Optical Scattering

Measurement and Analysis

second edition

John C. Stover

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Cover illustration: Geometry for the definition of BRDF.

For my family . . .

Donna
Sean
Shelly
Rhys
Margaux

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About the Second Edition

I wrote the first edition more for love than for money, and quite frankly, this attitude turned out to be quite appropriate. I was one of the Optical Engineering Series authors who suffered through a confusing publisher switch from Macmillan to McGraw-Hill. In the final rush to press, a number of things were left unfinished, and I have always been a little dissatisfied with some of the errors that crept in (yes, Figure 8.5 in the first edition is upside down!) and some of the material that lack of time forced me to leave out. So when McGraw-Hill announced that the first edition was going out of print, I took possession of the book and started back in to do it again. I have admired the professional attitude and performance of SPIE for more years than I care to admit, and when I realized that it might be possible to have them publish a second edition of *Optical Scattering*, I jumped at the chance. It makes a lot of sense that a book like this, which will never be printed in large numbers, have both author and publisher in it for love and not money.

A number of things in scatter measurement have changed or improved in the last four years and these are reflected in this edition. You will find some additions and changes in every chapter; however, three chapters underwent major changes. Chapter 2, on roughness calculations, has been reorganized—hopefully in a way that will make the analysis of surface-profile data more understandable. The inclusion in Chapter 7 of a section on rough surfaces is intended to help those readers who are interested in using light scatter as a source of process control for products that do not meet the smooth-surface criterion so blithely assumed in the optics industry. The new sections in Chapter 9, on inspection of silicon wafers and computer disks, are a result of real interest in those industries in catching up with the optics crowd in scatter/roughness metrology. Bare silicon wafers scatter mostly from surface topography (as opposed to films, discrete defects, etc.). Thus not only is silicon a great material for illustrating some of the points about roughness calculations via scatter measurements made throughout the book, but because roughness and roughness-induced haze are currently high-visibility issues (no pun intended) in the semiconductor industry, it is information of real contemporary importance. The same thing is true for the comments, and examples, on computer disk inspection, where roughness (called *texture* in that industry) is also an issue.

I do not expect a third edition. For one reason, SPIE has promised that

this edition will not go out of print as long as there is even a small market for the information. Secondly, my experience with the first edition has taught me that it is easier to retire on money than on love, and having already sown my wild academic oats, I probably need to concentrate on retirement and getting four kids through college (unfortunately not in that order). I wish all of you old and new "scatterbrains" the very best, and hope you find this edition worth your money and my time.

John C. Stover

Preface

This book originates from a set of notes developed over several years of teaching the fundamentals of light-scatter measurement and analysis to optical engineers (and those converting to optical engineering) at various conferences. Except for conference tutorials and a few isolated projects and classroom examples, very little is formally taught about the subject. The Universities of Arizona, Alabama, New Mexico, and Montana State have done most of the university scatter work, and combined they have probably produced less than 50 graduate students with thesis work on the subject. At the same time, as the sophistication, number, and expense of optical systems has grown over the 1970s and 80s, optical scatter has been increasingly recognized as a serious problem. Outside the optics industry, noncontact process-control and metrology scatter applications are just starting to be recognized. The high economic benefits associated with fast quality control in these higher-volume industries (paper, steel, aluminum, ceramics, etc.) have created a need for new inspection techniques. Current indications are that by the year 2000, there will be more scatter metrology applications found outside the optics industry than within. As a result, engineers, with or without an optics background, are finding themselves thrust (sometimes kicking and screaming) into the position of becoming "the company scatter expert" as new applications are recognized.

Hundreds of papers have now been written on the subject, using various notations, starting from different theoretical foundations, and describing small facets of an increasingly complex field of study. These papers can be categorized as "scatter in theory," "scatter is a system problem," or "scatter is a metrology solution." The intention of this book is to introduce engineers and physicists to scatter fundamentals for theory, problems, and solutions, as well as acquaint them with the rather diverse set of background subjects and literature required to help them become "the company scatter experts."

The first five chapters concentrate on background information. Chapter 1 is required reading for any other chapter, as it introduces much of the notation and basic concepts. Scatter is often tied to sample surface roughness, and Chapter 2 overviews the various roughness terms and definitions. Scatter can be analyzed from diffraction theory as shown in Chapter 3. The fourth chapter combines the results of Chapters 2 and 3 to

convert scatter data to surface statistics. Chapter 5 discusses polarization concepts: there are some very powerful polarization techniques that can be used in various process- and quality-control applications. Experimental instrumentation, techniques, limitations, and problems are covered in Chapter 6. In the seventh chapter, various scatter prediction techniques are presented. These include wavelength scaling for smooth optical surfaces and curve fitting for more generic samples. Chapter 8 discusses more advanced measurement and analysis techniques that take advantage of polarization for process- and quality-control applications. Chapter 9 provides a small sampling of industrial applications. In the last chapter, scatter specifications are illustrated through the use of several examples. Each chapter indicates in its opening paragraphs what material is required for background, and each chapter closes by indicating which of the following chapters contain material relating to the same topic. There are three appendices. The first is a review of field theory necessary for electromagnetic wave propagation. Appendix B covers some diffraction theory calculations too detailed for Chapter 3. Appendix C contains scatter data for several different materials taken at several different wavelengths and angles of incidence. It is organized so the various plots can be looked up by either wavelength or sample material. Its purpose is to give the reader some indication of expected scatter levels that may be encountered. For example, if after reading the book you are able to determine that your system needs a zinc selenide beamsplitter with a BTDF of less than 10^{-3} at 20 degrees at 10.6 μm, you will be able to determine if this is reasonable, based on previous data.

John C. Stover
July 1995

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Neither the first nor second editions of this book would have been possible without the help and cooperation of a great many people. First, I have to thank my wife and children for their patience and understanding during twenty long months of lost weekends and late suppers. I owe a tremendous debt to my coworkers at TMA. Bob Mathis and Don Bjork made it their job to lighten my load in order to provide enough time during the work week to complete the book. Marvin Bernt and Doug McGary are responsible for taking most of the scatter data that appears in the volume. I used a great deal of information generated by TMA authors for their technical publications and have had the pleasure, and advantage, of being able to discuss scatter issues with a first-class group of knowledgeable engineers and physicists who make their living doing scatter research. Dan Cheever, Kyle Klicker, Tod Schiff, and Dan Wilson, in particular, played key roles in designing and building the early instrumentation used to generate data and conclusions for the text. Michele Manry cheerfully typed through the seemingly endless supply of Greek symbols and manuscript changes to produce the first edition, and Cheryl Petersen repeated the process for the second edition. Mary Horan, senior editor at SPIE, did a great job of checking the details I find so easy to miss. Mark Stefan did the technical drawings. If every picture is worth a thousand words, he has saved us all considerable effort. Outside of Bozeman, I am indebted to several members of the optical community for their help and support. As indicated by the book references, Dr. Gene Church is a wealth of information on profile analysis and scatter. He reviewed the entire text and took time from his schedule to discuss his views with me on many key topics. In many respects, this book could have been his to write instead of mine. Win Baylies read the book and helped me a great deal with the additions on the semiconductor and computer-disk industries. Jean Bennett, Hal Bennett, Bob Breault, Tom Leonard, Steve McNeany, and Joe McNeely are just a few of the individuals who have given me the support (or needed stimulation) over the last two decades required to make the book possible. And last, but not least, I wish to thank Richard Skulski, my first industry supervisor (and good friend), for giving me the chance to work in this exciting technology.