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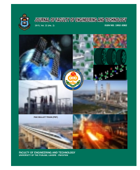

ENHANCED EFFICIENCY OF GAAS-GA$_x$AL$_{1-x}$AS LASER WITH /4 ANTIREFLECTIONS COATING OF TIO$_2$ THIN FILMS: AN OPTICAL ENGINEERING

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Abstract

Titanium dioxide (TiO_2) dielectric material was deposited as ~/4 antireflections (AR) coating on one facet of GaAs-GaxAl1-xAs double hetero-structure (DH) laser. Single layer ~ /4 AR coating was achieved by successive deposition of TiO2 thin films in vacuum in small steps by thermal evaporation technique, while measuring the threshold current after each coating outside the vacuum. Threshold current, reflectivity and far-field patterns of laser show the significant influence of AR coatings on light output characteristics. Internal loss parameter and the gain coefficient for the DH laser were determined from threshold current under the case temperature of the laser.

Keywords: Semiconductor lasers, antireflection coatings, thin films, hetero-structure

1. Introduction

AR and high reflection (HR) coatings are usually deposited on the semiconductor laser [1]. These coatings are important because AR coating increases the output power from the front facet of the laser and provides refractive index match between the laser and optical fibre whereas HR coating reflects back the light to the cavity [2] . Widely used dielectric materials for AR and HR coatings are SiO, ZnS, Al_2O_3, and TiO_2 having refractive indices of approximately (2.05), (2.28), (1.7), and (1.9) respectively–[3-4]. In this letter, we report the coating of TiO_2 material on the front facet of commercially available GaAs-GaxAl$_1$-$_x$As DH laser to observe the significant influence of AR coatings on the threshold current, reflectivity and far-field patterns.

Such types of lasers have potential applications in biological imaging modalities such as fluorescent probe imaging, microscopy, and tissue staining in light microscopy of histopathology where tuning is needed in the presences of near-infrared fluorescent dyes [5]. These methods are majorly capable in the diagnostic and therapeutic biomedical applications of light for many skin conditions, including vascular and pigmented lesions, tattoos, and scars. Optical spectroscopy is another attractive horizon for such types of tuning lasers by AR coating and have been proven to be the most reliable diagnostic methods in which optical tomography aimed to record 2D or 3D image is less invasive e.g. laser

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scanning microscopy, and optical coherence tomography (OCT) and diffuse tomography[6-7].

2. Materials and Methods

2.1. The optimum conditions for AR coating

GaAs has a high refractive index of approximately 3.6. In order to reduce the internal reflectivity, a dielectric film of a suitable material can be deposited on the laser facet. One facet of the laser was coated by the manufacturer, in order to increase the light output from the other facet of the laser. The reflectivity of the facet coated by the manufacturer is $R_2 = 0.85$. Reflectivity (R_1) of the second uncoated laser facet can be found from the relation [4];

$$R_1 = \left[\frac{n_L - n_a}{n_L + n_a}\right]^2 \tag{1}$$

Upon substituting the refractive index values of laser and air as $n_L = 3.6$ and $n_a = 1$ respectively, we get $R_1 = 0.32$. AR is based on destructive interference. Assuming normal incidence, the reflected waves at the air-film and film-laser interface interfere destructively to produce AR for a given incident beam. The condition for destructive interference is that the thickness of AR film should be equal to h = λ/4nf, where λ is the wavelength of incident beam and nf is the refractive index of the dielectric film. To ensure that both the reflected beams are of equal intensity for complete destructive interference, the AR film index must be $n_f = (n_L n_a)^{1/2}$. This is the condition for index matching[8]. Dielectric material for AR coating was selected satisfying the above criteria. Using the index of refraction of GaAs (n_L =3.6), nf is calculated to be 1.9, while the optimum film thickness for ~λ/4 AR coating is 112 nm. Therefore, TiO_2 having refractive index approximately 1.9 will be deposited in small steps on the laser facet in vacuum to achieve ~λ/4 AR coating.

2.2. Experimental Procedure

Commercially available semiconductor injection laser made up of GaAs-$Al_xGa_{1-x}As$ double hetero-structure (obtained from ITT, England) having cavity length (L) and width (W) 850 μm and 100 μm respectively was used in the present study. Thin films of TiO_2 were thermally deposited in vacuum in successive small steps on the uncoated facet of the laser in order to achieve ~λ/4 AR coating.

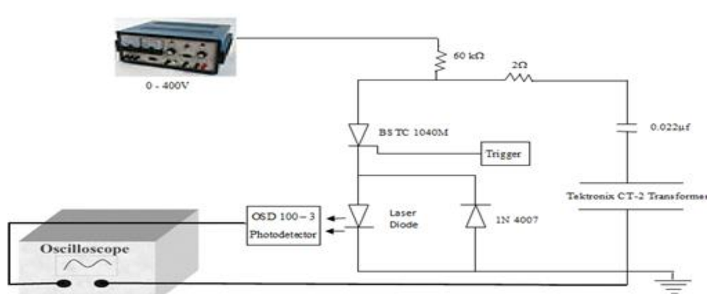

Figure 1: Schematic experimental set up for measuring light output and far field patterns of DH laser.

The Edward coating unit (E306A, Germany) with molybdenum boat was used for evaporation of material. During evaporation the thickness of the film on the laser was monitored using FTM-7 thickness meter which uses quartz crystal as standard. The measured thickness after each coatings of TiO_2 on laser facet is presented in Table 1. The laser was operated by a pulser circuit as shown in Figure 1. Diode in parallel to the laser but opposite in polarity was used for safety purposes. The light emitted by the laser diode was detected by the silicon photodiode. Both input current pulse and light output pulse were displayed simultaneously on dual trace oscilloscope (Tektronics 7613, Netherland).

Table 1: Measured values of different parameters of AR coated DH laser.

Coatings	I_{th} (A)	$J_{th} \times 10^3$ (A/cm^2)	h (nm)	R_1	$\frac{1}{2L}\ln\frac{1}{R_1R_2}$	E (eV)	FWHM (⊥) degree	FWHM (‖) degree
uncoated	0.7	1.489	0	0.32	32.5	1.3840	33	25
1st	1.25	2.659	24	0.20	57	1.3861	32.5	24.8
2nd	2.0	4.255	43	0.14	70.5	1.3887	32	24.2
3rd	2.25	4.787	75	0.11	78	1.3894	31.4	23
4th	2.65	5.638	98	0.07	97.5	1.3903	31	22
5th	2.85	6.064	115	0.042	109	1.3905	30	20

3. Results and Discussion

Figure 2 shows the light output against current (L-I) characteristics of the DH laser before and after six successive coatings of TiO_2 on one mirror of the laser. The fifth coating corresponds to ~λ/4 AR coating because at six coating the characteristics shifts back to lower current values. The threshold current (I_{th}) was found by extrapolating the light output against current characteristics. The threshold current (I_{th}) for uncoated laser is 0.7 A which increased to 2.85 A after ~λ/4 AR coating. The 5th coating is ~λ/4 AR coating at film thickness (118 nm).

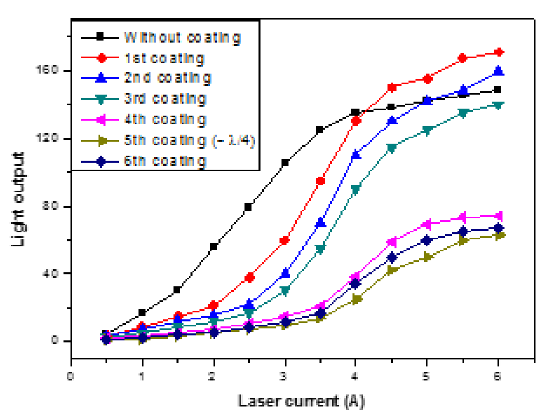

Figure 2: Light output characteristics of DH Laser before and after 6 successive coatings of TiO_2.

This optimum film thickness (118 nm) for ~λ/4 AR coating is approximately in agreement with calculated film thickness (112 nm). Moreover, nonlinearity in the light output characteristics of DH laser is detected. This deviation from linearity at higher currents is due to hole injection [9], the excitation of higher order modes[10] and loss of radiation out of the active region[11]. Such effects lead to deterioration of the optical cavity and hence cause the reduction in the efficiency of semiconductor laser. It is also seen from the (L-I) characteristics that the first, second and third coating have increased the slope of the light output versus current curve, while fourth and fifth coating have decreased the slope. Such behaviour is consistent with the results of single hetero-structure lasers reported by [12]. The interpretation of the effect can be given as it is the excitation of internally circulating non radiating modes. The unknown reflectivity of the AR coated facet is determined from the ratio of coated to uncoated differential quantum efficiencies using the relation[13] ;

$$\frac{\eta_c}{n_u} = [\frac{R_{1u}}{R_{1c}}(\frac{1-R_{1c}}{1-R_{1u}})]^{1/2} \qquad (2)$$

where η_c, η_u and R_{1c}, R_{1u} are the slope efficiencies (L-I) and the reflectances of coated and uncoated facets respectively. As $R_{1u} = 0.32$, then the coated reflectivities (R_{1c}) found from the above relation are 0.20, 0.14, 0.11, 0.07, and 0.042 for first, second, third, fourth, and fifth coating respectively and are also given in Table 1. The threshold current density is measured using the relation $J_{th} = I_{th}/(L \times W)$ [2] and values are given in Table 1. The plot of threshold current density against end loss 1/2L *ln* $1/R_1R_2$ is shown in Figure 3(a), which gives a linear dependence of threshold current density on end loss with the following [2] ;

$$\beta J_{th}^{b} = \alpha + \frac{1}{2L}\ln\frac{1}{R_1R_2} \qquad (3)$$

here, b = 1 is assumed as reported for semiconductor laser in the literature[12]. The loss parameter (α) is determined from the following relation [4];

$$\frac{[I_{th}]_{uncoated}}{[I_{th}]_{\lambda/4}} = \frac{[\alpha + \frac{1}{2L}\ln\frac{1}{R_1R_2}]_{uncoated}}{[\alpha + \frac{1}{2L}\ln\frac{1}{R_1R_2}]_{\lambda/4}} \qquad (4)$$

substituting the values concerned in Eq(3) and Eq(4), α becomes equal to 42.86 cm-1 and β to 1.64 × 10-2 cm/A for DH laser.

The photon energy is a function of threshold current because at higher currents the band tail is filled to a higher level than at lower currents. Mirror reflectivity has also strong effect on photon energy. The following relation can be used to measure the photon energy[4];

$$E = E' + E_0 \ln\left[\alpha L + \ln\left(\frac{1}{R_1R_2}\right)\right] \qquad (5)$$

Where $E' = 1.377$eV and $E_0 = 0.0092437$ are fitted parameters. From above relation E is determined and values are given in the Table 1. The wavelength of laser light is measured from the relation *λ=hc/E* that gives λ = 850 nm for uncoated DH laser and it is found to decrease to λ = 844 nm after ~λ/4 AR coating. The plot of photon energy (E) against threshold current density (J_{th}) is shown in Figure 3(b). The results show that energy of laser light increases with increasing threshold current density. Secondly, It is observed that plot is not a straight line, but bends towards the current axis at higher current values. The increase in energy with increasing current can be attributed to band filling process and the bending of the curve at higher values of current is possibly an indication of band gap shrinkage due to junction heating or due to increased carrier concentration. These results are consistent with the theoretical results of Casey and Stern et al. [14], including band tail and band gap shrinkage effects.

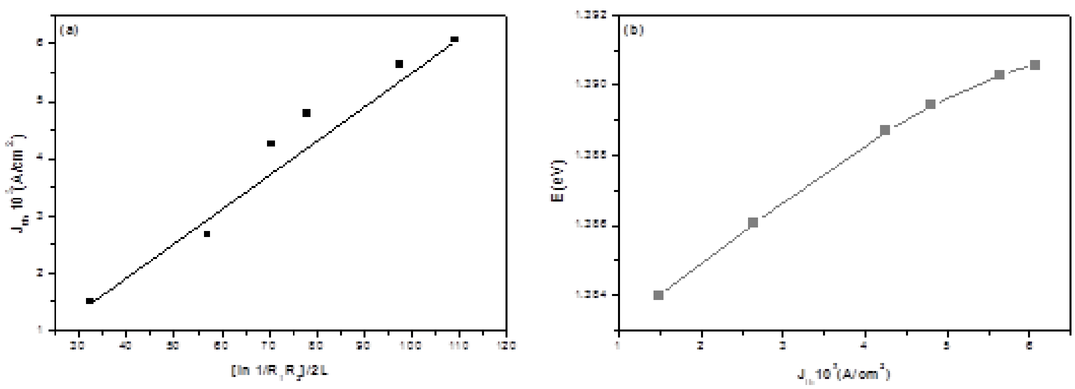

Figure 3: (a) Variation of threshold current density with end loss, and (b) Variation of photon energy with threshold current density for DH laser.

Figure 4(a) shows light output against current characteristics of laser recorded at different case temperatures in the range of (293 – 353 0K). The threshold current for the laser was 0.7 A at case temperature of 293 0K, which is increased to 1.15 A after increasing temperature up to 353 0K. This increase in threshold current due to increased temperature can be attributed to increased carrier concentration. Fig 4(b) shows the linear dependence of threshold current density on case temperature of the DH laser. From the measurements of J_{th} ~ expo (T/T0) [15], the characteristics temperature T0 is determined as 403 0K for DH laser.

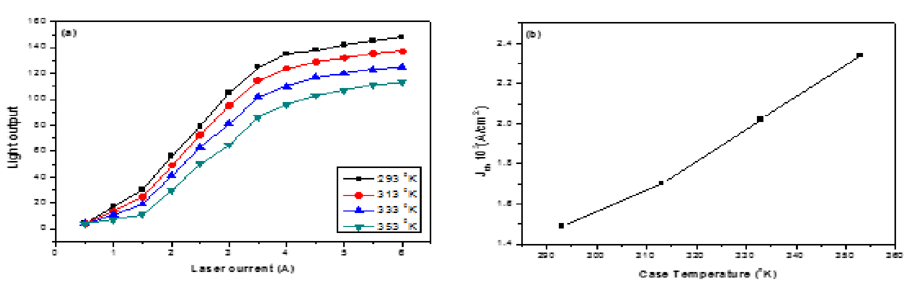

Figure 4: (a) Light output characteristics of DH laser at different case temperatures, (b) Threshold current density versus case temperature for DH laser. (Color online)

The far field patterns of coated and uncoated laser were investigated to check the influence of AR coating on beam divergence of laser beam. As a result, we found that far field patterns both perpendicular and parallel to active region are narrower for ~λ/4 AR coated DH laser and results are shown in Figure 5 and Table 1. The full width at half maximum (FWHM) of the far field pattern perpendicular to the junction plane for the uncoated laser is 330 which is decreased to 300 after ~λ/4 AR coating. Whereas FWHM parallel to the junction plane for the uncoated laser is 250 which is decreased to 200 after ~λ/4 AR coating. These results are in good agreement with previous study[15].

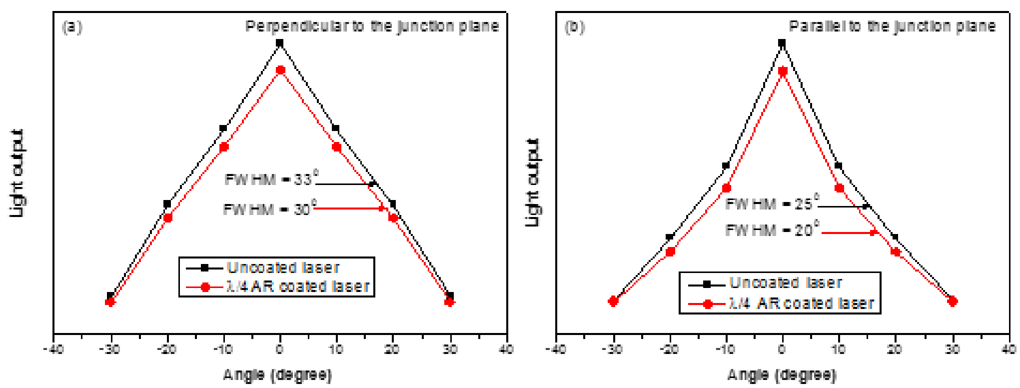

Figure 5: Far field radiation patterns (a) perpendicular to the junction plane and (b) parallel to junction plane measured at 1.5Ith. (Color online)

4. Conclusion

The light output, far field radiation patterns characteristics of semiconductor laser was studied with and without AR coatings of TiO_2 on one facet of the laser. It is observed that the threshold current increases due to decrease in the reflectivity after each successive AR coating of TiO_2. It attains its maximum value after ~λ/4 AR coating beyond optimum coating it decreases. This increase in threshold current is due to large non radiative recombination at higher carrier densities. Reflectivity decreases as the thickness of the film increases up to ~λ/4 AR coating. The photon energy was increased after each successive AR coating due to increased carrier injection. Threshold current was increased after increasing case temperature above room temperature due to increased carrier concentration. The effects of AR coatings of TiO_2 on far field radiation patterns were studied. It is observed that the beam width decreases parallel and perpendicular to the junction plane after AR coating.

Acknowledgment

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