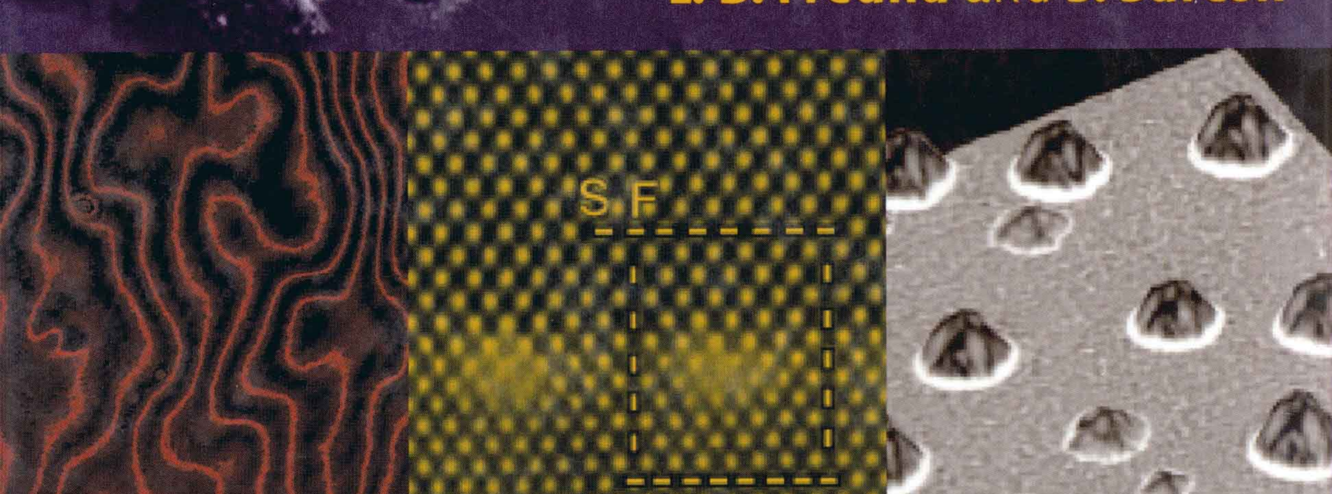
Thin Film Materials

Stress, Defect Formation and Surface Evolution

L. B. Freund and **S. Suresh**



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THIN FILM MATERIALS

Stress, defect formation and surface evolution

Thin films play an important role in many technological applications including microelectronic devices, magnetic storage media and surface coatings. This book provides a comprehensive coverage of the major issues and topics dealing with stress, defect formation and surface evolution in thin films. Physical phenomena are examined from the continuum down to the sub-microscopic length scales, with the connections between the structure of the material and its behavior described wherever appropriate. While the book develops a comprehensive scientific basis with which stress, deformation and failure in thin film materials can be characterized, an attempt is also made to link the scientific concepts to a broad range of practical applications through example problems, historical notes, case studies and exercises. Of particular interest to engineers, materials scientists and physicists, this book will be essential reading for senior undergraduate and graduate courses on thin films.

L. BEN FREUND is the Henry Ledyard Goddard University Professor in the Division of Engineering at Brown University.

SUBRA SURESH is the Ford Professor of Engineering and Head of the Department of Materials Science and Engineering, and Professor of Mechanical Engineering at Massachusetts Institute of Technology.

To our families

Preface

Within a period of a few decades, the field of materials science and engineering has emerged as a focal point for developments in virtually all areas of engineering and applied science. The study of *thin film materials* has been one of the unifying themes in the development of the field during this period. As understood here, the area encompasses films bonded to relatively thick substrates, multilayer materials, patterned films on substrates and free-standing films. Significant advances in methods for synthesizing and processing these materials for ever more specific purposes, as well as in instrumentation for characterizing materials at ever diminishing size scales, have been key to modern engineering progress.

At the dawn of the 21st century, the United States National Academy of Engineering reported the outcome of a project intended to identify the twenty most significant engineering achievements of the preceding century. It is evident from the list compiled that achievements of the second half of the twentieth century – electronics, computers, health technologies, laser and fiber optics, for example – were all based on the creative and efficient exploitation of materials; thin film materials represent a major component of this advance in materials technology. In fact, the impact of advances in the specialized uses of materials was so pervasive in the achievements being recognized by the Academy that the development of high-performance materials itself was included as one of the most significant achievements.

The goal of this book is to summarize developments in the area of thin film materials that have occurred over the past few decades, with emphasis on the generation of internal stress and its consequences. Internal stress can induce a variety of undesirable consequences including excessive deformation, fracture, delamination, permanent deformation and microstructural alterations. In spite of these possibilities, thin films have been inserted into engineering systems in order to accomplish a wide range of practical service functions. Among these are microelectronic devices and packages; micro-electro-mechanical systems or MEMS; and surface coatings intended to impart a thermal, mechanical, tribological, environmental, optical, electrical, magnetic or biological function. To a large extent, the success of this endeavor has been enabled by research leading to reliable means for estimating stress in small material systems and by establishing frameworks in which to assess the integrity or functionality of the systems. The prospect for material failure due to stress continues to be a technology-limiting barrier, even in situations in which load-carrying capacity of the material is not among its primary functional characteristics. In some circumstances, stress has desirable consequences, as in bandgap engineering for electronic applications and in the self-assembly of small structures driven by stored elastic energy. It is our hope that the information included in this book will be useful as an indicator of achievements in the field and as a guide for further advances in a number of new and emerging directions.

The first chapter is devoted largely to a discussion of the origins of residual stress in thin film materials and to identification of relationships between processing methods and generation of stress. The consequences of stress are discussed in subsequent chapters, with the presentation generally organized according to the size scale of the dominant physical phenomena involved. Overall deformation of film–substrate systems or multilayer structures is considered in Chapters 2 and 3. This is followed by examination of the general failure modes of fracture, delamination and buckling of films in Chapters 4 and 5. The focus then shifts to a smaller scale to discuss conditions for dislocation formation in Chapter 6 and inelastic deformation of films in Chapter 7. Finally, the issues of stability of material surfaces and evolution of surface morphology or alloy composition are considered in Chapters 8 and 9. The consequences of stress in thin films are linked to the structure of the film materials wherever possible.

It is recognized that each of the principal topics covered in the book could itself be developed into a substantial monograph, but the goal here is not the exhaustive treatment of a topic of limited scope. The area is inherently interdisciplinary, and the intention is to provide a comprehensive coverage of issues relevant to stress and its consequences in thin film materials. Adoption of this approach meant that many choices had to be made along the way about depth of coverage of specific topics and balance among different topics; we hope that readers will judge the choices made to be reasonable. The main purpose of the book is the coherent presentation of a sound scientific basis for describing the origins of stress in films and for anticipating the consequences of stress in defect formation, surface evolution and allied effects. Many references to original work are included as a guide to the archival literature in the area. In addition, the fundamental concepts developed are made more concrete through implementation in sample calculations and through discussion of case studies of practical significance. The description of experimental methods, results and observations is included as an integral part of developing the conceptual structure of the topics examined. Each chapter concludes with a set of exercises that further extend the material discussed and which can challenge newcomers to the area at applying concepts. It is our hope that, with this structure, the book will serve as a research reference for those pursuing the area at its frontiers, as a useful compilation of readily applicable results for practicing engineers, and as a textbook for graduate students or advanced undergraduate students wishing to develop background in this area.

The idea for the book grew out of a course on thin films that has been offered for students in solid mechanics and materials science at Brown University since 1992, as a natural outgrowth of emerging research activity in the area. We are grateful to the many students, postdoctoral research associates and colleagues who attended these lectures and whose enthusiasm gave this project its initial impetus.

We are also grateful to many colleagues who have contributed in various ways to the preparation of this book. We particularly thank John Hutchinson who used a draft of parts of the book for a course for graduate students at Harvard and MIT, and who provided valuable feedback on this material. Both John Hutchinson and Bill Nix kindly shared with us their own course materials on thin films. Several colleagues read drafts of various sections of the book and offered helpful recommendations; they include Ilan Blech, Eric Chason, Ares Rosakis, Vivek Shenoy and Carl Thompson. Several graduate students who took courses based in part on draft chapters, particularly Yoonjoon Choi and Nuwong Chollacoop, suggested a number of clarifications and improvements in the presentation. Finally, we are grateful to the many colleagues who provided figures and micrographs from their own work; in these cases, acknowledgments are noted along with the included material. Tim Fishlock at Cambridge University Press offered us considerable flexibility in the formulation of the scope of this book and in the preparation of the document. We also thank Desiree Soucy who secured the agreements necessary to reproduce proprietary material and who proofread the entire manuscript.

LBF is grateful to the Materials Research Science and Engineering Center, funded by the National Science Foundation at Brown University, for long-term support of research in the general area of thin films and for the collaborations fostered through the Center. He is also thankful to the Division of Engineering and Applied Sciences at Caltech for hosting a sabbatical leave; the kind hospitality and congenial environment afforded an opportunity for pursuing the book writing project at its early critical stage. SS is grateful to the Defense University Research Initiative in Nano-Technology, funded by the Office of Naval Research at MIT, and the Programme on Advanced Materials for Micro and Nano Systems, funded by the Singapore-MIT Alliance, for their support for research in the areas covered by the book.

A project of this magnitude would not have been possible without the support and encouragement of the members of our families. We are extremely grateful for their enduring patience and understanding during our long hours of immersion in this project over the past several years.

Contents

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Introduction and Overview

Thin solid films have been used in many types of engineering systems and have been adapted to fulfill a wide variety of functions. A few examples follow.

- Great strides in thin film technology have been made in order to advance the rapid development of miniature, highly integrated electronic circuits. In such devices, confinement of electric charge relies largely on interfaces between materials with differing electronic properties. Furthermore, the need for thin materials of exceptionally high quality, reproducible characteristics and reliability has driven film growth technology through a rapid succession of significant achievements. More recently, progress in the physics of material structures that rely on quantum confinement of charge carriers continues to revolutionize the area. These systems present new challenges for materials synthesis, characterization and modeling.
- The use of surface coatings to protect structural materials in high temperature environments is another thin film technology of enormous commercial significance. In gas turbine engines, for example, thin surface films of materials chosen for their chemical inertness, stability at elevated temperatures and low thermal conductivity are used to increase engine efficiency and to extend significantly the useful lifetimes of the structural materials that they protect. Multilayer or continuously graded coatings offer the potential for further progress in this effort.
- The useful lifetimes of components subjected to friction and wear due to contact can be extended substantially through the use of surface coatings or surface treatments. Among the technologies that rely on the use of thin films in this way are internal combustion engines, artificial hip and knee implants, and computer hard disks for magnetic data storage.
- Thin films are integral parts of many micro-electro-mechanical systems designed to serve as sensors or actuators. For example, a piezoelectric or