

# **Center for Research in Electro-Optics and Lasers**

## **CREOL**



### **FINAL REPORT TO**

### **NASA LANGLEY RESEARCH CENTER**

### **Laser Damage of HR, AR-coatings, Monolayers and Bare Surfaces at 1064 nm**

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**ABSTRACT**

Laser induced damage thresholds and morphologies have been investigated in the variety of uncoated and coated surfaces including monolayers and multi-layers of different chemical compositions. Both antireflective (AR) and highly reflective (HR) were tested. Testing was done at 1064 nm with 25 picosecond and 8 nanosecond YAG:Nd laser single pulses. Spot diameter in the experiments varied from 0.09 to 0.22 mm. Laser damage measurement procedure consisted of 1- on-1 (single laser pulse in the selected site) and N-on-1 experiments including repeated irradiation by pulses of the same fluence and subsequently raised from pulse to pulse fluence until damage occurred.

The highest picosecond damage thresholds of commercially available coatings averaged 12- 14 J/cm<sup>2</sup>, 50% less than thresholds obtained in bare fused silica. Some coatings and bare surfaces revealed a palpable preconditioning effect (an increase in threshold of 1.2 to 1.8 times). Picosecond and nanosecond data were compared to draw conclusions about pulsewidth dependence. An attempt was made to classify damage morphologies according to the type of coating, class of irradiating and damage level.

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Key words: laser damage, dielectric coatings, bare surfaces, picosecond pulses.

**2. INTRODUCTION**

The amount of investigation of optical resistance of dielectric coatings and bare surfaces to the action of ultrashort picosecond laser pulses is modest compared to the numerous works carried out in this field using conventional (nano-, micro-, and millisecond) laser pulses. The first extensive publications concerning this problem appeared in 1976-1977 [1-5]. Following that, few fragmentary reports appeared in the literature prior to the early 1990's. In 1992, new work on this topic was reported [6]. In ref [1] a variety of bare surfaces of the glasses, metals, polymers, and dielectric coatings including HR, AR and monolayers ZrO<sub>2</sub>, MaF<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> were tested using 125 ps laser pulses at 1064 nm. In ref [2] dielectric coatings TiO<sub>2</sub>, ZrO<sub>2</sub>, HfO<sub>2</sub>, SiO<sub>2</sub> were investigated with 30 ps pulses at 1064 nm and its harmonics (532 nm, 355 nm). The influence of the substrate material, substrate roughness, and deposition technique on the damage threshold was established in [3,4,5] where 150ps pulses at 1064 nm were used. Surface damage threshold values were also measured in these references. All the above thresholds were found to be relatively high : 12.7 J/cm<sup>2</sup> for fused silica [4], 10J/cm<sup>2</sup> for BK-7 [5], and 2-6 J/cm<sup>2</sup> for dielectric coatings [1,2,4].

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In later publications [7, 8, 9] the damage threshold of  $\text{ZrO}_2/\text{SiO}_2$  HR coating was reported at 1064 nm with 35 ps pulses. Authors of [10] conducted experiments in the subnanosecond range (0.6 ns).

It is important to complete the knowledge base of picosecond laser-induced damage for both fundamental and applied considerations. Ultrashort pulse lasers are now widely used with more powerful picosecond and femtosecond lasers being developed. The high intensity output of such lasers place serious demands on the optical elements of these lasers, particularly the surfaces and coatings of such components.

The investigation of laser-induced damage of surfaces in the pulsewidth range considered is aimed at clarifying the nature and mechanisms of damage, search for most resistant optical coatings and, in the end, recommendations for upgrading the coating technologies, starting from the selection of materials to the technique of their deposition. All the problems posed cannot be resolved in one single work, therefore emphasis was placed upon:

- accumulation of evidence on a large variety of surfaces and coatings.
- clarification of the main features of laser-induced breakdown, in particular, the dependence of the breakdown threshold upon the laser pulsewidth.
- precise measurement of threshold values.
- systematization of the obtained damage morphology data according to types of coatings, materials, conditions of laser action (single and multiple irradiation; conditioning).

### 3. EXPERIMENTAL

Figure 1 represents a block-diagram of the experimental set-up for picosecond laser-induced surface damage studies used in our work. A highly stable YAG:Nd laser with hybrid active-passive mode locking generated single picosecond pulses with the repetition rate up to 10 Hz at 1.06 microns. The pulses featured a smooth, Gaussian-like spatial-temporal intensity distribution:

$$I = I_0 \exp \left[ \left( \frac{-R}{R_0} \right)^2 - \left( \frac{T}{T_0} \right)^2 \right]$$

and output energy up to 10 mJ. Pulse duration  $T_0$  was measured to be 25-28 ps, and beam radius  $R_0=1.45$  mm. Energy variation from pulse to pulse did not exceed 5-7%. The radiation spatial profile of the input beam was measured by means of pinhole beam scans and the pulsewidth was measured by a conventional correlation method. The energy of the laser pulses was varied with an attenuator consisting of a polarizer and a half-wave plate rotated by a computer driven stepping motor (STAGE-1 in fig. 1). The pulse energy of each shot was monitored by a calibrated pyroelectric detector D1.

A long focal length ( $F=245$  mm) sapphire lens was used to increase the intensity of the laser radiation acting upon the material surface. Locating the sample behind the lens in a converging beam allowed displacement along the axis such that the diameter of the spot on the irradiated surface varied from 0.09 to 0.22 mm (FW 1/e M). The radiation intensity distribution on the surface was thoroughly analyzed with a 10 micron aperture at different positions of the beam revealing a slightly elliptical shape (15%) of the Gaussian beam cross section which was taken into account in the irradiance calculations. The above dimensions of the beam correspond to average values. The step driver STAGE-2 moved the sample perpendicular to the beam to change the sites for exposure.

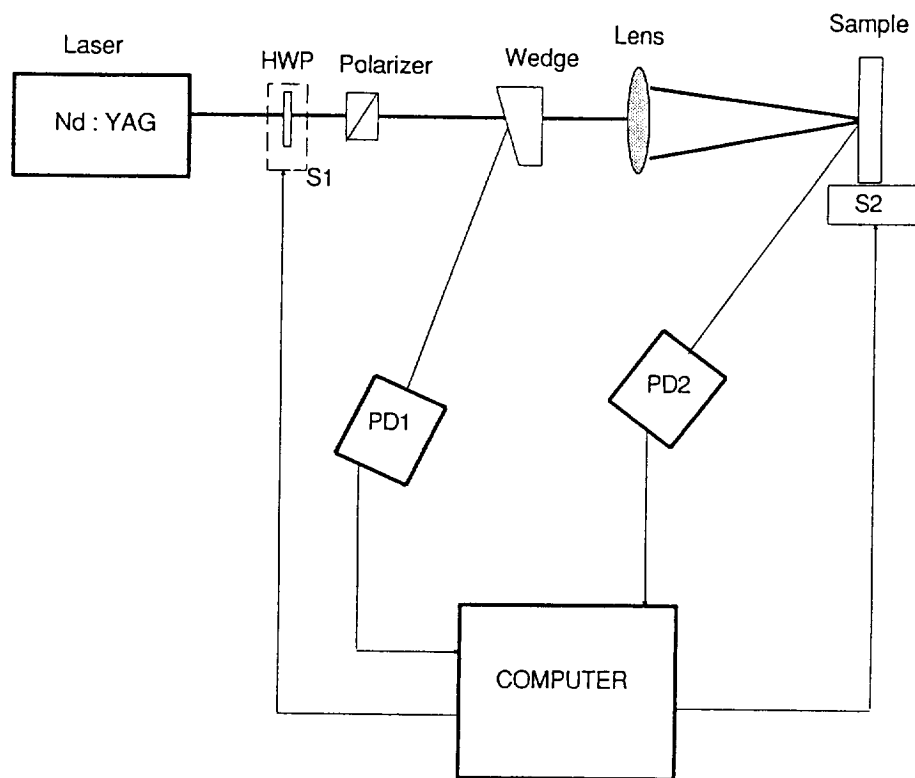


Fig. 1 Experimental setup. HWP is a halfwave plate. PD<sub>1</sub> and PD<sub>2</sub> are photodiode detectors.

The appearance of surface damage was identified by three independent methods: visual observation of a laser spark, measurement of residual scattering of radiation induced by the surface structural destruction, and Nomarski microscope diagnostics of optical inhomogeneities appearing on the surface. These independent damage diagnostics guaranteed registration of damage and reliable measurement of the breakdown threshold. The observation of increased scattering, or a spark did not always unambiguously testify to the presence of damage. In particular, the spark could be associated with improving surface quality as a result of laser cleaning, rather than with surface destruction. The cleaning effect was sometimes observed for surfaces and coatings with high optical resistance.

Identification of damage by observation of changes in light scattering from the irradiated surface, or by measuring changes in reflection and transmission, is more informative and widely used in practice. We have recorded the scattering of picosecond pulses with low intensity about two orders of magnitude lower than that of the "damaging" laser radiation. The surface area to be studied was irradiated with low intensity before and after the action of a high-power "damaging" pulse. A highly sensitive photodetector D2 placed at a small angle ( $20^\circ$ ) to the beam axis monitored the scattered light. A change in the ratio of the detector signals before and after the laser action indicated changes in the surface physical properties due to damage. Despite of the known advantages of this method, it has some shortcomings. The accuracy of measuring the breakdown threshold appears in this case to be dependent on the photodetector sensitivity and background scattering. For relatively low detector sensitivity, or

Table I. 25 Picosecond Damage Threshold of Bare Surfaces at 1064nm  
Spot diameter 0.11mm (FW 1/e M)

Material	Damage Threshold	
	1-on-1 test J/cm <sup>2</sup>	Preconditioned J/cm <sup>2</sup>
Fused Silica	-----	17.8 - 21.5
BK - 7	11.5 - 13.0	20.0 - 21.5
Spinel	13.0	13.8 - 16.5
CaF <sub>2</sub>	8.0 - 9.8	13.5 - 14.0
BaF <sub>2</sub>	5.0 - 9.0	14.0 - 16.0
Nd:YLF	7.5 - 9.5	10.0 - 12.5

Table II. Damage Threshold of Monolayers at 1064 nm

Material	25 picosecond data				8 nanosecond data		
	Thickness (nm)	1-on-1 (J/cm <sup>2</sup> )	Preconditioned (J/cm <sup>2</sup> )	Onset of scattering (J/cm <sup>2</sup> )	Thickness (nm)	1-on-1 (J/cm <sup>2</sup> )	Preconditioned (J/cm <sup>2</sup> )
Ta <sub>2</sub> O <sub>5</sub>	146	3.8 - 4.5	4.6 - 5.4	2.4 - 2.5	146	15	25
TiO <sub>2</sub>	185	6.5 - 7.0	3.1 - 3.4	3.1 - 3.4	185	----	9-18
SiO <sub>2</sub>	----	7.5 - 11.0	15 - 16	15 - 16	----	100	>140

Table III. Damage Threshold of HR ZrO<sub>2</sub>/SiO<sub>2</sub> and AR Al<sub>2</sub>O<sub>3</sub>/MgF<sub>2</sub> Multilayer Coatings

Material	Vendor	25 picosecond data		8 nanosecond data	
		1-on-1 Damage Threshold (J/cm <sup>2</sup> )	Preconditioned Threshold (J/cm <sup>2</sup> )	1-on-1 Damage Threshold (J/cm <sup>2</sup> )	Preconditioned Threshold (J/cm <sup>2</sup> )
HR ZrO <sub>2</sub> /SiO <sub>2</sub>	1	----	2.4 - 2.6	----	55 - 60
	2	12.5 - 13.7	19.5 - 21.5	114	127 - 155
	3	7.4 - 8.5	11.5 - 12.5	>130	>140
	4	----	6.5 - 7.8	11	44
AR Al <sub>2</sub> O <sub>3</sub> /MgF <sub>2</sub>	1	8.0 - 8.5	13 - 15	75	120 - 130
	2	5.6 - 6.0	13.4 - 14.5	----	----

Vendors: 1. Lightning Optical Corporation, 2. VIRGO Optics, 3. CREOL 2 (commercial supplier), 4. CREOL

for materials with high background scattering, some additional micron-size point defects - pits, appearing on the surface just at the instant of breakdown, do not significantly contribute to the scattering signal and can not be extracted. However, the scattering changes appear to be associated with smaller-scale laser-induced defects, which are not optically detectable (observed through a microscope). We define the breakdown threshold as the value of laser radiation intensity (fluence) which gives rise to the slightest visually (optically) detectable defects on the surface. Despite a seemingly randomness in the choice of criterion for breakdown, a more close consideration proves that this definition is implied in the majority of works. This final conclusion on damage has been made after a careful diagnostics of the irradiated surface using the Nomarski microscope.

The damage threshold measurements were taken from three different areas:

- single laser irradiation of a surface site (1-on-1 experiments).
- multiple laser irradiation of a certain site with a series of pulses with equal amplitude (N-on-1 experiments).
- laser pulses with amplitude successively mounting from pulse to pulse - (conditioning experiments).

Apart from this we considered a combination of conditioning and N-on-1 experiments, i.e. a gradual successive mounting of intensities up to some level, followed by irradiation of the site at this level. The pulse repetition rate was 0.5-1 Hz. In the conditioning experiments the energy was increased at a typical number of pulses from pulse to pulse. In this manner a series of 30 to 50 pulses were used to gradually increase the irradiance by as much as two orders of magnitude.

#### 4. RESULTS

The results of laser-induced damage thresholds measurements for the samples considered are presented in Tables 1-4. The first thing mentioned is the high values of breakdown thresholds for dielectric coatings and bare surfaces. Typical average values of picosecond laser damage thresholds, for instance, for  $\text{ZrO}_2/\text{SiO}_2$  dielectric mirrors (Table 3) are about  $10\text{J}/\text{cm}^2$  ( $2.2 \times 10^{11}\text{ W}/\text{cm}^2$ ), and the best samples are compatible in resistance with uncoated samples which resist light flux above  $20\text{J}/\text{cm}^2$  ( $4.5 \times 10^{11}\text{ W}/\text{cm}^2$ ). A similar situation takes place in the case of antireflective  $\text{MgO}/\text{Al}_2\text{O}_3$  coatings with a breakdown threshold of  $15\text{J}/\text{cm}^2$ .

Table IV. Damage Threshold Values of VIRGO Products

Sample	25 picosecond data		8 nanosecond data	
	1-on-1 Threshold ( $\text{J}/\text{cm}^2$ )	Preconditioned Threshold ( $\text{J}/\text{cm}^2$ )	1-on-1 Threshold ( $\text{J}/\text{cm}^2$ )	Preconditioned Threshold ( $\text{J}/\text{cm}^2$ )
HR $\text{ZrO}_2/\text{SiO}_2$	12.5 - 13.7	19.5 - 21.5	114	127 - 155
HR $\text{ZnS}/\text{ThF}_4$	2.7 - 2.9	2.5 - 2.7	51	73
High Heated AR $\text{Al}_2\text{O}_3/\text{MgF}_2$	5.4	4.9 - 5.0	----	127 - 152
Low Heated AR $\text{Al}_2\text{O}_3/\text{MgF}_2$	5.6 - 6.0	13.4 - 14.5	----	7.5 - 18.0

The thresholds listed in the Tables are determined mostly by two numbers, the lesser of which corresponds to the minimum value of damaging fluence, and the larger to the maximum nondamaging value. Each value is averaged over 10 or more measurements. A spread of thresholds from site to site for a given sample turned out in most cases to be insignificant due to high quality of surfaces tested and stable spatial and temporal parameters of the laser pulses. The thresholds measurement error depends on the accuracy of laser pulse parameters measurements (energy and diameter of the spot), on the methods of recording and the choice of breakdown criterion. (The dominant error in the damage threshold measurements is the error in the absolute measurement of pulse energy which is less than  $\pm 5\%$  for the detector used.)

The high values of breakdown thresholds can be explained, first, by significant progress in preparation of dielectric coatings. It should be mentioned that we also used for comparison samples of very "weak" coatings deposited more than ten years ago, whose breakdown threshold turned out to be much lower than those presented in this work. Second, high optical resistance can be explained by ultrashort laser pulses. It is of common knowledge that, according to the general rules [11, 12, 13], with shortening laser action time, the value of the threshold intensity increases, i.e. the sample optical strength grows. Below we dwell in detail on the analysis of the damage threshold temporal dependence.

Finally, relatively larger thresholds are observed for small spot sizes [13]. Our experiments have been performed at relatively small diameters of the laser spot (about 0.1-0.2 mm), and the resulting measured values of thresholds could differ from those typical of usual damage test conditions (spot diameter  $\sim 1$  mm). However, it should be particularly stressed that possible difference cannot be so significant as to prevent the results obtained from being applied in practice, since the spot sizes used in the work are of values for which the size dependence saturation usually starts. This spot size dependence is due to the presence or absence of "weak areas" in the interaction region (inclusions, impurities, structural defects, etc.) which range from a few microns to some tens of microns.

## 5. PULSEWIDTH DEPENDENCE

We consider it expedient to compare optical resistance of surfaces using picosecond and nanosecond laser radiation from scientific and practical viewpoints. Such investigations, if performed on the same samples under identical experimental conditions, allow one to make the definite conclusions on the breakdown threshold as a function of pulsewidth and, therefore, get a deeper insight into the mechanisms of the laser induced breakdown. In this work we have not undertaken such a challenge and have confined ourselves to mainly accumulating experimental data.

The coatings damage thresholds measurements have been performed in the nanosecond region using 8ns pulses from the YAG:Nd-laser (wavelength 1064 nm, Gaussian spatial distribution of intensity, symmetric bell-like shape in time). The configuration of the experiment, damage identification technique, and procedures of diagnostics and measurement of laser radiation parameters have been chosen to match those of the picosecond measurements. The diameter of the spot on the surface was 90 microns (FW 1/eM). Both 1-on-1 - experiments and conditioning experiments have been conducted. The breakdown threshold measurement results are presented in the Tables and illustrated in Fig. 2.

The first aspect attracting attention when comparing nanosecond and picosecond measurements is a great difference in the pulsewidth dependence of breakdown threshold for both various and same "type" of coatings, as well as for irradiation conditions (1-on-1; N-on-1 experiments and conditioning,

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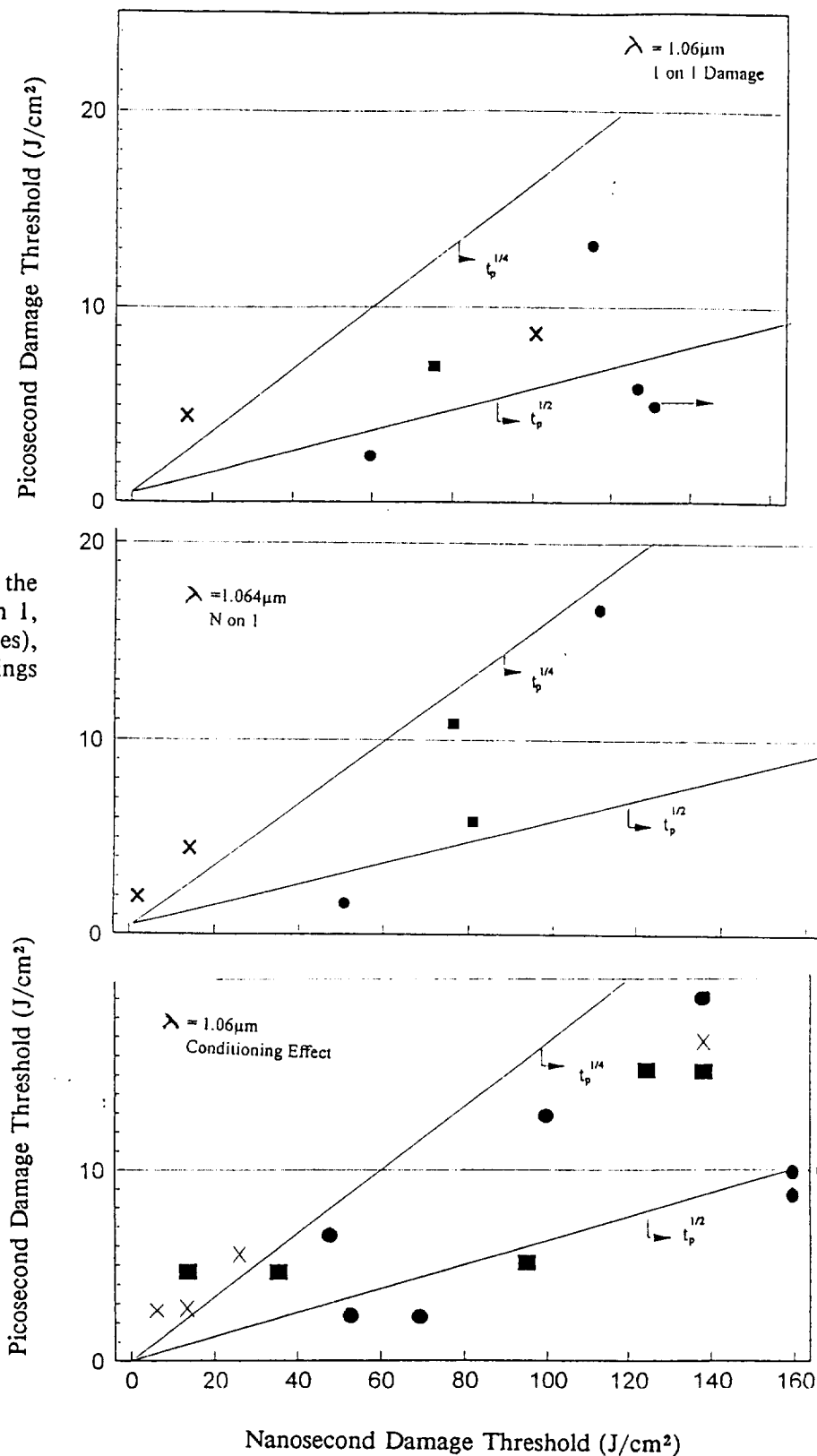


Fig. 2 Pulsewidth dependence of the damage threshold using 1 on 1, N on 1, and conditioning tests for HR (circles), Monolayers (X), and AR coatings (squares).

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see Fig.2). Such a behavior of breakdown threshold has to be attributed to the action of a particular damage mechanism. A deeper insight into the problem will require more extensive temporal dependence studies rather than two points (at 8 ns and 25 ps) on the time axis. However, even such a rough analysis of experimental data may appear to be useful for systematization of the results and for comparison with the data of other authors. With this end in view we will keep to the common representation of the temporal dependence as an exponential pulsewidth function:  $(T_0)^x$  (note that this form of dependence presentation is caused by simplicity in experimental data treatment rather than by very sophisticated regulations). As it is seen in Fig.2 the power  $x$  drastically changes from sample to sample showing the complexity of the problem of temporal behavior of the laser damage thresholds. One of the most important characteristics of coating damage with picosecond laser pulses is a conditioning effect. This effect was also observed in the nanosecond regime. We have detected the conditioning effect in the majority of materials studied, except for those in which various accumulation effects play an important role.

In the case of bare surfaces, conditioning resulted in a 1.2- 1.8 time increase in threshold, possibly associated with additional laser cleaning of the surface (see Table 1).

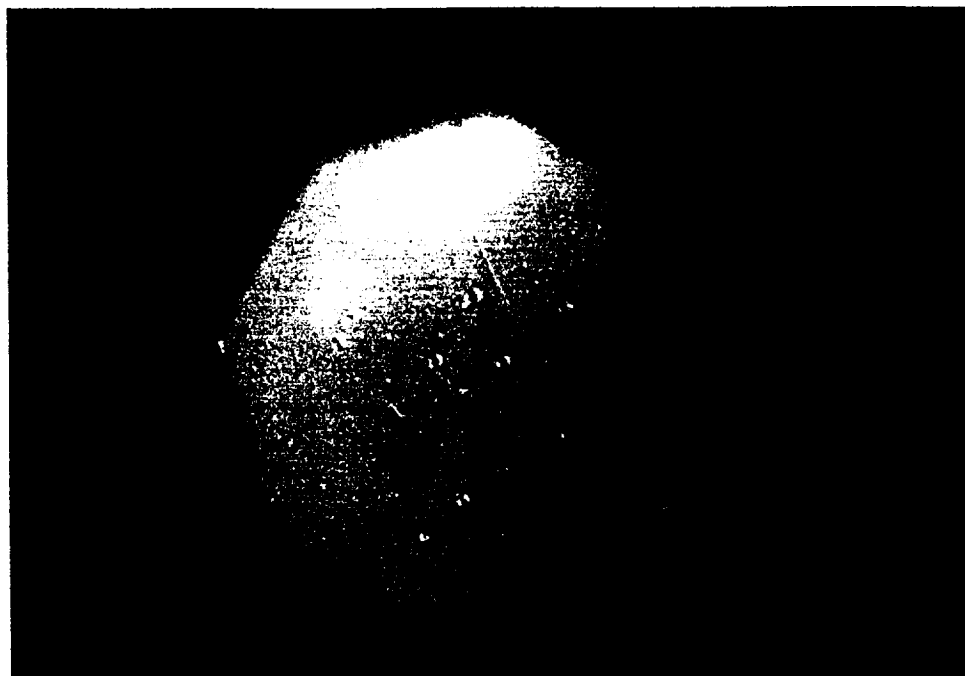
Among monolayers subject to conditioning, besides those featuring an approximate 1.5 increase in threshold ( $\text{SiO}_2$ , Table 2), there also were negative results - a decrease in threshold (significantly in some cases). For one  $\text{TiO}_2$  monolayer (thickness 185 nm, Table 2), a fifty percent decrease occurred. That very sample featured an appreciable accumulation effect: optical strength weakening under irradiation with a sequence of pulses, each of which does not cause damage. Sample damage in the N-on-1 experiments resulted (at the 130-150th shot), despite a 4- fold reduction of the laser pulses amplitude, as compared to the 1-on-1 threshold. In one instance of  $\text{Ta}_2\text{O}_5$  (Table 2), the N-on-1 experiments did not reveal any significant influence of accumulation. More than 120 pulses with amplitudes 10- 15% less than the 1-on-1 threshold were required to attain damage.

In the case of multilayer coatings, a similar situation took place. Table 4 indicates that both HR and AR coatings may either gain (greater than 200%), or lose strength as a result of conditioning, or lose it. The latter is observed in the case of accumulation. In the N-on-1 experiments, the HR: $\text{ZnS}/\text{ThF}_4$  coating features a 1.5 times less threshold than at single action. At this level of threshold, 50 shots are required to attain damage. The AR: $\text{Al}_2\text{O}_3/\text{MgF}_2$  coating ("high heated") disintegrates at the 70-100th shot when irradiated with a series of pulses of amplitude 1.8 times less than the threshold value for a single irradiation. For the other coatings presented in Table 4, the accumulation effect is either absent or weakly expressed. Damage to the AR: $\text{Al}_2\text{O}_3/\text{MgF}_2$  coating ("low heated"), requires approximately 100 pulses with an amplitude which closely corresponds to the 1-on-1 threshold. In this case, we cannot unambiguously make judgement on the cause of damage, which occurs either as a result of accumulation, or laser pulse duration fluctuation which changes the radiation intensity.

An absence (or presence) of any accumulation clearly manifests itself in the case of combined conditioning and N-on-1 experiments. For the HR: $\text{ZrO}_2/\text{SiO}_2$  sample (Table 4) on conditioning, after attaining an intensity level differing by only 5-7% from the threshold (and exceeding the single damage threshold 1.5 times), more shots were additionally required to attain breakdown.

The above comparison of thresholds for 1-on-1, N-on-1, and conditioning experiments can be generalized with due regard for all experimental evidence obtained in the work. When the 1-on-1 breakdown threshold does not exceed that for N-on-1 without accumulation, conditioning is observed in samples under study. In this case, conditioning threshold, combined conditioning, and N-on-1 threshold actually coincide.

1-on-1 mode



Preconditioning mode

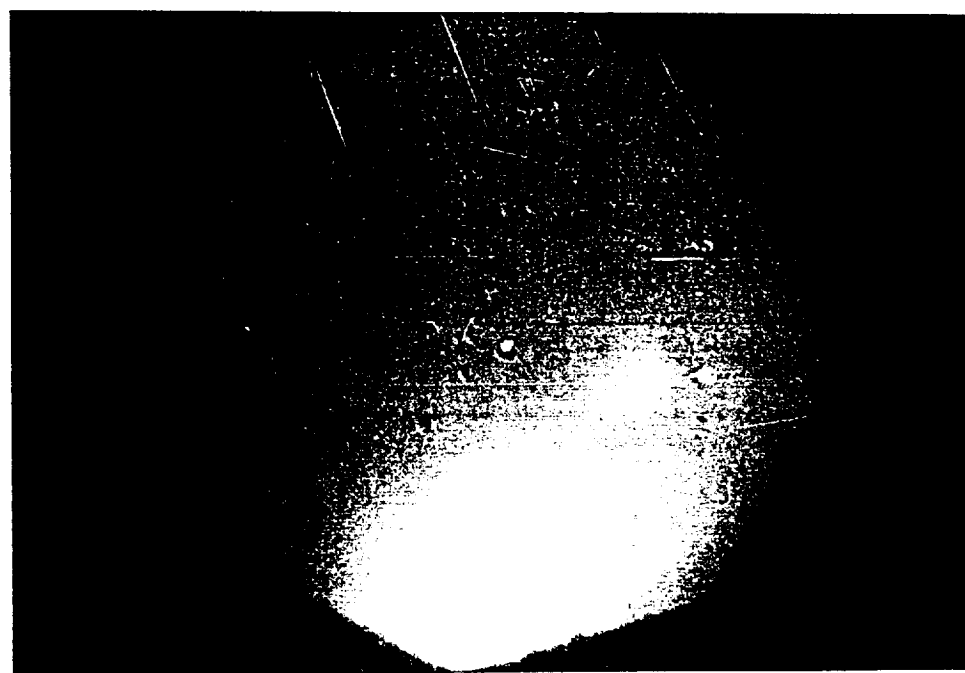


Fig. 3(a) Micrographs of the damage in  $\text{ZrO}_2/\text{SiO}_2$  HR coatings (vendor Virgo Optics). Magnification 110x.

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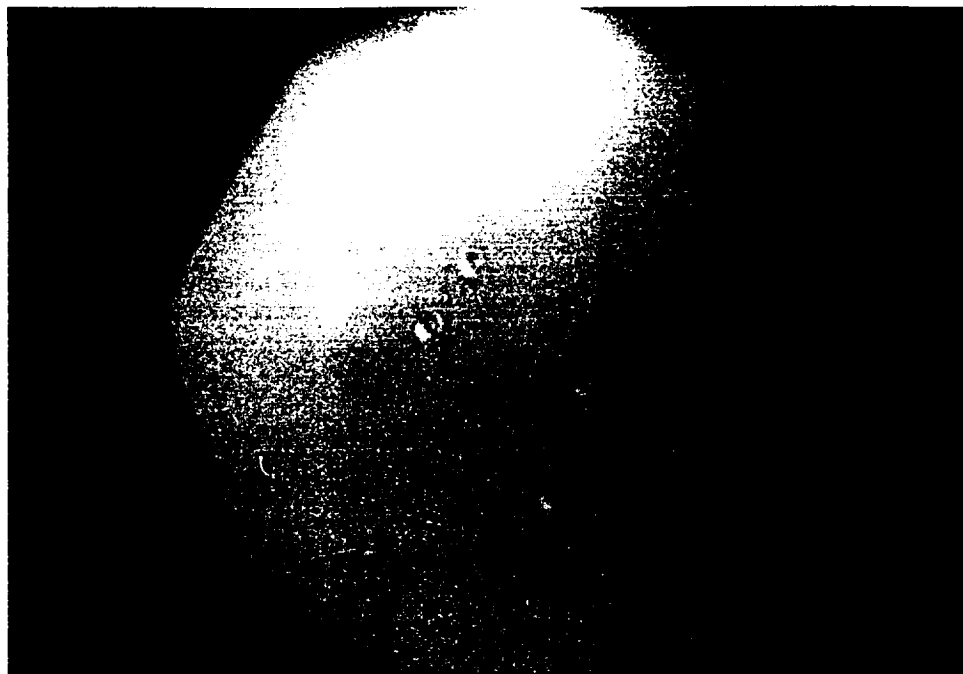
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1-on-1 mode



Preconditioning mode

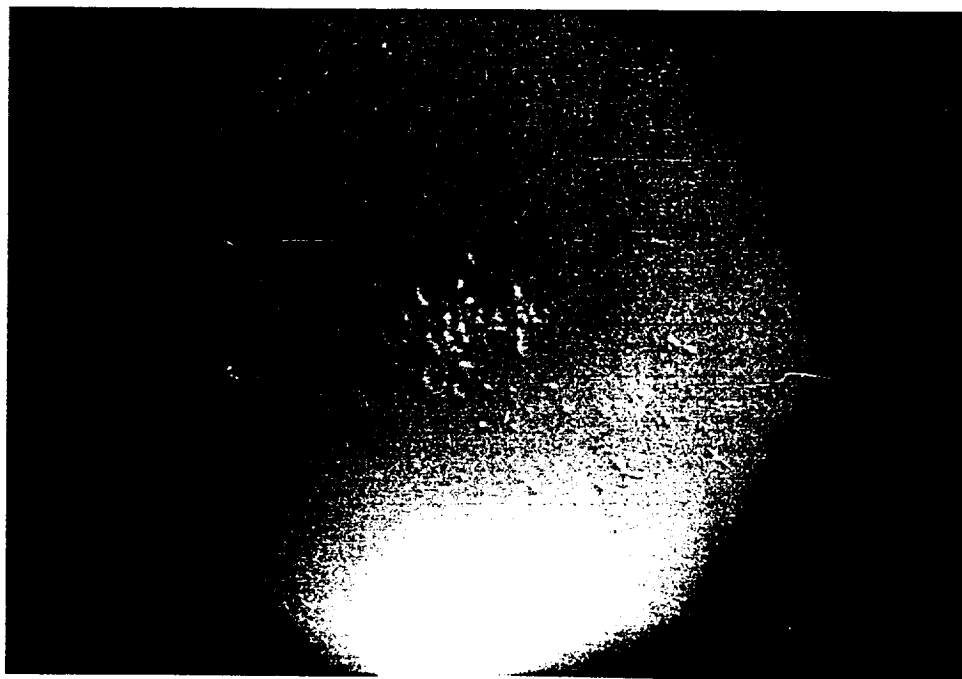
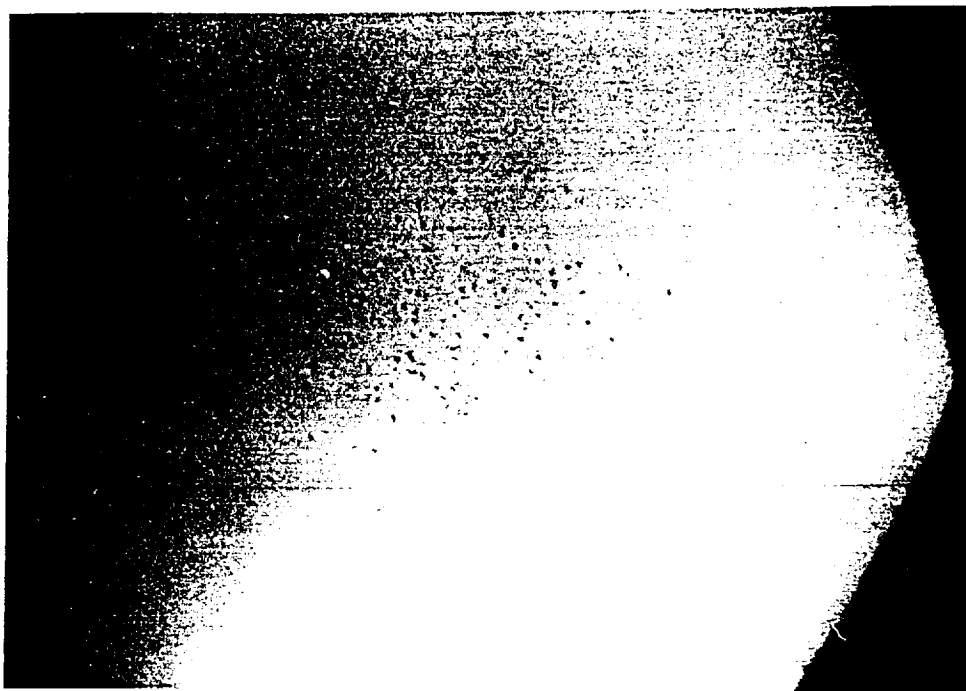


Fig. 3(b) Micrographs of the damage in  $\text{ZrO}_2/\text{SiO}_2$  HR coatings (vendor CREOL2). Magnification 110x.

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1-on-1 mode



Preconditioning mode

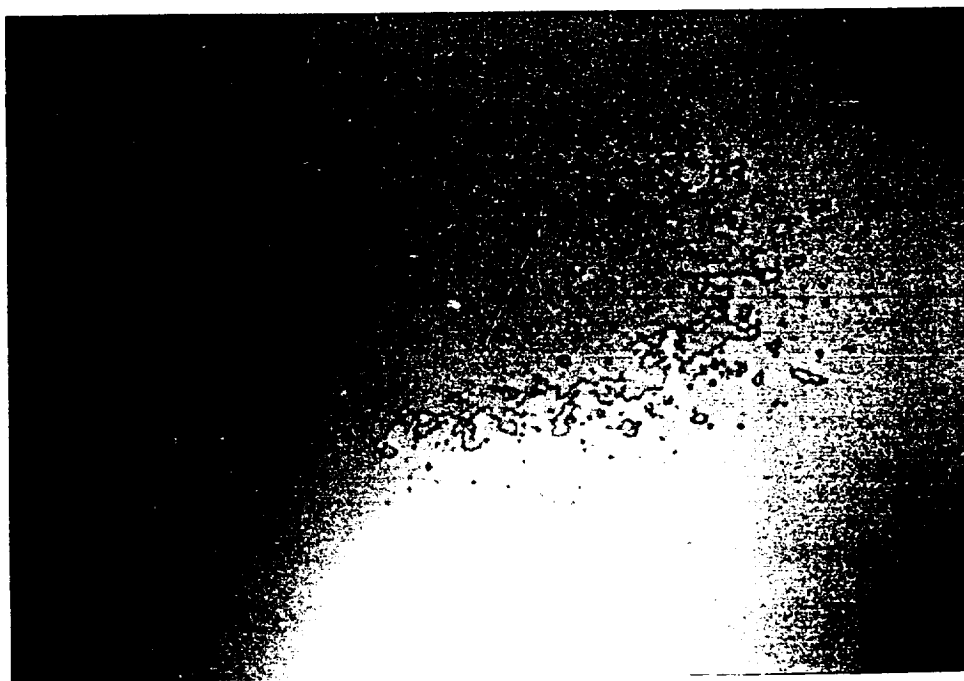


Fig. 3(c) Micrographs of the damage in ZnS/ThF<sub>4</sub> HR coatings (vendor Virgo Optics). Magnification 110x.

When accumulation takes place, the problem of conditioning becomes ambiguous and requires a more detailed consideration which takes into account specific experimental conditions, in particular, pulse repetition rate, amplitude increment from pulse to pulse, initial level of irradiation, etc. In this case, the question of the number of pulses in the N-on-1 experiments becomes of primary importance. Note that the characteristic values of N we used were relatively small and did not exceed several hundred shots. We have considered appreciable accumulation which greatly contributes to breakdown after merely a few dozen shots. Therefore, the conditioning threshold was lower than that of single action.

## 6. DAMAGE MORPHOLOGY

Collected data permits us to undertake two tasks: 1) classification of the picosecond damage patterns in the dielectric coatings and bare surfaces, and 2) comparison of the changes to the surface due to single-pulse or multi-pulse irradiation of the specimen. These changes can be in its chemical composition, damage threshold level and its likelihood to increase breakdown threshold by preconditioning or decrease it due to accumulation effect.

It should be stressed that primarily microdamage (i.e. faintest modifications) of the surface which can be displayed by Nomarski-microscope is under consideration.

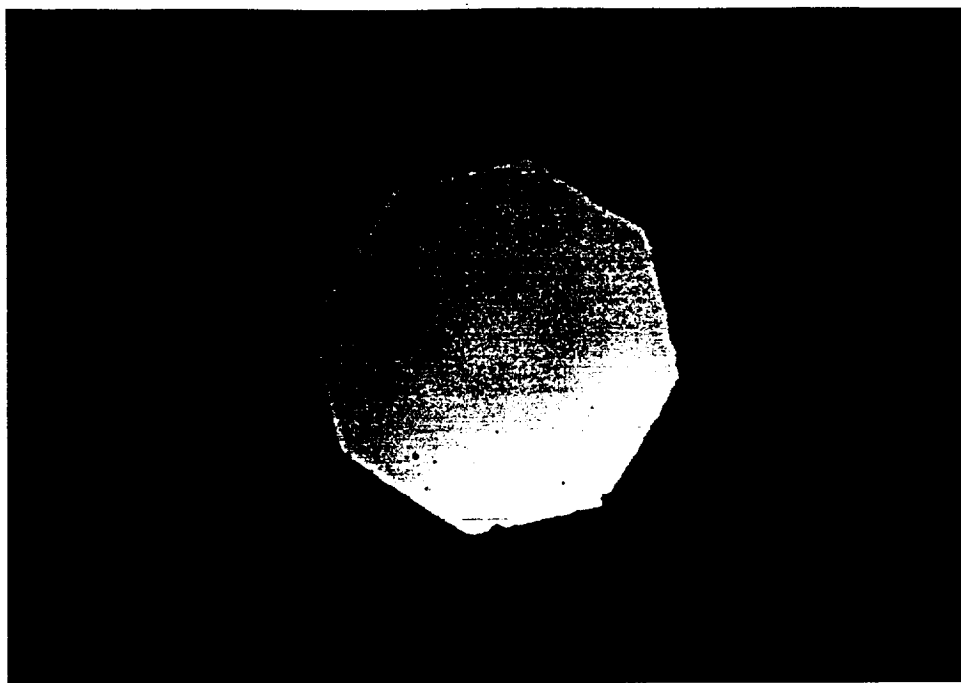
Two micrographs coatings from different vendors are shown in Figs.3(a) and 3(b) for  $\text{ZrO}_2/\text{SiO}_2$  mirrors. Left micrographs correspond to 1-on-1 damage tests and right photographs correspond to the test conditions with the pulse energy gradually increasing. Both coatings feature highest damage thresholds for picosecond and nanosecond tests and significant preconditioning effect. It is easily seen from pictures that microdamage morphology varies slightly for different modes of testing. Photographed micropits are essentially the same as observed in earlier picosecond damage experiments [1,8,14]. Typical crater diameters are of 1 to 3 micrometers. The only significant difference is the scattering of pit diameters in multishot damage sites which exceeds that of 1-on-1 sites.

However, the damage morphology of HR coatings in preconditioning and 1-on-1 tests can significantly differ. Fig.3(c) illustrates this in the case of HR  $\text{ZnO}/\text{ThF}_4$ . In the multishot experiment, the upper layer of the coating was removed to the ten micron area. This specimen features rather low damage threshold in the picosecond regime and double the  $\text{ZrO}_2/\text{SiO}_2$  threshold in the nanosecond regime test. Also observed was a slight decrease of optical resistance in N-on-1 experiments.

Figs. 4(a), and 4(b) are micrographs of the damage sites from AR  $\text{Al}_2\text{O}_3/\text{MgF}_2$  coatings demonstrating differences in fracture patterns for 1-on-1 and preconditioned damage tests. As shown on the left, the irradiation by a single pulse above the threshold results in slight changes of hue in the exposed site (blue haze). On the other hand, increasing irradiation by N-on-1 or pulse by pulse, was followed by the creation of several damage pits with 2-15 micron diameter. One noticeable fact is that contrary to the resemblance of damage morphology, damage threshold characteristics of these two samples reveal significant differences. Data in Table 4 demonstrate superiority in damage thresholds of AR coating in the left column superior to the right one (presented in Fig.4(a) and 4(b) respectively) for both (2.5 times for 25 ps preconditioning test and approximately 10 times for 8 ns). Moreover, an increase in picosecond threshold due to preconditioning was observed exclusively in the sample presented on Fig.4(a).

Damage morphology in  $\text{TiO}_2$  and  $\text{Ta}_2\text{O}_5$  monolayers are shown in Fig.5(a) and 5(b). Samples feature near equal thickness and entirely different optical damage properties (see table 2 ).

1-on-1 mode



Preconditioning mode

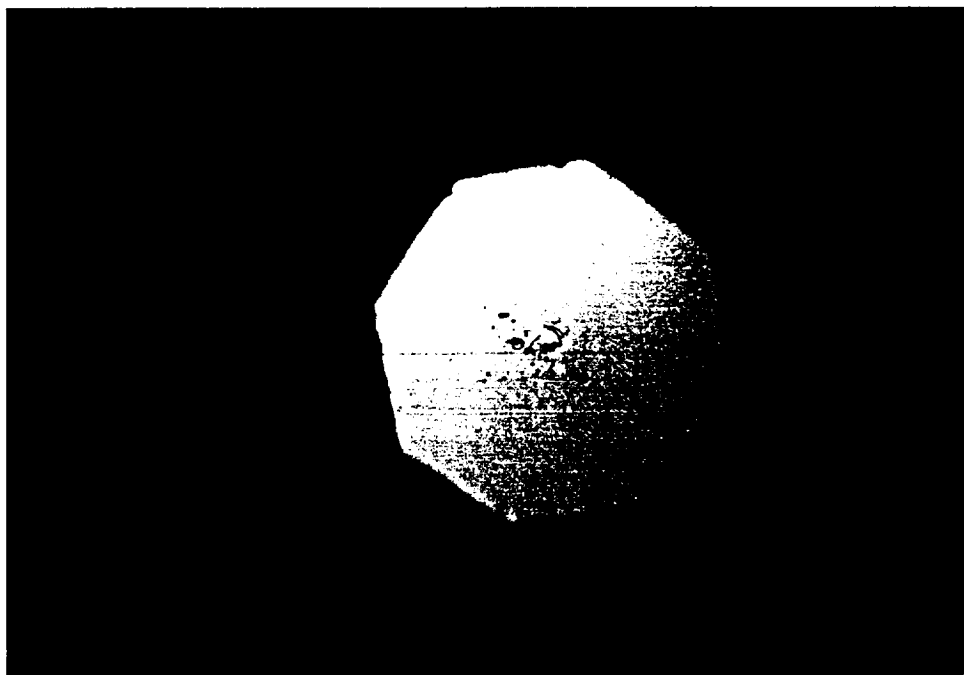
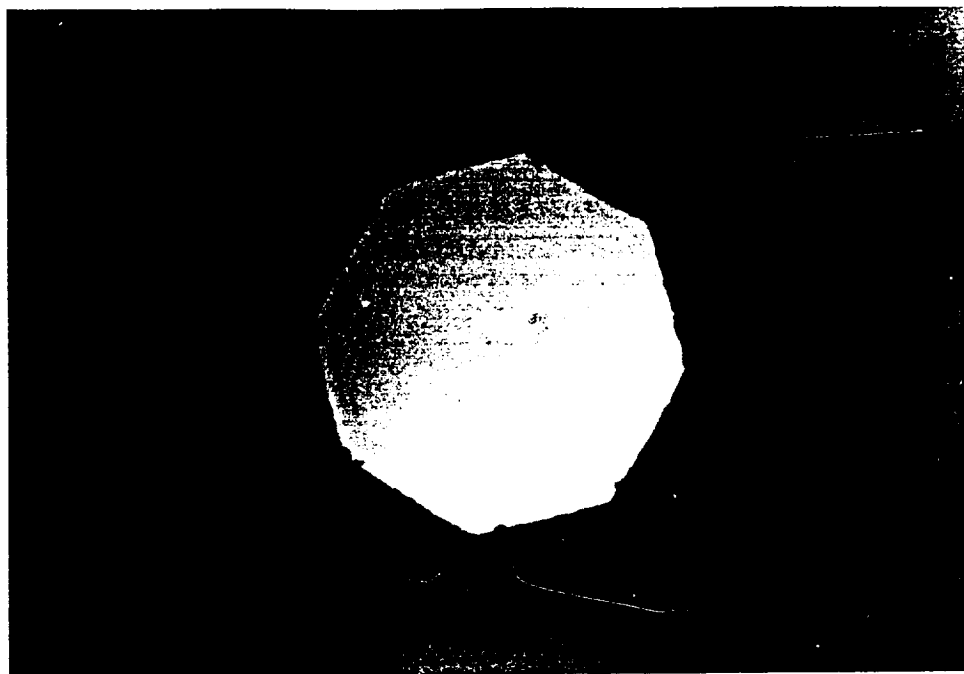


Fig. 4(a) Micrographs of high threshold damage in  $\text{Al}_2\text{O}_3/\text{MgF}_2$  AR coatings (vendor Virgo Optics). Magnification 22x.

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1-on-1 mode



Preconditioning mode

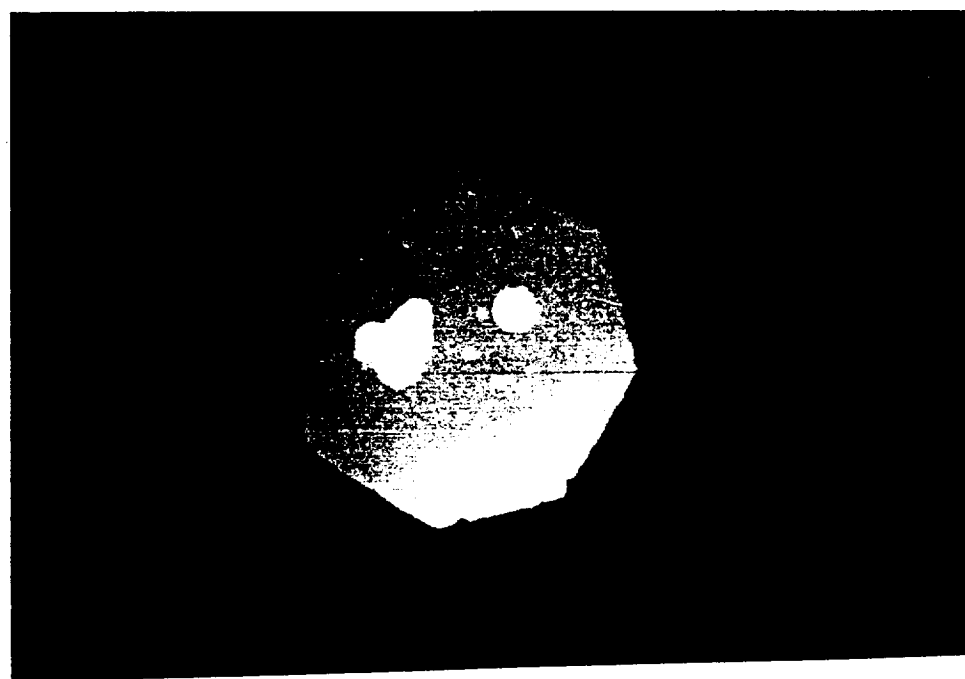
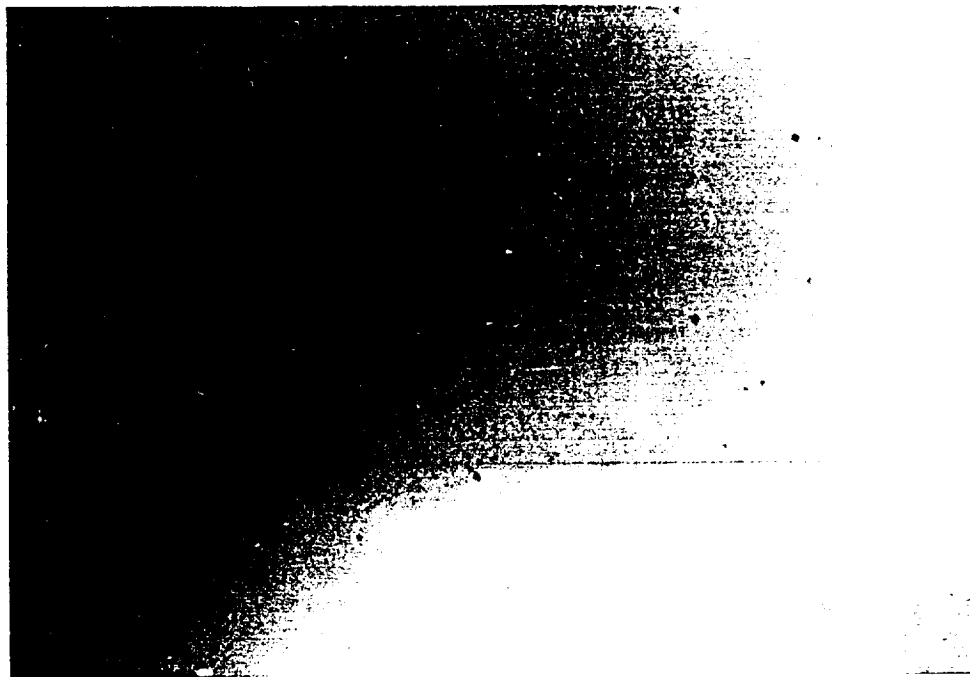


Fig. 4(b) Micrographs of low threshold damage in  $\text{Al}_2\text{O}_3/\text{MgF}_2$  AR coatings (vendor Virgo Optics). Magnification 22x.

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1-on-1 mode



Preconditioning mode

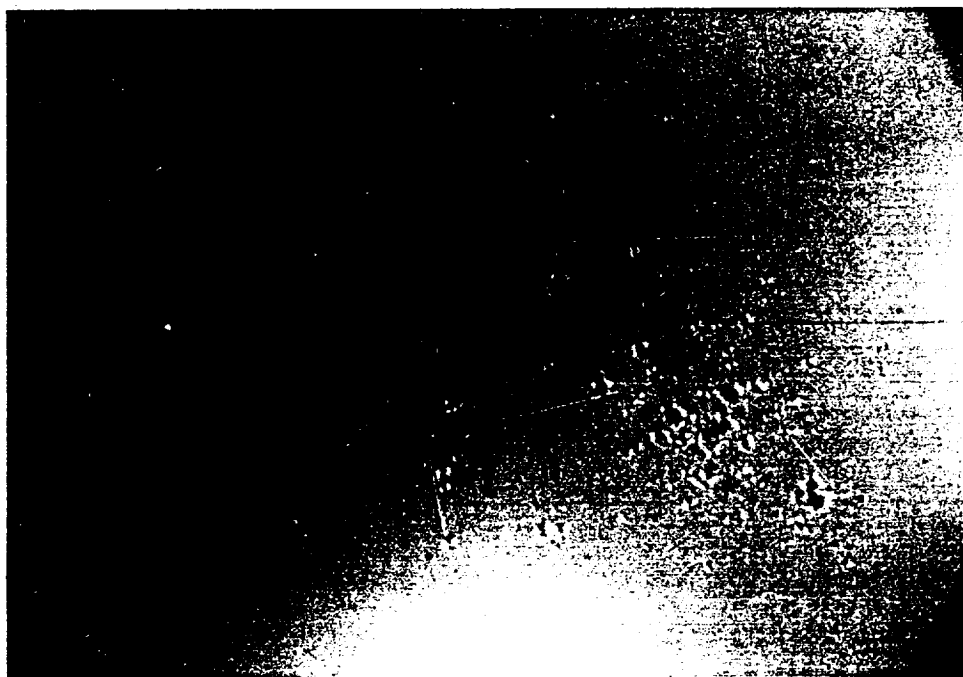


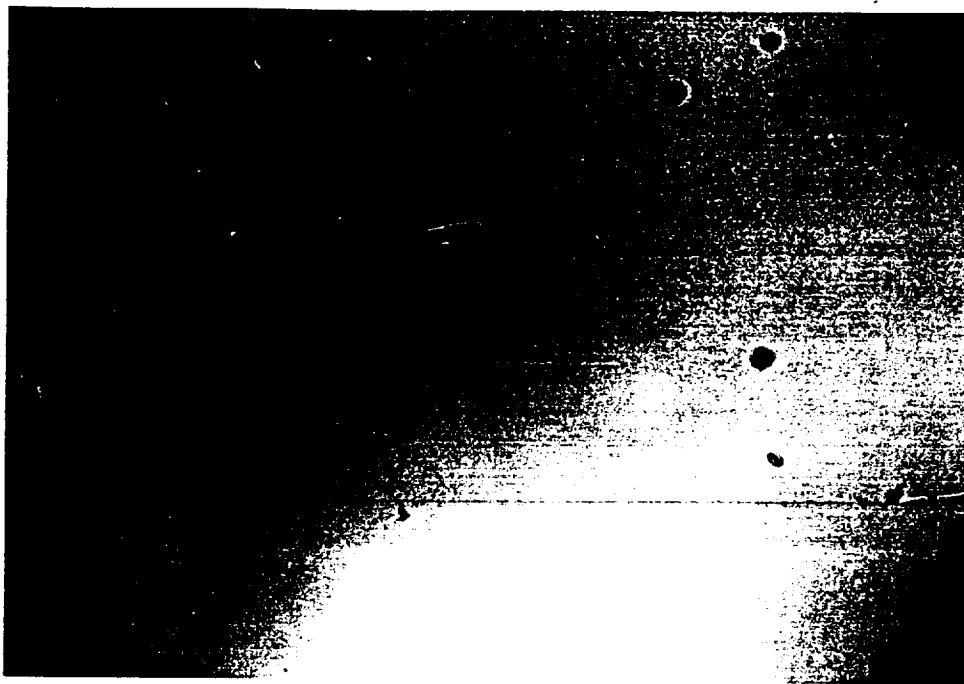
Fig. 5(a) Micrographs of the damage in 185 nm thick  $\text{TiO}_2$  monolayers. Magnification 110x.

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1-on-1 mode



Preconditioning mode

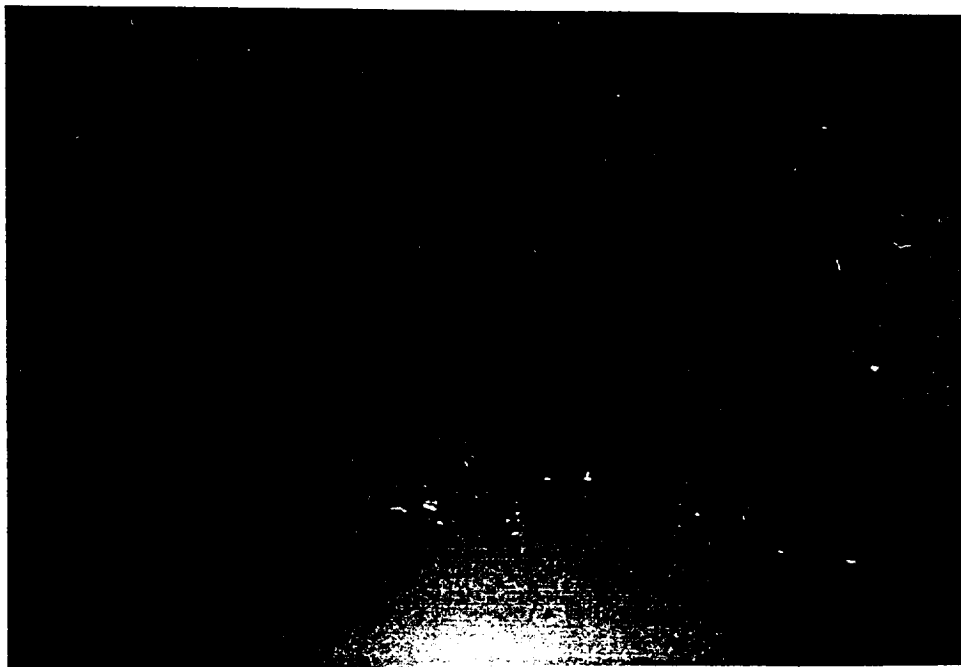
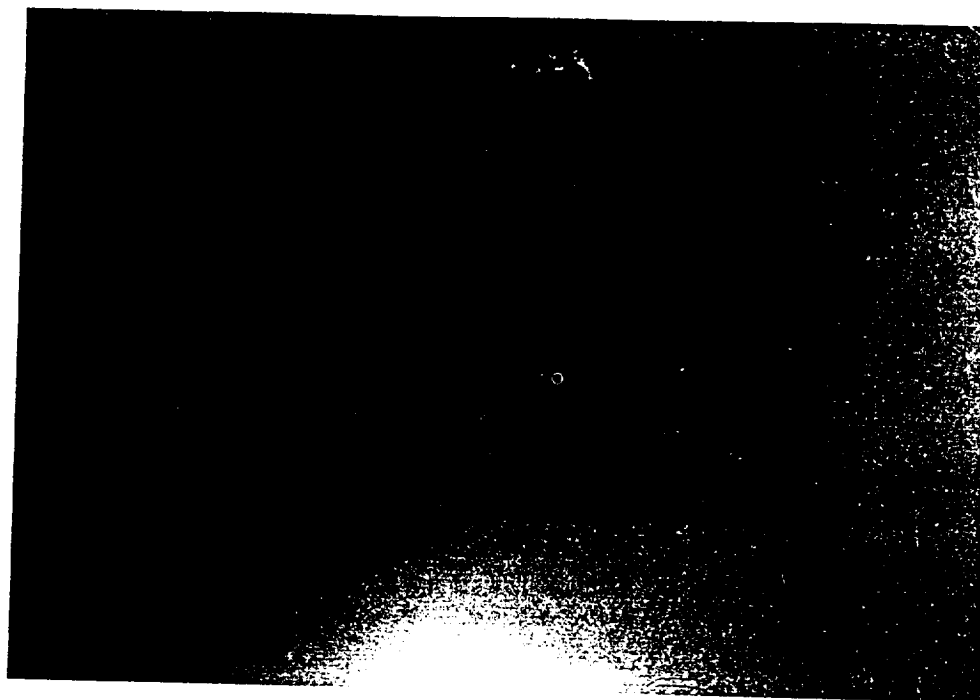


Fig. 5(b) Micrographs of the damage in 146 nm thick  $\text{Ta}_2\text{O}_5$  monolayers. Magnification 110x.

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1-on-1 mode



Preconditioning mode

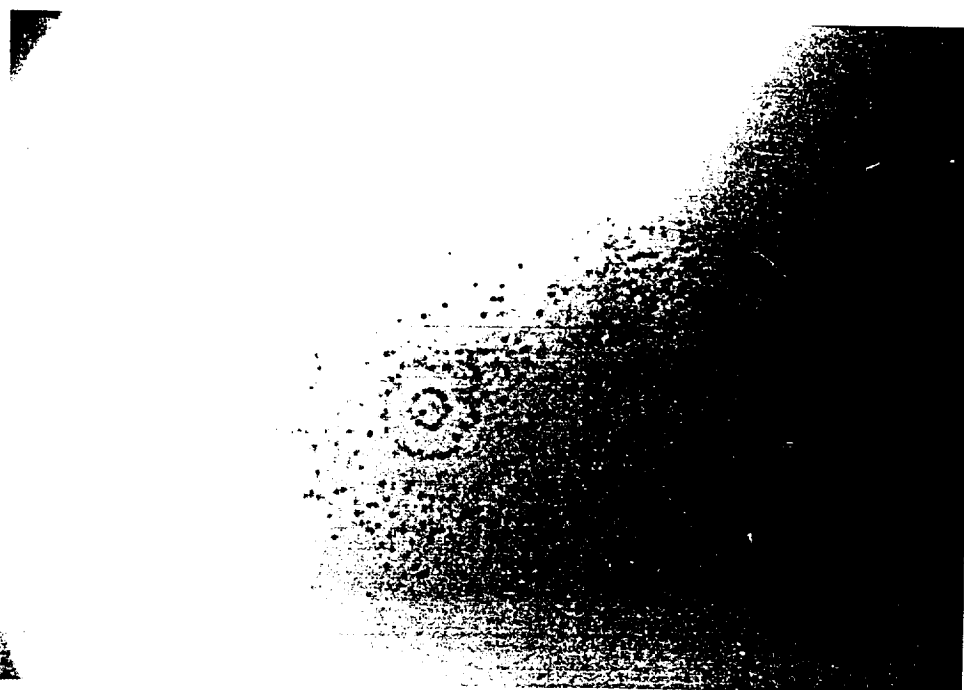


Fig. 6 Damage morphology of the BK-7 bare surface. Magnification 110x.

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To summarize coating morphology results, the greatest variety of the damage patterns was observed in the picosecond experiments. Data indicates that damage patterns seem to be determined in general by chemical composition of the layers and mode of laser irradiating (singleshot or multishot). In all instances of multishot action: preconditioning and two modes of N-on-1 irradiation resulted in similar damage patterns. One fact worth mentioning is that no correlation between morphology and damage thresholds was observed in our experiments.

Fig.6 shows damage patterns in the BK-7 surface as an example of the damage to well polished surfaces. Comparison of the micrographs displays pitting on the sample both in 1-on-1 and preconditioned tests. Typical pit size was about 1 micron. Pits in picosecond 1-on-1 damage experiments with uncoated optical materials were earlier observed in [1]. In our case, slight peculiarities in preconditioned pitting can be noticed as it is more dense than 1-on-1 pitting.

Preconditioned damage threshold in the sample was found to be two times higher (see Table 1 ). The same micrographs could also be presented for polished YLF:Nd. As for  $\text{CaF}_2$ ,  $\text{BaF}_2$  and Spinel samples, the damage morphology cannot be established correctly because of rough surface polishing.

An unexpected yet interesting result of our work was the observation of laser cleaning in  $\text{SiO}_2$  monolayer, originally marred with misperfections. Fig.7 illustrates the cleaning effect in the area around damaged spot. In spite of the bad optical quality, this sample revealed a damage threshold level close to the damage threshold of uncoated glass where the preconditioning increased the threshold by 1.5 to 2.0 times.

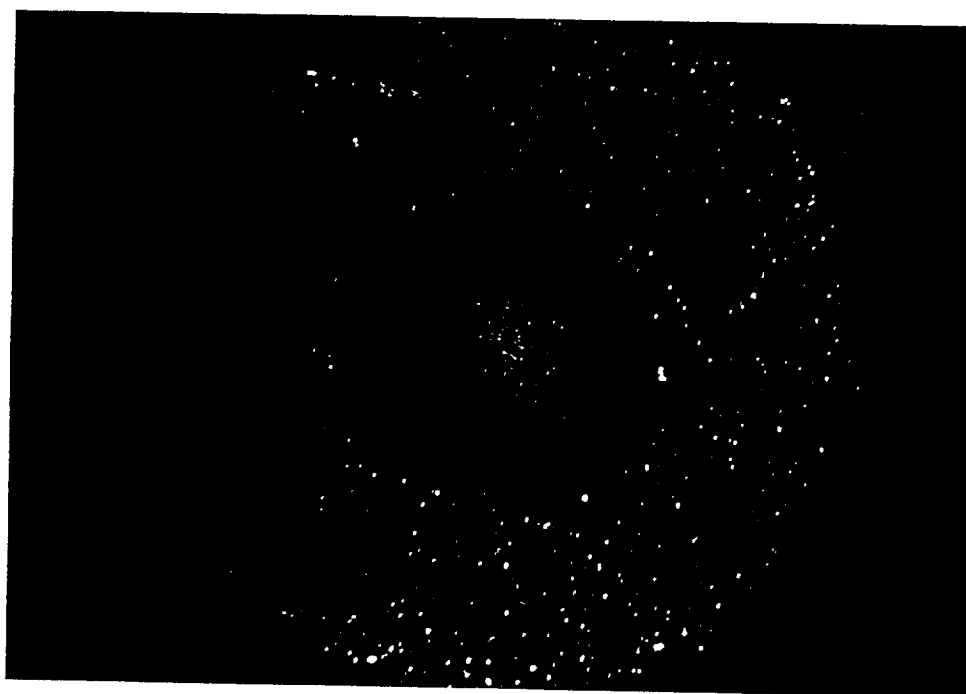


Fig. 7 Laser cleaning of the  $\text{SiO}_2$  monolayer coating

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## 7. CONCLUSIONS

Our investigations of optical damage to bare surfaces and dielectric coatings by picosecond (25 ps) and nanosecond (8 ns) 1064 nm laser pulses make it possible to conclude the following.

At both pulsewidths, the laser resistance of coatings is governed by their composition, deposition method, and irradiation modes (single and multipulse irradiation). The majority of surfaces considered (having no noticeable accumulation effect) feature an appreciable conditioning effect leading to almost a double increase in breakdown threshold, as against single pulse action.

In the picosecond region, the most resistant dielectric coatings have breakdown thresholds virtually coinciding with those for most resistant bare surfaces (fused silica and BK-7 glass) -  $20 \text{ J/cm}^2$  ( $4.5 \cdot 10^{11} \text{ W/cm}^2$ ).

The comparison of the picosecond and nanosecond laser damage thresholds measured under similar experimental conditions indicates that the duration of laser action has a significantly different impact upon the resistance of different types of coatings. The threshold behavior with varying pulsewidth depends upon the coating material, deposition method, and irradiation conditions. We have failed to present the obtained results consistently in the form of an exponential pulsewidth function.

The morphology of the picosecond damage to coatings is first of all determined by the coating material and irradiation mode. For coatings with the same composition, the damage structure does not depend on the threshold value. In multipulse action, the character of damage appears to be similar in N-on-1, conditioning, and N-on-1 plus conditioning experiments, but differs, in principle, from the case of single pulse action.

## 8. ACKNOWLEDGEMENTS

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