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Laser Induced Damage Studies on Al_2O_3, SiO_2, and MgF_2 Thin Films for Anti-Reflection Coating Application in High Power Laser Diode

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The laser diode facet damage is one of the impeding factors of the high-power laser diode operation. To overcome this restriction laser diode facet coating can be utilized. During the high power operation of the laser diode, it is observed that the single layer anti reflection (AR) coating at the front facet shows optical damage while the multilayer high reflective coating at the back facet remains undamaged. To determine the "*damage threshold*" of the materials used for AR coating, an e-beam evaporated Al_2O_3, MgF_2, and SiO_2 single layer thin films on GaAs substrate have been optimized for the wavelength ~ 1060 nm. The diode pumped Q-switched Neodymium Yttrium Aluminum Garnet (Nd:YAG) laser (1064 nm) was used to damage the samples. The damage on the sample was observed under the microscope. The effective damage radius on the samples was 150 μm and average continuous wave laser induced damage threshold was found > 10 W.

Keywords: Laser induced damage, Antireflection coating, Laser diode.

PACS numbers: 42.79.Wc, 81.15.Jj, 87.64.M –

1. INTRODUCTION

The utilization of the high power laser diodes (HPLDs) increases with technological advancements. The application of the HPLD systems is not only limited to the consumer electronics but also used in high energy systems [1]. Hence, the HPLD is required to operate over a long period of time without any significant degradation in performance. The high power operation of the laser diode is primarily limited due to the thermal rollover and/or the laser facet damage. The thermal limitations of the laser diode can be eliminated by various laser structure designs e.g. quantum well intermixing [2, 3] while the laser facet damage can be improved by facet coating with appropriate dielectric materials besides the laser structure improvement [4].

The laser diode performance improvement can be achieved by single-layer ($\lambda / 4$ thick) anti-reflection (AR) and $\lambda / 4$ thick multi-layer high reflection (HR) coatings at front-and-back facet, respectively [5]. This dielectric facet coating serves as passivation and protection against external effects viz. oxidation, moisture effects, etc. It also enhances the maximum output power and efficiency by modification in facet reflectivity [6, 7], and shows good stability during the long term operation [8]. Hence, with the development of high power laser diode the facet coating with high damage resistance need to be optimized.

The most common practice to investigate the laser diode facet coating properties is the pre- and post-laser diode characterization viz. Optical power (L)-Current (I)-Voltage (V) testing. In addition to that some researchers put efforts to measure the long term reliability and catastrophic optical mirror damage (COMD) test of the laser diode after facet coating. The COMD of the laser diode is a spontaneous (occurs without prior significant) event due to the high power density at the facet region. As the COMD event is random and the theoretical models proposed for the damage mechanism are device dependent. The probability of COMD occurrence in most of the applications of the laser diode is infrequent, especially in case of longer wavelength devices. So it is good to characterize the facet only for its damage threshold rather than characterize it after device facet coating, which costs not only the material processing but also the whole device failure.

One possible way to find the damage threshold of the optical thin-film is the laser induced damage testing. The laser damage threshold (LDT) is defined as the fluence (energy density per unit surface area, J/cm^2) at which an irreversible damage/change occurs in the optical material as a result of laser illumination [9]. Various methods have been demonstrated for measuring the laser induced damage threshold (LIDT) of the thin-film optical coating viz. 1-on-1, S-on-1, R-on-1 etc. A common method is to expose a focused laser beam onto the sample and after illumination the coating is inspected for the damage using microscopy [10], as shown in Fig. 1.

The present manuscript discusses the LDT measurement of the optical thin-films deposited on to the GaAs samples with varying thicknesses viz. $\lambda / 4$, $3\lambda / 4$, and $5\lambda / 4$. The diode pumped Q-switched Neodymium Yttrium Aluminum Garnet (Nd:YAG) laser (1064 nm) was used to damage the samples. The sample prepared for LDT was characterized for its reflectivity before the damage test. The laser induced damage was observed

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initially by visible flash and finally under microscopic observation. The preliminary results show that the damage on the samples was only due to the heating effect rather than optical absorption into the sample. Moreover, there was no significant effect observed on LDT as a function of film thicknesses.

2. EXPERIMENTAL

The single layer anti reflection (AR) coatings of the Al_2O_3, MgF_2 and SiO_2 (MERCK) were deposited in a 270° bend 6 kW electron beam evaporation system in a high vacuum coating unit (Hind High Vacuum Co. (P) Ltd.). The system is equipped with thin film deposition controller (SQC-122c SIGMA) to precisely monitor and control the thickness and deposition rate of the thin film. The single layer coatings were carried out on GaAs substrate and optimized for the wavelength ~ 1060 nm. The substrate was cleaned thoroughly using trichloroethylene (TCE), acetone, and methanol. The AR films have been deposited with constant rate of 2 Å/sec on a rotating substrate (30 rpm). Radiant heater was used to maintain the desired substrate temperature of 200 °C. The reflectivity of the deposited film on a GaAs substrate was measured ex-situ.

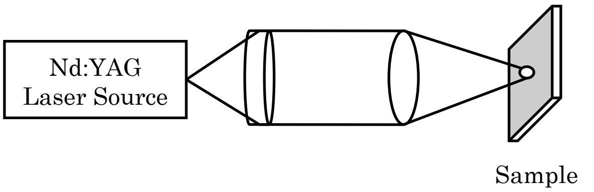

Fig. 1 – The schematic of the laser damage threshold measurement

The standard methods for the laser damage threshold measurement are 1-on-1, and S-on-1 tests [9]. The limitations of these methods are: time consuming complex implementation and data analysis and each experimental condition required to expose a sample to the new damage site. Hence, an unconventional laser damage test has been performed as per the available facility. The LDT test was carried out using diode pumped Q-switched Nd:YAG laser system (Model. Hallmark Diode, Sahajanand Laser Technology Ltd., INDIA). The laser produced a beam with a Gaussian spatial profile. The detail technical specification of the laser system used for pulsed LDT is mentioned in Table 1.

The beam spot size was set by adjusting the distance between sample and positive/focusing lens (focal length = 70 mm) i.e. 1.17 mm for pulsed and 0.39 mm for continuous wave (CW) LDT measurement. (focal length = 77 mm). The sample was adjusted slightly displaced from the normal in order to avoid the effect of interference and reflection of the irradiated laser from the sample to the source. The average output power of the collimated laser beam was measured with power meter (Laser power meter, OPHIR Photonics). The servo motor enables the sample to travel across the laser path (with speed of 200 mm/s) which irradiates the laser with frequency of 200 Hz. The damage sight on the coated sample was observed using a polarization microscope (LABOURLUX 11, Leitz).

Table 1 – Laser system specification used for the pulsed LDT measurement

Laser Source	Diode Pumped, Q-switch Nd:YAG
Wavelength	1064 nm
Beam Mode	TEM_{00}, M2 < 1.2
Laser Power (Avg.)	0.5 to 1.5 W
Pulse width	100 ns
Pulse Frequency	200 Hz
Resolution	1 μ
Output beam diameter	6 mm ($1/e^2$)

3. RESULTS AND DISCUSSIONS

3.1 Reflectivity Measurement

The mirror polished GaAs sample was coated with single layer quarter wave optical thick (QWOT) of different dielectric materials viz. Al_2O_3, MgF_2, and SiO_2. The LDT was measured for the samples with different material thickness viz. $\lambda / 4$, $3\lambda / 4$ and $5\lambda / 4$ optimized for the wavelength ~ 1060 nm. The reflectivity of the coated thin films on GaAs substrate was measured using self assembled reflectivity measurement setup. The experimental reflectivity was measured in reference with standard gold mirror and compared with simulated results. Figure 2 shows the experimental and simulated reflectivity of the optimized sample. The reflectivity simulation was discussed by V.A. Kheraj et al. in detail [11]. The reflectivity measured for other samples with different thickness is shown in Table 2.

Table 2 – The measured and calculated thin film parameters

Material	Thickness (Å)	Reflectivity (%)	
		Exp.	Sim.
Al_2O_3	$\lambda / 4n$	4.89	4.97
	$3\lambda / 4n$	6.63	7.09
	$5\lambda / 4n$	5.63	6.32
MgF_2	$\lambda / 4n$	8.21	8.33
	$3\lambda / 4n$	7.04	8.24
	$5\lambda / 4n$	6.60	6.75
SiO_2	$\lambda / 4n$	5.83	5.75
	$3\lambda / 4n$	5.20	5.32
	$5\lambda / 4n$	6.57	6.61

3.2 LDT Measurement

The samples were irradiated with increasing beam fluence up to 1.5 W average power (starting from 0.1 W with 0.1 W step increase) for pulsed LDT. In case of CW LDT measurement the power was increased up to the damage with 1 W step increase. The spacing between consecutive damage spot with different fluence was kept enough to avoid the intermixing of damage conditioning on nearby damage spots. The preliminary confirmation of the damage to the samples was: by observing spark/flash during irradiation and also using CCD camera (75X zoom) mounted on the laser system. After each irradiation to the sample the damage site's

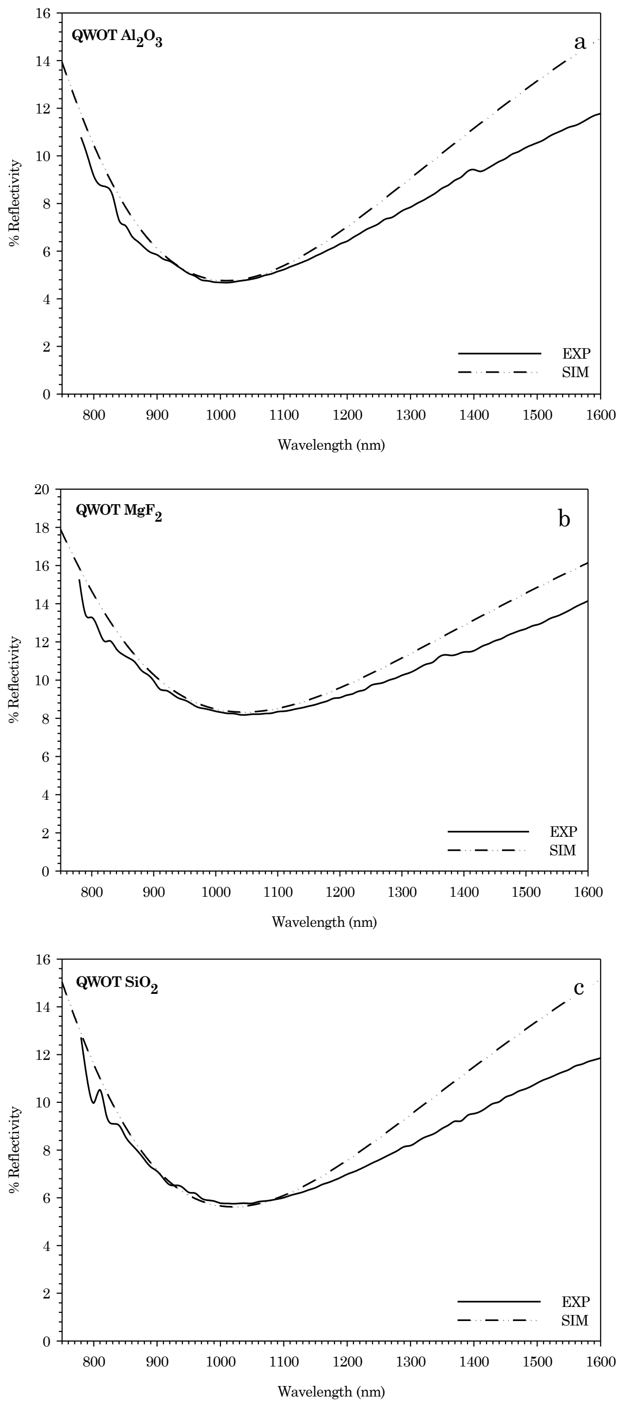

Fig. 2 – Optimized QWOT single layer facet reflectivity curve for Al_2O_3, MgF_2 and SiO_2

snap shot was taken to compare the influence of the increasing damage fluence.

In case of pulsed LDT measurement increase in damage spot diameter with increasing laser power was observed for all samples, as shown in Fig. 3. Table 3 and 4 contains the LDT data of Al_2O_3, MgF_2 and SiO_2 measured in pulsed and CW operation, respectively.

As followed the optical microscopy the damage threshold of the sample with different thickness is almost equivalent and there is no observable difference found.

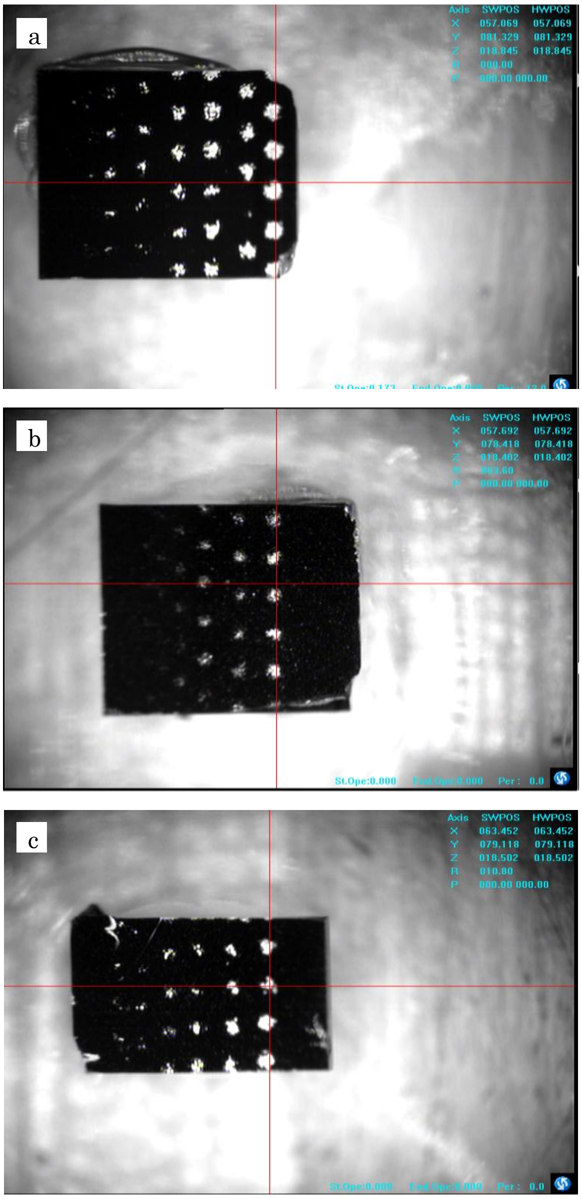

Fig. 3 – Photographs of pulsed laser induced damage for single layer QWOT (a) Al_2O_3, (b) MgF_2, and (c) SiO_2 on GaAs substrate

It has been reported by T.W. Walker et al. that the LDT of the oxide materials shows no significant change as a function of thickness while MgF_2 shows slight variation in LDT with thickness [10]. The microscopic observation of the CW laser induced damaged site clearly illustrates the melt substrate material as shown in Fig. 4.

The damage to the sample is entirely because of the heating effect. The impurity percentage and surface defects in the substrate and the deposited material play a vital role in absorption and heating in to the sample. The absorption of the laser energy leads to the nonradiative relaxation on excited electrons and hence causes the heating. The heat around the irradiated area causes expansion of material and finally melts it. Also, A.V. Kaunar et al. have reported that the GaAs with mirror polished surface has less surface absorption than other rough surfaces and therefore higher

Table 3 – Laser damage threshold (Pulse mode) of materials with beam diameter = 1.17 mm, frequency = 200 Hz, Pulse width = 100 ns

Experimental Parameters	Materials		
	SiO_2	Al_2O_3	MgF_2
Average Power (W)	0.85	0.8	0.7
Energy / pulse (mJ)	4.25	4.00	3.50
Peak power (kW)	42.5	40.0	35.0
Peak power density (MW/cm^2)	3.95	3.72	3.26

Table 4 – Laser damage threshold (CW mode) of materials with beam diameter = 0.39 mm

Experimental Parameters	Materials		
	SiO_2	Al_2O_3	MgF_2
Average Power (W)	10	16	11
Power density (kW/cm^2)	8.37	13.39	9.21

laser damage threshold [12]. The average damage spot site diameter was ~ 150 μm, which leads to CW LDT > 55 kW/cm^2. The COD limit of the commercially available bare high power laser diodes is of the order of few hundred watts. Hence we can certainly utilize this facet coating to improve laser diode COD limit.

4. CONCLUSIONS

The laser damage threshold of the single layer Al_2O_3, MgF_2, and SiO_2 has been measured. The damage on the quarter wave optical thick dielectric films deposited on the GaAs was done by using Q-switched Nd:YAG laser in both pulsed and CW mode. The laser induced damage on the samples was only due to the heating effect. The surface defects and impurity in the deposited thin film causes absorption and hence the occurrence of damage on the surface. The effective damage radius on the samples was ~ 150 μm and average continuous wave laser induced damage threshold was found > 10 W. The optimized single layer QWOT thin films have potential for laser diode facet coating application.

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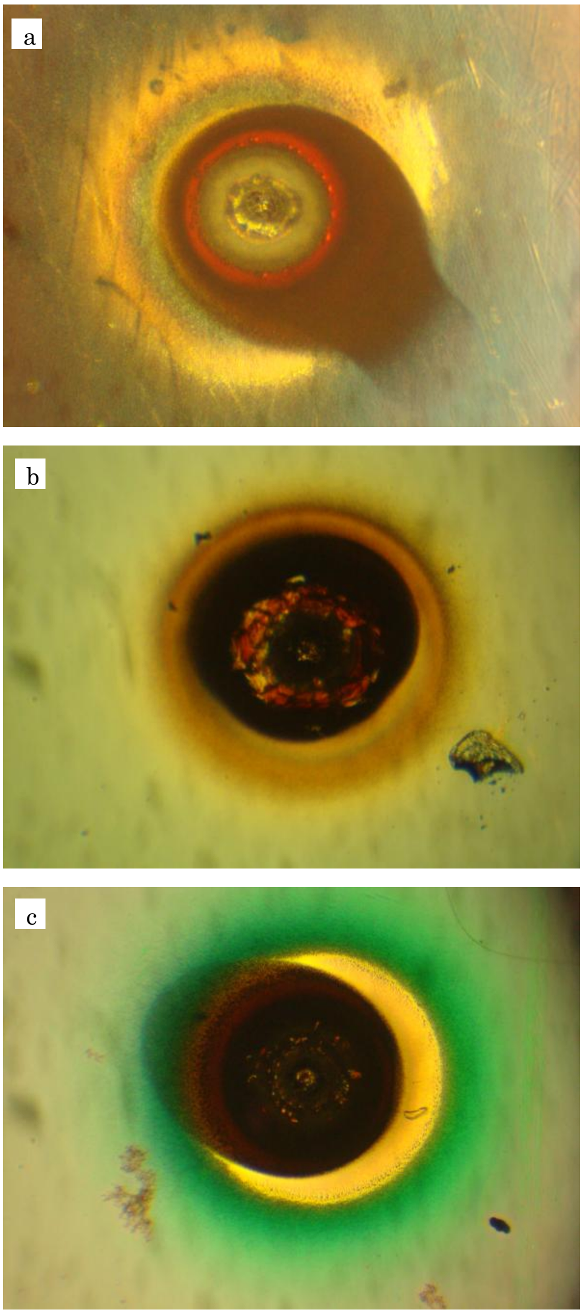

Fig. 4 – Microscopic view of the single layer QWOT (a) Al_2O_3, (b) MgF_2, and (c) SiO_2 CW laser induced damage site

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