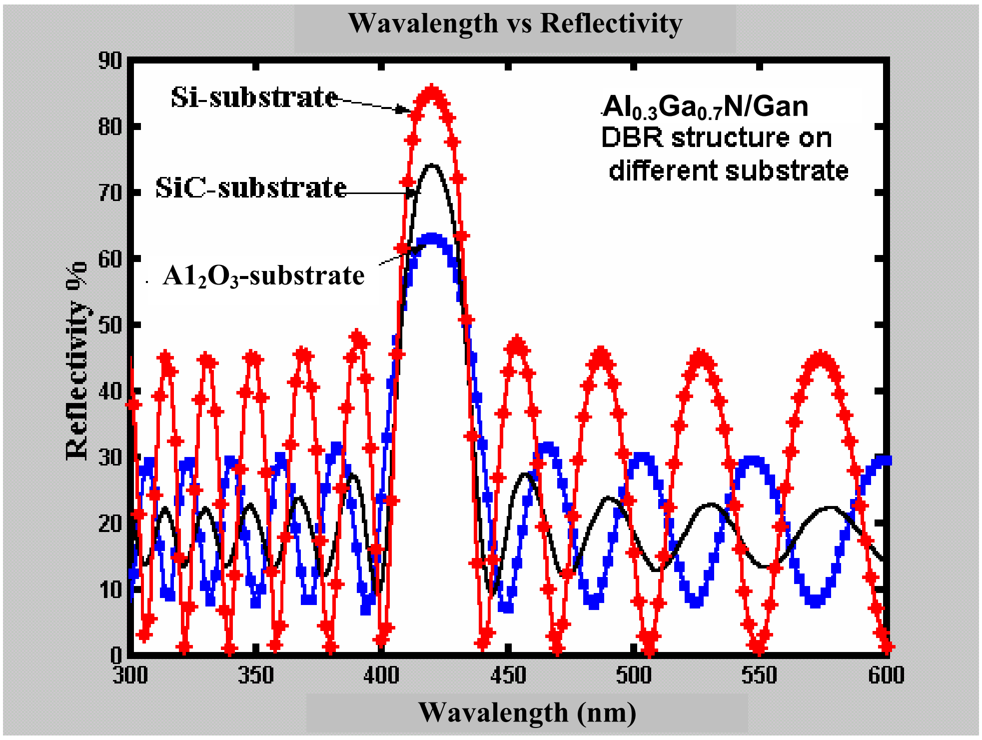

Figure 3: Reflectance spectra of 15 pairs of $Al_{0.3}Ga_{0.7}$ N/GaN DBRs with different substrate Al_2O_3, SiC, Si

Photoluminescence (PL) measurements were studied at room temperature using a He-Cd laser for 325 nm excitation with approximately 2 mW illuminating area of about 0.049 mm^2. Spectra were obtained in the wavelength range of 340–420 nm, using a 0.75 m spectrometer and CCD camera as a detector. The PL spectra for the three different substrate structures are shown in Figure 4.

Figure 4 gives comparison of the near-band-edge PL emission at room temperature for three different substrates. The (Al_2O_3) curve shows the PL emission for GaN epitaxial layer deposited on sapphire substrate. The (SiC) curve shows the PL spectra for a GaN epitaxial layer deposited on SiC substrate. And the (Si) curve shows the PL spectra for a GaN epitaxial layer deposited on Si substrate. The GaN/Si exhibited the strongest intensity in arbitrary unit close to 10000 while other samples GaN/SiC, GaN/sapphire showed intensities of 8000 and 4000, respectively.

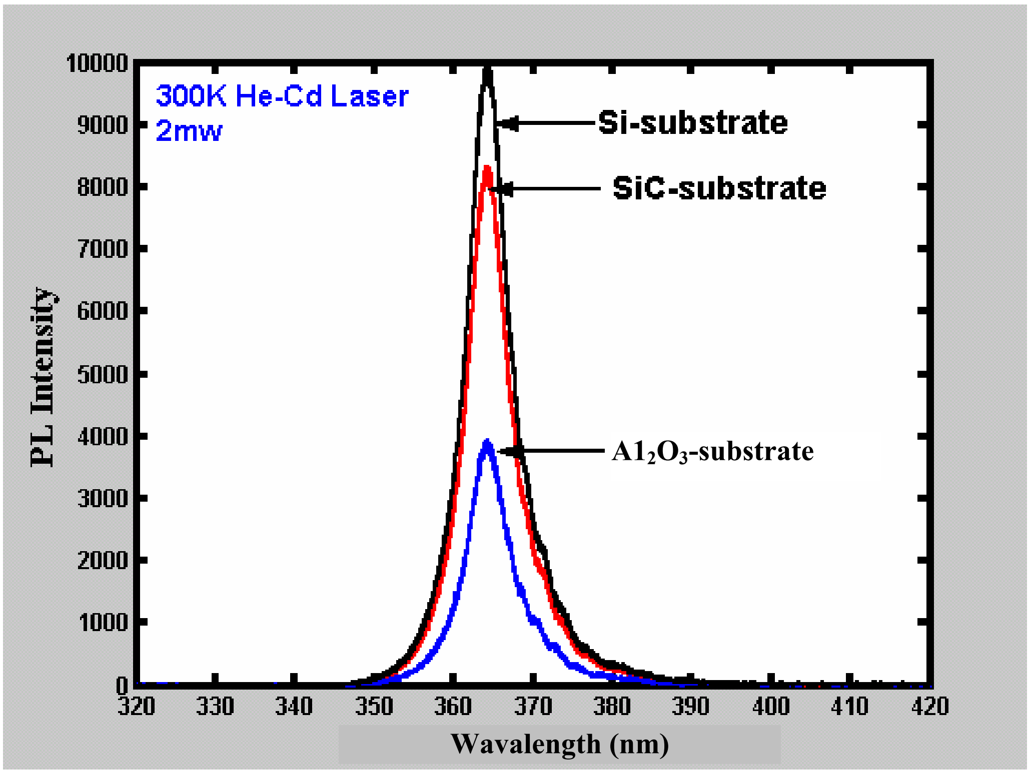

Figure 4: PL spectra recorded at room temperature for GaN epitaxial layers deposited on: (a) sapphire substrate, (b) SiC substrate, and (c) Si substrate

5. CONCLUSION

The results reported here indicate that Si, SiC and Al_2O_3 are promising substrates for high reflecting DBR mirror structure with reduced number of layers. However, MOVPE process parameters for the GaN on alternative substrates need further optimization to reach the quality of GaN layer grown on different substrates (Si, SiC and sapphire). We found that the reflectivity of DBR structure on Si as a substrate produced the highest measured peak as compared to other substrates. There is also evidence for quite large difference in PL intensity of structure on Si substrate as compared to other substrates. In conclusion, Si is a very promising substrate for high reflectivity DBR mirrors with reduced number of pairs.

6. ACKNOWLEDGEMENTS

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