



NIST SPECIAL PUBLICATION **752**

U.S. DEPARTMENT OF COMMERCE/National Institute of Standards and Technology

# **Laser Induced Damage in Optical Materials: 1986**



*BOULDER DAMAGE SYMPOSIUM*



**STP 1028**

# Laser Induced Damage in Optical Materials: 1986

---

Proceedings of a Symposium Sponsored by:

National Institute of Standards and Technology  
(formerly National Bureau of Standards)  
American Society for Testing and Materials  
Office of Naval Research  
Department of Energy  
Defense Advanced Research Project Agency  
Air Force Office of Scientific Research

November 3-5, 1986

NIST (formerly NBS), Boulder, Colorado 80303

Edited by:

Harold E. Bennett  
Naval Weapons Center  
China Lake, California 93555

Arthur H. Guenther  
Air Force Weapons Laboratory  
Kirtland Air Force Base, New Mexico 87117

David Milam  
Lawrence Livermore National Laboratory  
Livermore, California 94550

Brian E. Newnam  
Los Alamos National Laboratory  
Los Alamos, New Mexico 87545

**NOTE:** As of 23 August 1988, the National Bureau of Standards (NBS) became the National Institute of Standards and Technology (NIST) when President Reagan signed into law the Omnibus Trade and Competitiveness Act.



*BOULDER DAMAGE SYMPOSIUM*

---

U.S. DEPARTMENT OF COMMERCE, C. William Verity, Secretary

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, Ernest Ambler, Director  
(formerly National Bureau of Standards)

Issued September 1988

**Library of Congress Catalog Card Number: 88-600571**

**National Institute of Standards and Technology  
Special Publication 752, 724 pages (Sept. 1988)  
CODEN: XNBSAV**

**U.S. GOVERNMENT PRINTING OFFICE  
WASHINGTON: 1988**

---

**For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325**

## Foreword

The Proceedings contain the papers presented at the Eighteenth Symposium on Optical Materials for High Power Lasers held at the National Bureau of Standards in Boulder, Colorado, on November 3-5, 1986. The Symposium was jointly sponsored by the National Bureau of Standards, the American Society for Testing and Materials, the Office of Naval Research, the Defense Advanced Research Projects Agency, the Department of Energy, and the Air Force Office of Scientific Research. The Symposium was attended by almost 200 scientists from the United States, the United Kingdom, Japan, France, and the Federal Republic of Germany. It was divided into sessions devoted to the following topics: Materials and Measurements, Mirrors and Surfaces, Thin Films, and finally Fundamental Mechanisms. The Symposium Co-Chairmen were Dr. Harold E. Bennett of the Naval Weapons Center, Dr. Arthur H. Guenther of the Air Force Weapons Laboratory, Dr. David Milam of the Lawrence Livermore National Laboratory, and Dr. Brian E. Newnam of the Los Alamos National Laboratory. They also served as editors of this report.

The editors assume full responsibility for the summary, conclusions, and recommendations contained in the report, and for the summaries of discussion found at the end of each paper. The manuscripts of the papers presented at the Symposium have been prepared by the designated authors, and questions pertaining to their content should be addressed to those authors. The interested reader is referred to the bibliography at the end of the summary article for general references to the literature of laser damage studies. The Nineteenth Annual Symposium on this topic will be held in Boulder, Colorado, October 26-28, 1987. A concerted effort will be made to ensure closer liaison between the practitioners of high peak power and the high average power community.

The principal topics to be considered as contributed papers in 1987 do not differ drastically from those enumerated above. We expect to hear more about improved scaling relations as a function of pulse duration, area, and wavelength, and to see a continuing transfer of information from research activities to industrial practice. New sources at shorter wavelengths continue to be developed, and a corresponding shift in emphasis to short wavelength and repetitively pulsed damage problems is anticipated. Fabrication and test procedures will continue to be developed, particularly in the diamond-turned optics and thin film areas.

The purpose of these symposia is to exchange information about optical materials for high power lasers. The editors will welcome comment and criticism from all interested readers relevant to this purpose, and particularly relative to our plans for the Nineteenth Annual Symposium.

H. E. Bennett, A. H. Guenther,  
D. Milam, and B. E. Newnam  
Co-Chairmen

### **Disclaimer**

Certain papers contributed to this publication have been prepared by non-NBS authors. These papers have not been reviewed or edited by NBS; therefore, the National Bureau of Standards accepts no responsibility for their accuracy, nor for their comments or recommendations.

Certain commercial equipment, instruments, and materials are identified in this publication in order to explain the experimental procedure adequately. Such identification in no way implies approval, recommendation, or endorsement by the National Bureau of Standards, nor does it imply that the equipment, instruments, or materials identified are necessarily the best available for the purpose.

## CONTENTS

	<u>Page</u>
Foreword .....	iii
H.E. Bennett, A.H. Guenther, D. Milam, and B.E. Newnam	
Disclaimer .....	iv
Symposium Welcome .....	xiii
A.H. Guenther	
Summary of Meeting .....	1
H.E. Bennett, A.H. Guenther, D. Milam, and B.E. Newnam	
1.0 Introduction .....	1
2.0 Overview .....	2
3.0 Acknowledgements .....	10
4.0 References .....	11

## Materials and Measurements

Development of Silicophosphate Glass HAP-3 .....	13
T. Izumitani, M. Matsukawa, C. Hata, K. Tanaka, and H. Toratani	
Development of Composite Polymer-Glass Edge Claddings for for Nova Laser Disks .....	19
J.H. Campbell, G. Edwards, F.A. Frick, D.S. Gemmell, B.M. Gim, K.S. Janacaitis, E.S. Jessop, M.K. Kong, R.E. Lyon, J.E. Murray, H.G. Patton, J.H. Pitts, H.T. Powell, M.O. Riley, E.P. Wallerstein, C.R. Wolfe, and B.W. Woods	
Mass Spectrometric Studies of Laser Damage in Calcium Fluoride .....	42
N.S. Nogar, E.C. Apel, and R.C. Estler	
CaF <sub>2</sub> : An ESCA Study .....	50
T. Raj and Marilyn Law	

LIMA in Damage Diagnostic .....	55
Ian Laidler, Graham J. Edge, David C. Emmony and Paul A. Temple	
Laser-Induced Damage to Titanium-Doped Sapphire Using 532 nm Wavelength Pulses of 10 ns Duration .....	65
S.C. Seitel and L.G. DeShazer	
High-Energy Pulsed Laser Beam Profiling System .....	70
D.B. Nichols, P.D. Texeira and T.M. Donovan	
Performance Characteristics of a Beam Profiling System Consisting of Various Solid State Imaging Devices and an 8-Bit Image Processor .....	73
Robert M. O'Connell and Alan F. Stewart	
Laser-Induced Damage Detection and Assessment by Enhanced Surface Scattering .....	83
S.C. Seitel and Mark T. Babb	
Thermal Properties of Optical Materials .....	89
D.L. Decker	
Beam-Induced Spherical Aberration in Cooled CW Laser Light Transmitting Components .....	96
Claude A. Klein	
Sum-Frequency Generation on Dye-Coated Surfaces using Collinear and Noncollinear Excitation Geometries .....	127
R.E. Muenchausen, D.C. Nguyen, R.A. Keller and N.S. Nogar	
Thresholds for and Time Dependence of UV-Photon-Induced Desorption of Lithium Atoms from Lithium-Fluoride Single Crystals .....	136
Richard F. Haglund, Jr. and Norman H. Tolk	
Radiation Hardness of Nd:YAG and Nd:Cr:GSGG Laser Rods .....	137
M.A. Acharekar, M.M. Kaplan and D.P. McCarthy	
The Effect of Impurities on U.V. Damage in CaF <sub>2</sub> .....	151
Ian Laidler and David C. Emmony	
Effect of Cleaning on the Optical Absorption of Calcium Fluoride and Fused Silica at 351 nm .....	159
D.J. Gallant, Marilyn Law and Brad Pond	

Chemically Strengthened Slab Laser Glass with Optical Surface Quality .....	168
C. Hata, T. Inazumi and T. Izumitani	
Comparison of Frequency Response Characteristics of an Optical Scatterometer and a Mechanical Profilometer .....	176
S.R. Wilson, G.A. Al-Jumaily and J.R. McNeil	
UltrasMOOTH Sapphire Produced by Noncontact Polishing .....	189
J.J. Shaffer and J.M. Bennett	
Optical Damage in Epoxy Polymers by Millisecond Light Pulses .....	194
C.R. Wolfe, J.H. Campbell, R.E. Lyon, J.H. Pitts and H.T. Powell	
Variations with Laser Pulse Duration of the Thresholds at 350-nm and 1064-nm for Bulk Damage in Crystals of KDP .....	206
R.P. Gonzales, M.C. Staggs, M.F. Singleton, D. George, C.L. Weinzapfel and S. Weinzapfel	
Production Oriented Laser Damage Testing at Hughes Aircraft Company .....	207
David W. Mordaunt, Jonathan W. Arenberg and Mark E. Frink	
Laser Damage Testing at the Atomic Weapons Research Establishment (AWRE) .....	211
C.J. Norman	
Temperature Effects on Laser Induced Damage and Accumulation in Silicon .....	216
John R. Platenak, Rodger M. Walser and Michael F. Becker	
End-Group Effects on the Wavelength Dependence of Laser-Induced Photodegradation in Bisphenol-A Polycarbonate .....	232
J.D. Webb and A.W. Czanderna	

#### Thin Films

Scatter Intensity Mapping of Laser-Illuminated Coating Defects .....	235
M.B. Moran, R.H. Kuo and C.D. Marrs	
Spectral Emission Studies of Optical Coating Defects .....	245
C.D. Marrs, S.J. Walker, M.B. Moran and J.O. Porteus	



Photothermal Measurement of Optical Coating	
Thermal Transport Properties .....	251
Randall T. Swimm and Lisa J. Hou	
Dependence of Damage Threshold of Anti-Reflection Coatings	
on Substrate Surface Roughness .....	259
Y. Nose, Y. Kato, K. Yoshida and C. Yamanaka	
Mechanical Stability and Absorptance of Metal Films .....	270
Michael McGuirk	
Highly Damage Resistant Anti-Reflection Coating on the Chemically	
Etched Surface for High Power Lasers .....	271
K. Yoshida, H. Yoshida, Y. Kato, C. Yamanaka and M. Ohtani	
Influence of Solution Chemistry on the Microstructure of	
Sol-Gel Derived Films .....	272
Kim F. Ferris, Gregory J. Exarhos and Clark Nguyen	
Quantification of the Magnitude and Duration of the Preconditioning	
Effect in AR Coated BK-7 Glass .....	279
M.E. Frink, J.W. Arenberg, D.W. Mordaunt, S.C. Seitel and E.A. Teppo	
Microstructural and Physio-Chemical Investigations of	
Dielectric Multilayers .....	288
Karl H. Guenther and Walter T. Pawlewicz	
An Investigation of Laser Processing of Thin Film Coatings .....	289
Annetta J. Weber, Alan F. Stewart and Gregory J. Exarhos	
Influence of Post-deposition Treatment by UV Light and Oxygen (ozone)	
on 350 nm Damage Thresholds of SiO <sub>2</sub> Films Deposited From Sols .....	297
I. Thomas, J. Wilder, A. Lee and D. George	
Laser Induced Damage of Dielectric Phase Retardation Mirrors	
at 1.064 Microns .....	300
D. Ristau, S.M.J. Akhtar and J. Ebert	
Amorphous Silicon for CO <sub>2</sub> Laser Mirror Coatings .....	313
F. Dutois, J. Mouchart, B. Pointu and G. Villela	
A Study of Thin Film Growth in the ZrO <sub>2</sub> - SiO <sub>2</sub> System .....	321
E.N. Farabaugh, Y.N. Sun, J. Sun, A. Feldman and H.-H. Chen	

Admixture of SiO <sub>2</sub> to Suppress TiO <sub>2</sub> Crystallization .....	332
J.R. Sites, J.S. Postek, R.S. Robinson, T.D. Schemmel and C.Y. She	
Long-Range Pulselength Scaling of 351 nm Laser Damage Thresholds .....	336
S.R. Foltyn and L. John Jolin	
Time to Failure in Single Pulse Laser Induced Damage in Thin Film Optical Coatings .....	344
J. Boyer	
Thermal Conductivity of Dielectric Films and Correlation to Damage Threshold at 1064 nm .....	345
S.M.J. Akhtar, D. Ristau and J. Ebert	
Correlation of Damage Levels at 1.06 $\mu$ m Varying Modal Content and Irradiance History on Representative Coated Laser Optics .....	352
Jonathan W. Arenberg, Mark E. Frink, David W. Mordaunt, Gordon Lee, Steven C. Seitel and Edward A. Teppo	
1064 nm and 350 nm Laser Damage Thresholds of High Index Oxide Films Deposited from Organic Solutions and Sols .....	361
I. Thomas, J. Wilder, R. Gonzales and D. George	
Fabrication of Fluoride Thin Films using Ultra-High Vacuum Techniques .....	365
K.L. Lewis, A.M. Pitt, N.G. Chew, A.G. Cullis, T.J. Wyatt-Davies, L. Charlwood, O.D. Dosser and I.T. Muirhead	
Chemical Vapor Deposition of TiO <sub>2</sub> Thin Films at Room Temperature .....	387
J. Wilder and I. Thomas	
Nondestructive Depth Profiling of Optically Transparent Films by Spectroscopic Ellipsometry .....	392
K. Vedam, S.Y. Kim, L. D'Aries and A.H. Guenther	
Application of Sol-Gel Coating to Slab Laser .....	397
T. Inazumi, K. Hara and T. Izumitani	
Properties of IAD Single-and Multi-Layer Oxide Coatings .....	401
James J. McNally, F.L. Williams, S.R. Wilson and J.R. McNeil	

Comparison of the Optical Properties of some High-Index Oxide Films prepared by Ion Beam Sputter Deposition with those of Electron Beam Evaporated Films .....	410
Brad Pond, R.A. Schmell, C.K. Carniglia and T. Raj	
An Analysis of Rugate Filter Behavior .....	418
Roger J. Becker	
Damage Thresholds of Antireflection Coatings at 790 nm .....	484
Gerald Gallegos, Steve Foltyn and Jim Boyer	
Photon Induced Desorption and Emission from Thin Film Dielectric Surfaces .....	488
John A. Kardach, Alan F. Stewart, Arthur H. Guenther and John K. McIver	
The Effect of Layer Thickness Errors in the Design of Coatings with Reduced Electric Field Intensity .....	505
Geza L. Keller	
Wavelength Dependence of Laser-Induced Sputtering from the (111) Surface of BaF <sub>2</sub> .....	506
J. Reif, H. Fallgren, W.E. Cooke, and E. Matthias	
Layer-Dependent Laser Sputtering of BaF <sub>2</sub> (111) .....	518
J. Reif, H. Fallgren, H.B. Nielsen, and E. Matthias	
<u>Surfaces and Mirrors</u>	
Impact of Thermal Blooming on Laser Damage Measurement Accuracy .....	531
Brian E. Newnam	
Characterization of Calcium Fluoride Optical Surfaces .....	532
M. Law, J. Bender and C.K. Carniglia	
An Investigation of Laser Processing of Silica Surfaces .....	542
Annetta J. Weber, Alan F. Stewart, Gregory J. Exarhos and W. Kent Stowell	
Spot Size Dependent Laser Materials Interactions due to Surface Electromagnetic Waves .....	557
R.T. Swimm, M. Bass, L. Fathe, J.Z. Lin and R. Kurtz	

Super-Polished Single Crystal Molybdenum Mirror for XUV X-Ray Radiation .....	561
K. Yoshida, K. Takeuchi, Y. Kato, E. Fujiwara, C. Yamanaka, K. Yamashita, K. Kurosawa, W. Sasaki, K. Uehara and H. Okamoto	
Effect of Diamond Machining on Laser Damage Threshold of Germanium .....	567
K.L. Lewis, L. Charlwood, N.G. Chew, A.G. Cullis, O.D. Dosser and A. Mannion	
Damage Morphologies and Cumulative Behavior of Laser Damage on Single Crystal Metal Surfaces .....	575
Yong Jee, Michael F. Becker and Rodger M. Walser	
Scattering Distribution from Multilayer Mirrors - Theoretical Research of a Design for Minimum Losses .....	594
C. Amra	
<u>Fundamental Mechanisms</u>	
Initiation of Laser Induced Damage by Small Metallic Particles .....	603
W. Becker, J.K. McIver and A.H. Guenther	
Some Comments on: Temperature Dependent Effects in Laser Induced Damage .....	611
M.R. Lange, J.K. McIver and A.H. Guenther	
Laser Induced Damage Threshold Derived from Chaotic Electron Dynamics .....	620
W. Becker, J.K. McIver and A.H. Guenther	
The Mechanism of Prebreakdown Nonlinear Energy Deposition from Intense Photon Fields at 532 nm in NaCl .....	621
S.C. Jones, X.A. Shen, P.F. Braunlich, Paul Kelly and A.S. Epifanov	
An Anomalous Absorption Model to Account for Accumulation in N-on-1 Damage in Si and GaAs .....	634
N.R. Shetty, M.F. Becker and R.M. Walser	
A Model for Probing Small Absorption Changes during Multiple Pulse Laser-Induced Damage .....	649
D. Kitriotis	

Nonlinear Absorption Initiated Avalanche Breakdown in Dielectric $\text{ZrO}_2$ .....	657
N. Mansour, E. Canto, M.J. Soileau and E.W. Van Stryland	
An Investigation of the Possibility that Laser-Induced Color Centers Are Responsible for Multiple Pulse Damage .....	670
Dimitrios Kitriotis and Larry D. Merkle	
Influence of Impurities and Defects on 1964 nm and 532 nm Damage in Quartz .....	677
Larry D. Merkle and Pradip K. Bandyopadhyay	
Model Comparison with Glancing Incidence Measurements of Overcoated Metal Mirrors .....	684
W.D. Kimura, F.J. Woodberry and L.F. DeSandre	
Closing Remarks .....	693
APPENDIX I. List of Attendees .....	696

**WELCOME TO THE EIGHTEENTH ANNUAL SYMPOSIUM  
ON OPTICAL MATERIALS FOR HIGH POWER LASERS**

Arthur H. Guenther  
Air Force Weapons Laboratory  
Kirtland Air Force Base, New Mexico

On behalf of my three co-chairmen, Hal Bennett, Dave Milam and Brian Newnam, we would like to welcome you to this, the eighteenth in this continuing series of symposia. Unfortunately, Hal Bennett is not able to be with us this year. He was here until yesterday, but he had to appear in court to settle some legal matters in California and he wishes to express his regrets that he is not going to be present. He'll be here in spirit certainly. As you just heard from Dr. Kamper, we are welcome back next year. I'm sure Hal will be with us at that time.

As the first viewgraph shows, the conference continues its steady growth. Last year we had 67 papers and about 225 attendees. This year we have 75 papers and I don't know what we will have in attendance but the 145 or so pre-registered was the largest number so recorded through any of these meetings, and there were at least another 40 to 50 who signed in last night.

I think it is important to note that the symposium continues to reflect the recent interest in thin films at this particular meeting. This year there are still twice as many papers in that category as in any of the others that we normally separate our papers into: materials and measurements, surfaces and mirrors, and fundamental mechanisms. In fact, we have moved thin films up in the sequence to follow materials and measurements since it encompasses a very large part of the meeting.

We hope that the proceedings from the 1984 meeting will be available for you to pick up tomorrow afternoon if the printing office delivers as promised. (They were.) This meeting has been the most dynamic in scheduling and I would ask that each of you please check your program and the short, late-change sheet to ensure that you know where we are and that if you have a paper, you know where it occurs. If you can't find it, please let us know right away. We do have a couple of slots open because we have had some extra poster boards made and one cancellation has given us an additional oral position.

The '85 proceedings are progressing but at last count there are 16 manuscripts that have not been received. Some wanted me to read the delinquent authors' names and ask them to stand up so that you could look and see who they were, but even I didn't want to start off the meeting in that manner. Rather, I would like to ask those of you

who are here who have manuscripts that are still among the missing, they are listed on the bulletin board outside, to please check off the status and give an indication when we might expect them. I will say we are progressing very rapidly to sending the proceedings to the publisher. In fact, three manuscripts were delivered this morning from last year's meeting, so they made it within a year, but we do have 16 that are still delinquent.

This is an opportunity to say a few words to you on a subject I think is most important. Without a doubt, these symposium proceedings, in my opinion, form the best and most comprehensive chronology of power optics problems and solutions from 1969 on. I think they continue to form the framework of the most significant work in the field. They have led not only to an efficiency in our progress in advancing optical materials for high power lasers but a recognition and recording of previous work resulting in avoidance of duplication. In fact, they have formed the basis of a tutorial in an educational sense for others entering or working in the field. I can't emphasize enough the investment we've all made and the need to continue to document results as we solve problems and proceed to new areas. In fact, the very format of this meeting, to wit, no parallel sessions, lots of discussion opportunities, and unlimited documentation, has engendered the technical world a cadre of mature well-informed specialists who are frequently called upon to overcome a major constraint in laser development, applications, or to improve designs.

Let me now add a few words about the state of affairs concerning the topics of today's interests as relates to this meeting. We continue to see new materials coming on the scene, primarily driven by applications such as short wavelength operation. For example, there is a lot of attention being given in the transparent case to calcium fluoride and some to lithium fluoride or metallics or inter-metallics in the case of substrates or reflectors both at short wavelengths and in the infrared. Just as applicable, however, I don't know why polymers have not really caught on more and it is unfortunate that we just heard last week that Professor Manenkov will not be with us to share his latest results in this field. Certainly polymers is an area that has caught on quite heavily in the Soviet Union. On the other hand, we do continue to see continued improvements and opportunities in sol-gel and related material technologies.

However, as I indicated, coatings still dominate the meeting and there is no question as to why that is; there is considerable leverage because of the multitude of applications. There is, as well, an inherent belief that there is a lot of room for improvement. The focus this year comes in several categories. First, and perhaps foremost, is the attention that is being given to the issue of thermal conductivity in thin films. Thermal conductivity is a very structure-dependent property of the material. This quality has a great impact upon the modeling that we have heard so much about in the last few years. In the past, if people used the thermal conductivity of bulk material, to come up with an estimate to compare with experimental measurements of

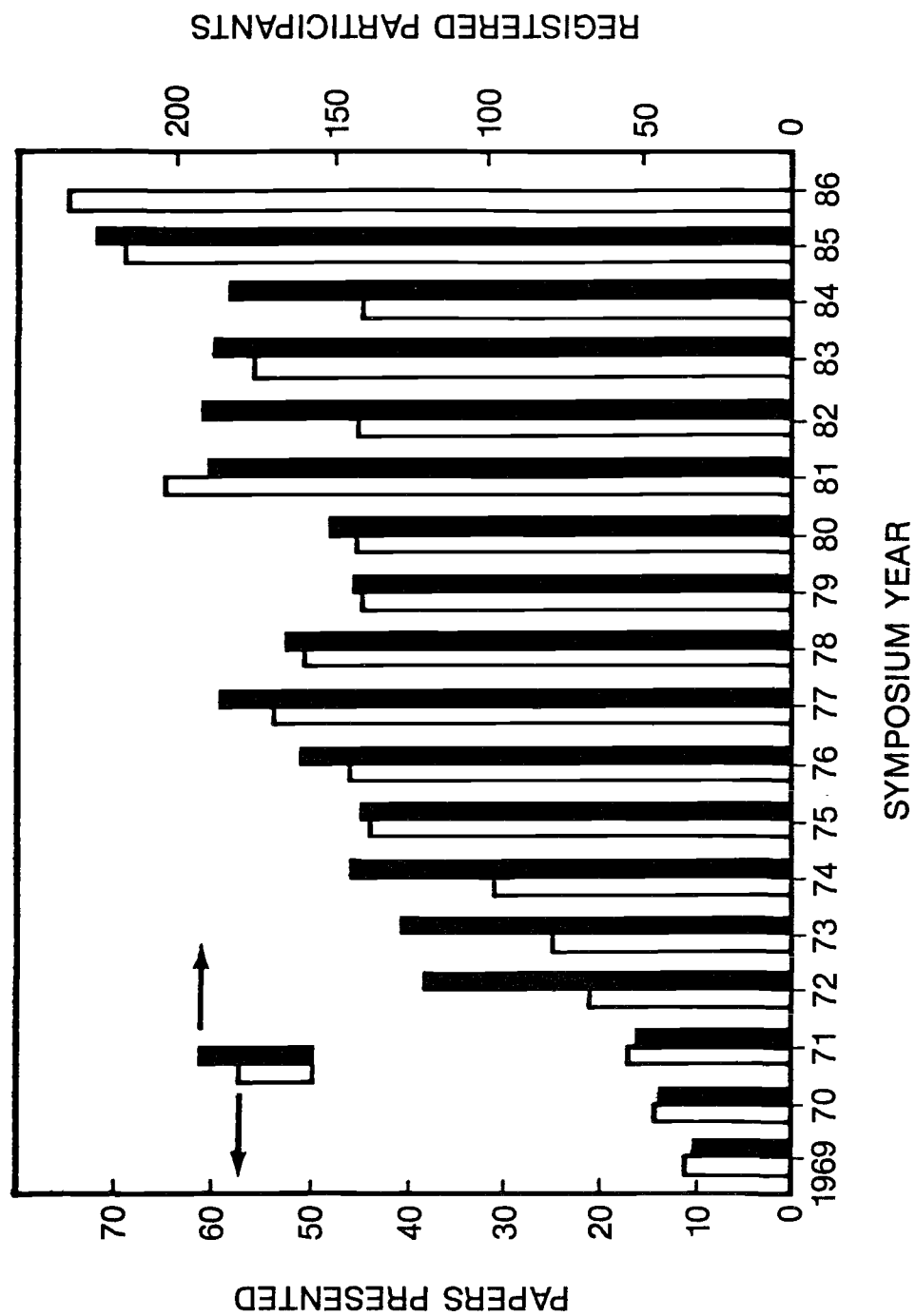
damaged threshold, they had to evoke an extremely high and fictitious absorption level, too high in fact to be credible. People were starting to look for other explanations to explain the high absorption levels. Recent reports of thermal conductivity measurements, where we see decreases ranging from 50 to 500, and in some cases maybe even to 1000, greatly alleviates this apparent inconsistency in that it limits the amount of heat that can be conducted away from an absorbing site. This in fact will, I am sure, bring better agreement between the modeling estimates and the quality experimental measurements of the damage threshold that we obtain in the laboratory.

Another area that has received a lot of attention is certainly the application driven area. Free-electron lasers certainly come to mind immediately. Brian Newnam pointed out a few years ago that there is going to be a problem with high fluences and there's going to be a problem with the diverse duty cycles of rf and inductive driven accelerators; which give you entirely different pulse train considerations. Add to this the wavelength agility which others see as an advantage in FELs. It becomes nothing but a problem for the people who wish to design FELs to have all the advances that they inherently offer.

We do see continued advances in instrumentation, and you will hear some interesting papers this year on spectroscopic ellipsometry. There has been a lot of attention given to this work over the last two or three years at the Naval Weapons Center, at Bell Laboratories, and at the Materials Research Laboratory at Penn State. It appears now that this technique is starting to give us some information about the structure inside films and as was pointed out earlier this year by Hal Bennett and others, one can actually determine surface roughness by this technique. There has been excellent agreement between that predicted from the ellipsometric measurements and that determined from surface profilometry. But, of course, on the same issue of instrumentation, we still are seeking that illusive and what we hope eventually to be a widely accepted facile pre-catastrophic damage indicator. It still seems that a lot of people are working on the issue of desorption as one possible solution to their problem, and there are several papers on that subject at the meeting today. Finally, from the instrumentation standpoint, it is gratifying to note the increase in the automated damage testing facilities throughout the world and I think this can only help advance coating technologies in allowing more rapid and economical assessment of perhaps the last active coating area, and that is process improvement. Which is leading in its own way to better coatings, and I mean better in terms of the eventual application, which may not be the one that you went out to solve.

There is no question that the hallmark of this meeting has been its flexibility to go where the action is and to consider and conquer new problems in both a systematic and synergistic manner.





**U.S. Department of Commerce**  
National Institute of Standards and Technology  
(formerly National Bureau of Standards)  
Gaithersburg, MD 20899

Official Business  
Penalty for Private Use \$300



Stimulating America's Progress  
1913-1988