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High damage threshold single and double layer antireflection (AR) coatings for Nd:YAG Laser: conventional systems

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This paper gives a comprehensive study of designing, fabrication and determination of damage thresholds of single and double layer antireflection coatings. Single quarter wave layers were prepared form MgF_2 and mixtures of MgF_2 with other fluorides. An oxide-fluoride mixture was also tested. Double layer "V" coatings were studied taking SiO_2 and MgF_2 as low refractive index material in combination with HfO_2, ZrO_2, Ta_2O_5, Nd_2O_3, CeO_2 and TiO_2 as a high refractive index material next to the substrate. All coatings were prepared in a Leybold-Heraeus vacuum coating pant at a base pressure of $\leq$ 1E-5 mbar on Suprasil substrates by conventional electron beam evaporation method. Film thickness was controlled by usual optical method. Reflectance, scattering, absorption and damage threshold were measured. Damage morphology was done by Nomarsky and scanning electron microscopy (SEM). Influence of barrier layers on damage thresholds of AR-2 systems was also investigated. Besides this, an overcoat effect on AR-2 systems with MgF_2 as an outer layer was also observed. Substrate polishing effects on damage threshold of bare as well as AR-coated systems are also reported.

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1. Introduction

Antireflection coatings are of fundamental importance in laser and thin film optical technology. Especially, high power lasers require high damage resistant films. The only approach to improve the coating performance is to produce films with low optical losses and high environmental stability so that their damage threshold could be raised. In general there are several factors such as optical materials, deposition parameters, surface quality of the substrate, and cleaning procedures etc, which influence the damage thresholds drastically. As a matter of fact, laser damage in thin film optical systems is a complicated phenomenon and depend on laser parameters, environmental stability and film production methods. For the last many decades scientists and researchers are trying to find new materials and methods to enhance the damage thresholds. The previously reported damage thresholds lie in the range of 3 - 20 J/cm² [1-13] at 1064 nm. Most of these designs were prepared by TiO_2 / SiO_2 and Ta_2O_5 / SiO_2. However, during the last decade major stress was given to the material HfO_2 and SiO_2 being very low absorbing materials. In the present investigation, a detailed study of AR-systems prepared by conventional electron beam evaporation with existing standard materials as well as with some mixtures has been made. Various methods were employed to improve the damage thresholds.

2. Damage mechanism in antireflection coatings

In AR-coatings damage usually occur at the film-substrate interface because in the ideal case this interface is affected by the intensity equal to the incident radiation. The damage mechanism in these systems is mainly influenced by the presence of residual contaminations of polishing compounds. Moreover, glass substrates some times have manufacturing defects such as pits, voids, cracks and other absorbing inclusions on the surface [13]. For the reduction of this effect, a $\lambda/2$ layer of SiO_2 is put next to the substrate which provides a physical and chemical isolation between first layer and substrate and possibly improves the quality of the surface. Field intensities in this barrier layer remain constant and do not affect the optical properties of the system.

The concept of interface absorption in HR and AR systems has been discussed by Bennet et al [14], who developed simple theoretical expressions to calculate absorptions at substrate-film or film-film interfaces. An experimental technique to separate volume and interface absorption is given by Ristau et al [15]. They found that the absorption in the vicinity of a thin film interface may be larger than in the entire film volume. A possible method of avoiding this effect is to prepare layer systems with inhomogeneous or gradual interfaces.

In antireflection coatings MgF_2 is frequently used as a low refractive index material. Coatings of this material prepared by conventional systems show more inherent stress than other materials. Especially in the case of AR-2 designs with MgF_2 as an upper layer which may have high stresses. If such surfaces are exposed to the intense laser radiation, damage may occur at the surface producing cracking or other types of damages in the film.

In AR-systems intensity distribution play an important role in producing damage. The problem of field intensity distribution in single and multilayer was first dealt by Veremei etal [16]. Studies to understand the phenomena of damage in thin films suggested that the internal field intensity distributions in a layer system could play an important role to spell disaster. The absorption of radiation at any point is directly proportional to the field intensity at that point. In order to minimize the likelihood of damage, layers which exhibit high field intensities should be carefully designed so that possible sources of absorption are reduced. Field intensities and their effect on absorption and damage threshold have been discussed by many authors [17,18]. Mathematical formulation and computational methods to obtain standing wave field pattern for layer systems can be found in published literature [18].

High damage resistant antireflection coatings require additional design considerations in addition to zero reflectance condition. A general criteria is that the absorption is greater in high refractive index layer as compared to low refractive index layer. Therefore, non-quarter wave designs are preferred for high power applications. The thickness of the design is so optimized that high refractive index layer is less than a quarter wave in order to minimize absorption losses. The role of intensities in an antireflection system is fixed because of the pre-condition R=0. Under this condition the electric field strength is always one at the film-substrate interface and the intensity is equal to the ratio of the refractive index of the high refractive index layer to that of the substrate. However, we have used a computer program which yields standing wave field patterns and calculate intensities at every point in the system in order to design our AR-2 coatings. Thickness of both the materials is so optimized that standing wave pattern shows no reflection wave in the air. We have selected HfO_2, ZrO_2, Ta_2O_5, TiO_2, Nd_2O_3 and CeO_2 as the high refractive index materials in combination with SiO_2 and MgF_2 as low refractive index material. As an example, we show the standing wave field pattern of the AR-2 coating of HfO_2/ SiO_2 and CeO_2/MgF_2 in Fig. 1a & 1b, respectively. The field pattern in the air do not show any reflection wave, this means R=0 and the incident wave is totally transmitted.

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The optimized optical thickness for the said designs are .46/1.26 and .44/1.23 (in quarter wave), respectively. To increase the damage threshold of multilayer systems, a $\lambda/2$ layer of SiO_2 or some other material is sometimes used as an undercoat or overcoat layer. Field intensities in such a half wave barrier or overcoat layer remain constant and do not affect the optical properties of the system.

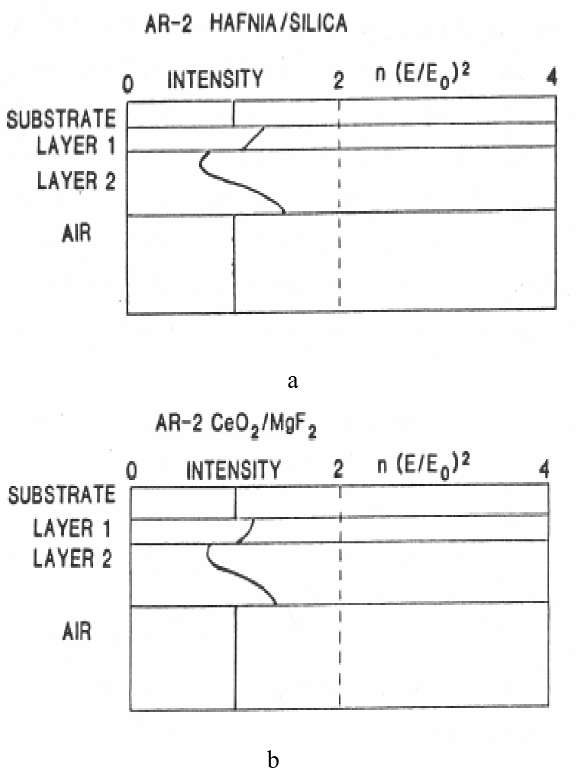


Fig. 1. Standing wave field pattern of AR-2 designs: (a) AR-2 HfO_2/ SiO_2, (b) AR-2 CeO_2/MgF_2.

3. Material selection, deposition method and damage experiment

For designing AR-systems, low refractive index materials are essentially required. Unfortunately, only few suitable materials such as SiO_2 and MgF_2 are available for preparing hard AR-coatings. Previously, we had performed a study on dielectric materials, which is presented elsewhere [20], and on selected materials which showed low absorption coefficients and scattering. Various oxides were selected as a high refractive index material in combination with SiO_2 and MgF_2 as a low refractive index material in order to design and fabricate AR-2 "V" coats. These coating designs give zero reflectance at single wavelength which is in our case 1064 nm for Nd-YAG laser. All the materials were deposited at a base pressure of $\leq$ 1E-5 mbar by two E-gun sources. Deposition parameters, for example substrate temperature, evaporation rate and partial pressure of oxygen (in case of oxides) were selected for minimal optical losses. All the samples were prepared on Suprasil II substrates.

Laser Induced Damage Threshold (LIDT) was determined using a high power, pulsed Nd-YAG laser with an amplification stage. The experimental setup for damage studies is shown in Fig. 2.

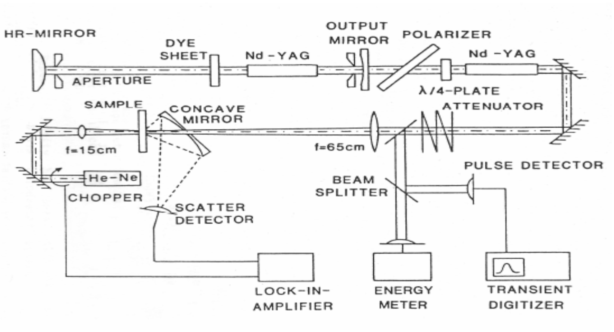


Fig. 1. Experimental setup for damage experiment.

The measurements were taken with a pulse width of 14 ns (FWHM) and a beam diameter of 300 micron. A rectangular matrix was formed on the test sample with a minimum of 20 to 30 shots on the basis of one pulse per site. For the damage detection laser scattering method was used. The damage sites were then inspected by Nomarsky or Scanning Electron Microscope (SEM) technique. Damage thresholds were determined by taking an average between the highest energy density at which NO DAMAGE and lowest value of energy density at which DAMAGE takes place. The experimental parameters for damage experiment are listed below:

Test wavelength	1064 nm
Sample preparation	Dry Nitrogen blow
Test geometry	In focus of a convergent beam
Lens focal length	650 mm
Spot diameter at sample ($1/e^2$ intensity)	300 micrometers
Angle of incidence	Normal
Test site array	Rectangular
Test site separation	2 mm
Pulse per site	1

Pulse per sample	25, minimum
Laser source	Nd: YAG
Polarization	Linear, horizontal
Mode of operation	TEMoo
Temporal profile	Gaussian
Spatial profile	Gaussian
Pulse duration (FWHM)	14 ns
Damage definition	Scatter change
Detection of damage event	He-Ne scatter. Nomarsky & SEM

4. Results and Discussion

4.1 Single Layer AR-Coatings

For glass, single layer antireflection coatings are normally prepared by depositing a quarter wave layer of MgF_2. It is the only hard low refractive index material which is available for such purposes. CaF_2 is another low refractive index material but it is not useable because of its softness and poor adhesion to the glass. Among oxides, SiO_2 is a hard low refractive index material but cannot be used as a single layer AR-coating due to its mismatch with substrate material and also because of relatively high refractive index than MgF_2. In order to look for new high damage threshold materials[20] for AR coatings, we have not only studied AR-1 systems by preparing quarter wave layers of pure MgF_2 but also by preparing mixtures of MgF_2 with CeF_3, CaF_2, SrF_2 and NdF_3 on Suprasil II substrates. As an additional exercise, a mixture of SiO_2 + CaF_2 was also tried. Such sort of oxide-fluoride mixtures have been reported by Austin et al [20] for SiO_2 and MgF_2 as a single inhomogeneous layer to reduce stress in the film. Results of our observations on refractive indices, scattering, reflectance, absorption and damage threshold for the investigated systems are listed in table 1.

Table 1. Results of AR-1 layers (λ/4) prepared with MgF_2 and various mixtures at 1064 nm.

Material	Refractive Index (n)	Total Integrated Scattering (%)	Reflectance R (%)	Absorption A (ppm)	Damage Threshold (J/cm^2)
MgF_2	1.38	0.02	1.13	58	49 ± 12
$MgF_2 + CeF_3$ (10%)	1.36	0.03	1.21	26	38 ± 3
$MgF_2 + CaF_2$ (10%)	1.36	0.05	1.20	93	35 ± 6
$MgF_2 + SrF_2$ (4%)	1.35	0.06	1.39	331	31 ± 5
$MgF_2 + NdF_3$ (4%)	1.36	0.04	1.37	718	42 ± 9
$MgF_2 + CaF_2$ (2:1)	1.35	0.03	1.10	57	69 ± 13

In fluorides, pure MgF_2 with CeF_2 shows a reduction in absorption approximately by a factor of two but no improvement has been noticed in damage threshold. Other mixtures with CaF_2, SrF_2 and NdF_3 show an increase in absorption & scatter values. All these Fluoride - Fluoride mixtures exhibit almost the same damage thresholds within their error limits. Lowest reflectance is obtained by pure MgF_2 films and with the mixtures of CeF_3 and CaF_2.

SiO_2 + CaF_2 mixture gives the best results. It has the lowest refractive index and reflectivity. Absorption is of the order of MgF_2 and has the highest damage threshold (69J/cm²). Scattering value is increased a little bit from the pure MgF_2 film. Films are found to be hard and resistant. If we compare the values of damage thresholds of pure MgF_2 and this mixture, it is clearly evident that the mixture of SiO_2 + CaF_2 shows an increase in damage threshold by 40% whereas the spread in damage thresholds6 of these two materials is approximately the same.

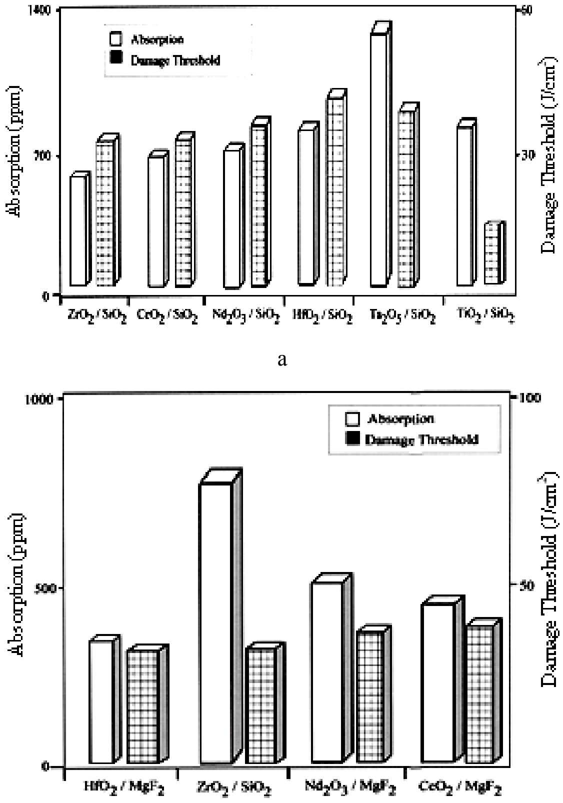
4.2 Double Layer Antireflection Coatings

Table 2 shows the results of AR-2 systems. All designs are fabricated with non-quarter wave layer thicknesses. Reflectance for most of the designs are measured to be less than 0.20% at 1064 nm. Looking on to the absorption and damage threshold values for coatings with SiO_2 as low refractive index outer layer, it is apparent that ZrO_2/SiO_2 gives the lowest absorption but it does not show the highest damage threshold. On the other hand, Ta_2O_5/SiO_2 shows the highest absorption but damage threshold is also high. Best result is obtained by HfO_2/SiO_2 system (46/J/cm²).

Table 1. Double layer antireflection coatings, AR-2.

Material / SiO_2	**Designs in Q-wave optical thicknesses**	**Reflectance [%]**	**Absorption [ppm]**	**Damage Threshold [J/cm^2]**
HfO_2	.46 / 1.26	.15	748	46 ± 3
ZrO_2	.55 / 1.22	.13	510	35 ± 1
Ta_2O_5	.38 / 1.30	.43	1242	43 ± 1
Nd_2O_3	.54 / 1.22	.12	670	10 ± 5
CeO_2	.80 / 1.10	.33	639	35 ± 4
TiO_2	.28 / 1.35	.31	769	14 ± 3
Material / MgF_2				
HfO_2	.35 / 1.28	.11	347	32 ± 2
ZrO_2	.39 / 1.26	.10	816	32 ± 3
Nd_2O_3	.40 / 1.22	.14	517	37 ± 6
CeO_2	.50 / 1.21	.09	451	39 ± 5

Fig. 3a shows the histograms of absorption and damage threshold for AR-2 coatings with SiO_2 as an outer layer. Similar results were obtained by systems with MgF_2 (Fig. 3b). The damage thresholds for Nd_2O_3/MgF_2 and CeO_2/MgF_2 are relatively higher than HfO_2 and ZrO_2 systems. It is interesting to note that these two materials show a very low value of damage threshold as a single layer [11-20] and in AR-system prove to be the best. This suggests that they may have a strong dependence on film thickness because in AR-systems high refractive index CeO_2 and Nd_2O_3 have very small thicknesses. TiO_2 is a high absorbing material [19] that is why it shows a low value of damage threshold in TiO_2/MgF_2 system. If we compare the designs of oxides with that of MgF_2, it is apparent that AR-2 coatings with both oxides prove to be better than systems with Magnesium fluoride regarding damage threshold. The behavior of absorption in both types of systems is different. In all coatings with both oxides, absorption is found to be higher than designs with MgF_2. Such a behavior is ambiguous and is difficult to explain. Each sample has been prepared three times and the damage thresholds were found to be fairly reproducible. It is evident from the overall results that absorption is not the only factor which affect damage threshold of these systems. No correlation can be established between absorption and damage threshold.



a

b

Fig. 3. Histogram of absorption and damage threshold: (a) AR-2 with SiO_2 as an outer layer. (b) AR-2 with MgF_2 as an outer layer.

4.3 AR-2 with low refractive index mixtures

AR-2 designs prepared with low index mixtures of MgF_2+CeF_3 and SiO_2+CaF_2 in combination with high index oxides behave differently in relation to absorption and damage threshold. The results of these measurements are listed in Table 3.

Table 2. AR-2 Coatings with low refractive index mixtures.

Material / MgF_2+CeF_3	Designs in Q-wave optical thicknesses	Reflectance [%]	Absorption [ppm]	Damage Threshold [J/cm^2]
HfO_2	.31 / 1.28	.26	128	28 ± 5
ZrO_2	.35 / 1.26	.11	347	32 ± 6
Nd_2O_3	.34 / 1.26	.17	411	31 ± 6
CeO_2	.44 / 1.22	.25	466	24 ± 2
MgO	.70 / 1.12	.11	560	37 ± 4
TiO_2	.20 / 1.32	.12	126	15 ± 2
Material / SiO_2 + CaF_2				
HfO_2	.35 / 1.28	.11	347	38 ± 10
ZrO_2	.39 / 1.26	.10	816	38 ± 7
Al_2O_3	.40 / 1.22	.14	517	35 ± 4
CeO_2	.50 / 1.21	.09	451	37 ± 9

No improvement in damage threshold was observed but a reduction in absorption is clearly visible in systems with MgF_2+CeF_3 as compared to pure MgF_2. On the other hand, AR-2 designs with SiO_2+CaF_2 mixture exhibit an increase in absorption, though the damage threshold lies in the same range as in the case of pure SiO_2. In fact, it is difficult to expect any regular trend or behavior in dealing with different kind of dielectric mixtures. The procedure of mixture preparation and its application in multilayer optics is more related to trial and error method. Among AR-2 coatings with MgF_2+CeF_3 as an outer layer in conjunction with MgO gives the highest damage threshold but these coatings show a poor environmental stability and are not useable for high power laser applications. Systems with ZrO_2 and Nd_2O_3 have nearly the same damage threshold. It is difficult to explain the behavior of systems with oxide-fluoride mixture. Normally such mixtures react chemically, affecting the absorption and damage threshold. One candidate for such type of a reaction is Ta_2O_5 and MgF_2 in which a drastic increase in absorption and decrease in damage threshold was observed. It may be possible that AR-2 systems with SiO_2+CaF_2 as a low refractive index outer layer show similar reactions which in turn increase the absorption.

4.4 Barrier Layers

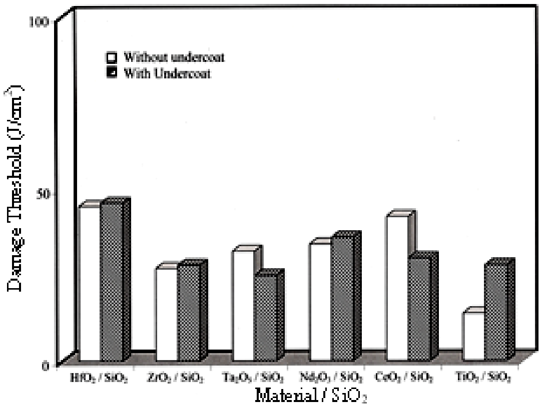
The improvement in damage thresholds of AR-coatings due to barrier layer has been reported by many authors [21,22]. The results show different behaviors depending upon the material of undercoat, thickness of the barrier layer, coating design and wavelength.

Table 3. Shows results of AR-2 coatings with and without a barrier layer

Material / SiO_2	Damage Threshold [J/cm^2]	
	Without Undercoat	With Undercoat
HfO_2	45 ± 1	46 ± 6
ZrO_2	27 ± 6	28 ± 1
Ta_2O_5	32 ± 5	25 ± 8
Nd_2O_3	34 ± 4	36 ± 4
CeO_2	42 ± 2	30 ± 7
TiO_2	14 ± 3	28 ± 1
Material / MgF_2		
HfO_2	31 ± 4	18 ± 1
ZrO_2	39 ± 6	40 ± 2
Nd_2O_3	36 ± 7	24 ± 4
CeO_2	37 ± 5	22 ± 9

Sometimes an increase and sometimes no change or decrease of damage threshold was observed. In most of the cases, the results have been reported for systems with TiO_2. The results of these studies cannot be compared with ours due to un-identical experimental conditions. As an approach to improve the damage thresholds of the antireflection systems, we have also prepared systems with a barrier layer. A λ/2 layer of SiO_2 was deposited between substrate and first high refractive index layer. The designs without and with undercoat were prepared in the same batch. Results of this experiment have been listed in Table 4.

Fig. 4a shows the histogram of damage thresholds for AR-systems with SiO_2 as an outer layer. It can easily be noticed that designs with HfO_2, ZrO_2, Ta_2O_5, Nd_2O_3 and CeO_2 does not show any noticeable improvement in damage threshold. Only in the case of TiO_2/SiO_2, effect of an undercoat was clearly observed in which threshold was increased by a factor of two. Similarly designs with MgF_2 (outer layer) in combination with HfO_2, ZrO_2, Nd_2O_3 and CeO_2 does not show improvement (Fig. 4b). In some cases, damage threshold is rather decreased. According to our results it is obvious that barrier layers do not play any effective role in most of the AR-2 coatings.



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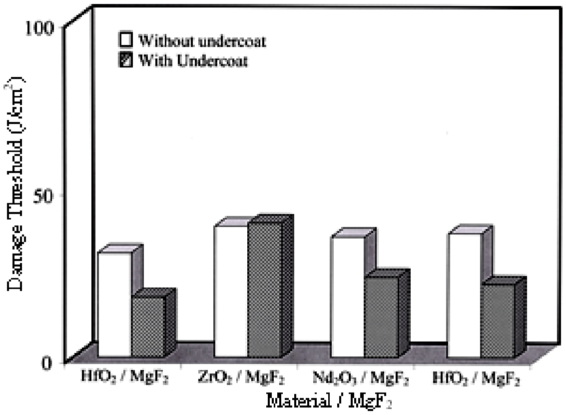

b

Fig. 2. Histogram of damage threshold for AR-2 coatings with and without a barrier layers a. AR-2 systems with SiO_2 as an outer layer. b. AR-2 systems with MgF_2 as an outer layer.

4.5 Overcoats

Overcoats are mainly used to increase the damage thresholds of high reflection mirrors [22]. However, in the present investigation, effect of an overcoat as well as an under and overcoat layer of SiO_2 (λ/2) has also been under taken in AR-systems with MgF_2. An antireflection design of CeO_2 / MgF_2 was deposited without under & overcoat, with overcoat and with under and overcoat. Results (table 5) of such coatings revealed that an overcoat layer enhances the damage threshold. Sample with under and overcoat shows a decrease in damage threshold.

Table 4. Results of an overcoat layer (SiO_2) on some AR-2 designs with MgF_2 as low refractive index material.

Sample	Scatter without overcoat [%]	Scatter with Overcoat [%]	Damage Threshold [J/cm²]		
			Without U&O-Coat	With O-Coat	With U&O-Coat
CeO_2 / MgF_2	.04	.07	32 ± 8	41 ± 3	24 ± 9
HfO_2 / MgF_2	.03	.07	37 ± 6	42 ± 13	------
ZrO_2 / MgF_2	.02	.03	32 ± 6	45 ± 4	------

In CeO_2 / MgF_2 with under and over coat layers, there is a considerable decrease in damage threshold. This can be explained on the basis of increased number of interfaces, which in turn increase the absorption and scattering in the layer system. To see the reproducibility of the overcoat effect, two other designs with HfO_2/MgF_2 and ZrO_2/MgF_2 were deposited without and with overcoat in the same batch. Now, if we compare the results of damage thresholds of these three designs, an average increase of damage threshold is being found in systems with an overcoat layer of silica. Stress is the main cause of damage in MgF_2 films. The improvement in damage threshold due to an overcoat layer of Silica can be explained on the basis of stress compensation in such systems. Inherent stresses are normally generated in MgF_2 layers during evaporation process. An overcoat layer of SiO_2 may stabilize the inherent stress in MgF_2 film and make the layer damage resistant. Although damage threshold is increased, an increase in scatter is also observed. Fig. 5 shows the histogram of damage threshold for overcoat layers.

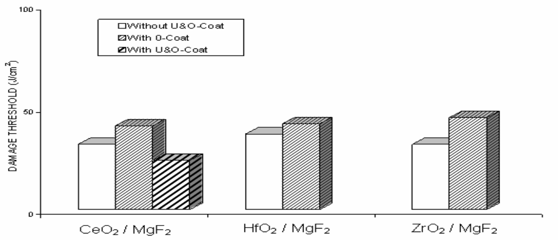

Fig. 3. Histogram of damage threshold for AR-2 coatings (MgF_2as low refractive index material) with an overcoat layer of SiO_2 (λ/2).

4.6 Polished Surfaces

In order to study substrate polishing effects on AR-coatings, BK-7 substrates (6 mm thick and 25 mm in diameter) were prepared by pitch polishing method (OPTIK HANDEL GmbH). Three types of polishing compounds were used to treat the BK-7 surfaces for three sets of samples P-1, P-2 and P-3. First sample, P-1 is polished by a mixture of Cerium oxide (65%, grain size: 3u) and Aluminum oxide (35%). A commercially available powder Opaline + Cerium oxide (99.9%, grain size: 2u) was used to prepare sample P-2 and the third surface P-3 was treated by a mixture of Cerium oxide (70%, 2.5u) + Ceri 600 + Aluminum oxide. After polishing, all the samples were further treated for 30 minutes in distilled water in order to remove the polishing contaminations. Some early work regarding substrate effects and laser – induced damage threshold has been reported which shows a strong dependence of surface roughness on damage thresholds [23]. However, our studies on single films of various materials, revealed no such dependence [19].

Table 5. Total Integrated Scattering values of three types of polished substrates and damage thresholds of bare as well as AR-coated surfaces.

Sample	Polished BK-7 (P-1) Th = 6 mm	Polished BK-7 (P-2) Th = 6 mm	Polished BK-7 (P-3) Th = 6 mm
Grain size [µm]	3.00	2.00	2.50
Total Integrated Scattering [%]	0.03	0.01	0.02
Damage Threshold [J/cm²]			
Uncoated Substrates	68 ± 12	76 ± 1	72 ± 5
AR-2 HfO_2 / SiO_2	35 ± 5	47 ± 16	38 ± 6
AR-2 Ta_2O_5 / SiO_2	38 ± 1	44 ± 3	30 ± 10
AR-2 Nd_2O_3 / MgF_2	24 ± 3	34 ± 6	15 ± 3

Results of scattering measurements and damage threshold for uncoated polished substrates are listed in table 6. In case of uncoated substrates, two conclusions can be drawn from scatter and damage threshold values:

1) If the grain size of the polishing compound is increased, scatter is increased.

2) Damage threshold is found to be the same within the error limits for all the substrates polished with different grain sizes.

Three different AR-2 designs of HfO_2 / SiO_2, Ta_2O_5 / SiO_2 and threshold values for these designs are also listed in the same table. In AR-2 systems with Silica as an outer layer, if we compare the results, damage thresholds are found to be almost same within their error limits. Polishing of the substrates with different grain sizes does not exhibit a profound influence on damage thresholds. However, qualitatively we can say that coatings deposited on sample P-2 (Polished with 2 micrometers grain size powder) exhibit better results regarding damage thresholds. AR-2 coatings with MgF_2, prepared on polished substrates P-1, P-2 and P-3 show a marked increase in damage thresholds. Although no trend is apparent in these systems too, but best results have been obtained by the coatings prepared on P-2 substrates. Histogram of damage threshold for uncoated polished surfaces and AR-coated substrates are depicted in Fig. 6.

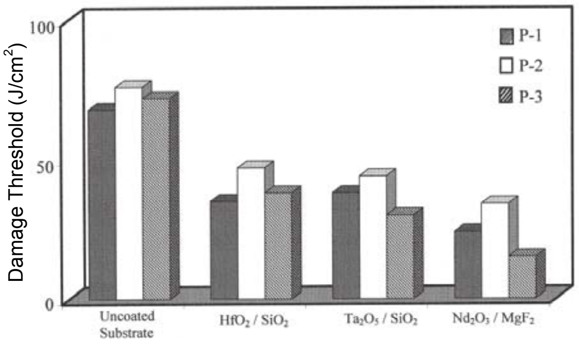

Fig. 4. Histogram of damage threshold for bare BK7 as well as AR-2 coated polished surfaces P1, P2 and P3.

5. Damage morphology

In general, all AR-2 coatings with SiO_2 and MgF_2 as an outer layer show a removal of upper layer due to absorption and stress. In the beam center where energy is maximum, a total removal of both high and low refractive index material is observed. This sort of peel off or de-lamination suggests a poor adhesion at the film-film interface. Fig. 7 shows the Nomarsky photograph of a damage spot at Ta_2O_5/SiO_2 AR-2 coatings. Among oxide-fluoride AR-2 systems, some designs such as Nd_2O_3/MgF_2 exhibit a parquet structure. This type of damage is only observed in Nd_2O_3/MgF_2 coatings. The reason for such damage is stress which is normally present in MgF_2 coatings. The reason for such damage is stress which is normally present in MgF_2 films. Another reason could be an adhesion problem between Nd_2O_3 and MgF_2.

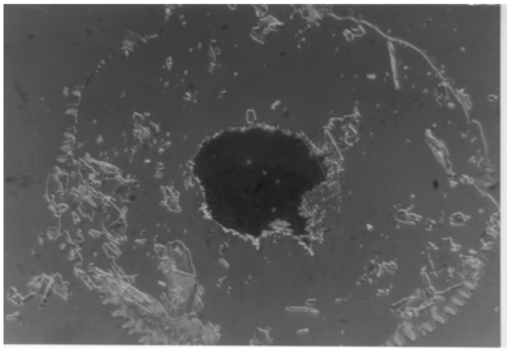

Fig. 5. Optical Nomarsky micrograph (×250) of Ta_2O_5/ SiO_2 AR-2 coating on Suprasil at 80J/cm².

The damage morphology of AR-2 systems with undercoat layer reveals similar type of damage as without undercoat, in most of the cases. In some samples like ns / SiO_2/ ZrO_2 / MgF_2 / air absorption + inclusion damage was observed. Low energy damage spots show a de-colouration of the upper layer only. For systems with an overcoat layer for example ns/HfO_2/MgF_2/SiO_2/air show a pure inclusion damage. No removal of the upper layer is observed. Scanning electron micrograph (Fig. 8) exhibits craters, pinholes and other defects in the center. Rest of the area seems to be undamaged.

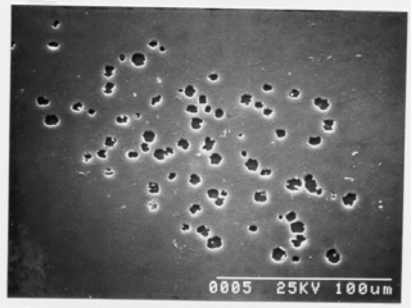

Fig. 6. Scanning electron micrograph of HfO_2 / MgF_2 AR-2 coating an overcoat layer of SiO_2 on Suprasil at a fluence of 33 J/cm².

6. Conclusions

The main results of our study on high damage threshold AR-systems are summarized as follows:-

For single layers, quarter wave MgF_2 layer gives the best result as for as pure material is concerned. Among mixtures, AR-1 with Silicon dioxide + Calcium fluoride shows a significant improvement in damage threshold. For double layer 'V' coats, damage threshold vary from 14-46 J/cm². Design with HfO_2 / SiO_2 gives the highest damage threshold (46J/cm²). Two other designs with Neodymium and Cerium oxide in combination with Magnesium fluoride prove to be the best with damage thresholds of 37 and 39 J/cm², respectively. AR-2 coatings prepared with low refractive index mixtures do not show any improvement in damage thresholds. In most of the designs, barrier layers of Silica do not show any profound influence on damage threshold. However, AR-2 designs with MgF_2 show an overcoat layer (λ /2, Silica) effect. In all the coatings prepared for this purpose, an increase in damage threshold by 15-40% was observed. In order to study the effect of substrate polishing on different AR-2 coatings, laser grade (λ /10) BK-7 substrates were prepared by pitch polishing method. Scatter and damage thresholds are found to be dependent on grain sizes of the polishing compounds. AR-2 coating with HfO_2/SiO_2 again demonstrated highest damage threshold value of 47 J/cm² on P-2 sample (polishing compound grain size: 2 micron). Damage morphology of AR-systems exhibit mixed damage mechanisms. In most of the coatings a de-lamination of the low refractive index upper layer was observed to be damaged.

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