MATERIALS CHARACTERIZATION SERIES

Series Editors: C. Richard Brundle and Charles A. Evans, Jr.

材料表征原版系列丛书

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CHARACTERIZATION OF Integrated Circuit Packaging Materials

Thomas M. Moore
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CHARACTERIZATION OF INTEGRATED CIRCUIT PACKAGING MATERIALS

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MATERIALS CHARACTERIZATION SERIES
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Foreword

What do we mean by the term "packaging" of semiconductor integrated circuits? If we adopt the recently formulated viewpoint that "packaging bridges the gap between silicon and systems," then it is evident that packaging is much more than the traditional encapsulation of the silicon chip. It not only offers opportunities for major advances in microsystem performance, but also it presents serious challanges for choosing product-conforming designs and interconnections, low-cost materials and processes, and for building in reliability for cost-effective ownership.

With this new definition of "packaging" in mind, we can clearly see two major driving forces for the development of IC packages which are active today and are expected to continue to be active far into the next century in a considerably enhanced and more vigorous manner. The first driver is the pulling force of commercial and military markets. They demand better power management, low-noise operation, and reliability under even extreme environmental conditions—all of this at equal or preferably lower cost than today. This market pull is projected to accelerate due to higher levels of integration and wider penetration of commercial and military product segments. Eventually, this will drive semiconductor electronics to have a dominant share of the overall world economy—and packaging will increasingly be the enabler.

The second driver is an intensive technology push, nourished by an increase in the stream of industrial, university, and government laboratory investigations. Emphasis is placed on developing computer simulations of the electrical, thermal, and mechanical stress performance of interconnections and packages. Also, materials characterization of package components, reliability prediction, and simulation of failure mechanisms of IC components and systems are receiving increased attention. This technology push continues unabated today and, because of its fundamental nature, it is anticipated to increase in importance in the future, with prime emphasis placed on knowledge of materials and processes. After all, they not only determine the electrical and thermal performance of packages, but to a great extent the reliability characteristics as well. With a solid data base of materials and process characteristics, there is hope that processes can be controlled so tightly that building in reliability (as opposed to testing in) will become a reality, making testing of IC systems more manageable.

In view of this, this volume, *Characterization of Integrated Circuit Packaging Materials*, is a most welcome addition to the book series on Materials Characterization. It covers a wide spectrum of materials employed in the packaging of IC components and systems and familiarizes the reader with generic aspects of selecting, measuring, and processing these materials. The scope stretches from computer

simulation of mechanical stress in these materials to the reliability assessment of finished semiconductor subsystems; also, adhesion between diverse materials, hermeticity and moisture sensitivity, molding compounds and solderability aspects, and thermal and electrical performance are discussed.

This book will be especially welcomed by those readers—even non-specialists—who need to understand the essentials of characterization techniques so that they can intelligently identify the key materials features important to their specific packaging application. Most often this will require an appreciation of the trade-offs between seemingly conflicting materials characteristics and an appreciation of the manner in which carefully selected processes can be used to enhance the desired materials characteristics. The importance of the knowledge of packaging materials and process data cannot be overemphasized for high reliability IC systems. In addition, this goal must be accomplished through cost-effective manufacturing.

It is hoped that this book, grown out of many years of experience and written by experts in their respective fields, will stimulate readers to get involved in (and even to get enchanted by) the complexities and possibilities of materials and process characteristics so that they may contribute to the promising potential of IC systems.

Dr. Walter H. Schroen
TI Fellow

Preface to the Reissue of the Materials Characterization Series

The 11 volumes in the Materials Characterization Series were originally published between 1993 and 1996. They were intended to be complemented by the *Encyclopedia of Materials Characterization*, which provided a description of the analytical techniques most widely referred to in the individual volumes of the series. The individual materials characterization volumes are no longer in print, so we are reissuing them under this new imprint.

The idea of approaching materials characterization from the material user's perspective rather than the analytical expert's perspective still has great value, and though there have been advances in the materials discussed in each volume, the basic issues involved in their characterization have remained largely the same. The intent with this reissue is, first, to make the original information available once more, and then to gradually update each volume, releasing the changes as they occur by on-line subscription.

C. R. Brundle and C. A. Evans, October 2009

Preface to Series

This Materials Characterization Series attempts to address the needs of the practical materials user, with an emphasis on the newer areas of surface, interface, and thin film microcharacterization. The Series is composed of the leading volume, *Encyclopedia of Materials Characterization*, and a set of about 10 subsequent volumes concentrating on characterization of individual materials classes.

In the *Encyclopedia*, 50 brief articles (each 10 to 18 pages in length) are presented in a standard format designed for ease of reader access, with straightforward technique descriptions and examples of their practical use. In addition to the articles, there are one-page summaries for every technique, introductory summaries to groupings of related techniques, a complete glossary of acronyms, and a tabular comparison of the major features of all 50 techniques.

The 10 volumes in the Series on characterization of particular materials classes include volumes on silicon processing, metals and alloys, catalytic materials, integrated circuit packaging, etc. Characterization is approached from the materials user's point of view. Thus, in general, the format is based on properties, processing steps, materials classification, etc., rather than on a technique. The emphasis of all volumes is on surfaces, interfaces, and thin films, but the emphasis varies depending on the relative importance of these areas for the materials class concerned. Appendixes in each volume reproduce the relevant one-page summaries from the *Encyclopedia* and provide longer summaries for any techniques referred to that are not covered in the *Encyclopedia*.

The concept for the Series came from discussion with Marjan Bace of Manning Publications Company. A gap exists between the way materials characterization is often presented and the needs of a large segment of the audience—the materials user, process engineer, manager, or student. In our experience, when, at the end of talks or courses on analytical techniques, a question is asked on how a particular material (or processing) characterization problem can be addressed the answer often is that the speaker is "an expert on the technique, not the materials aspects, and does not have experience with that particular situation." This Series is an attempt to bridge this gap by approaching characterization problems from the side of the materials user rather than from that of the analytical techniques expert.

We would like to thank Marjan Bace for putting forward the original concept, Shaun Wilson of Charles Evans and Associates and Yale Strausser of Surface Science Laboratories for help in further defining the Series, and the Editors of all the individual volumes for their efforts to produce practical, materials user based volumes.

C. R. Brundle *C. A. Evans, Jr.*

Preface to the Reissue of *Characterization of Integrated Circuit Packaging Materials*

Eighteen authors (ten of them from Texas Instruments) were involved in originally putting this comprehensive volume together. There have been significant advances in IC packaging since the original publication, but the basic functions of the packaging remain the same, and the approaches discussed here towards the analysis and characterization of the wide range of materials involved remain valid, with the underlying principles unchanged. Following the reissue of the volume in close to its original form, it is our intention to release updates and new material as on-line downloads, as they become available.

C. R. Brundle and C. A. Evans, December 2009

Preface

Market opportunities have driven a dramatic increase in the functionality of integrated circuits (ICs), placing greater demands on the performance and reliability of the IC package. The IC package serves several functions, including

- mechanical protection for the die during assembly and use
- electrical interconnection between the die and the surrounding system
- a thermal path for heat removal from the die
- a geometric form compatible with the system design.

Over the past decade there have been increases in die sizes from 1 mm^2 to over 400 mm^2, in leads on a package from 8 to over 500, and in power dissipation from 10 mW to over 35 W, with power densities approaching 100 W/cm^2. The encapsulation of very large die in plastic packages produces interfacial shear stresses that can lead to failure during temperature cycling. Also, surface mount technology exposes the body of the plastic package to such high temperatures during assembly that moisture-related mechanical failure of the package can occur. When one considers the demands now placed on the IC package and the relatively high reliability of the IC die, one realizes that the package has become the primary factor limiting the performance and reliability of the finished IC product.

The selection of materials for both hermetic and non-hermetic packages is influenced by the mechanical, electrical, and thermal requirements of the device and its surrounding electrical system and by the environment to which the device will be exposed. The reliability of the finished device will depend not only on the characteristics of the individual materials but also on the interaction of package materials at interfaces during exposure to such stresses as thermal gradients, temperature cycling, moisture, and contamination. In the development of improved IC packages, the matching of mechanical properties at interfaces has become an important factor.

This volume addresses the characteristics of IC packages and materials-related problems in the industry. It is unlike most other volumes in the Materials Characterization series in that it does not deal with a distinct class of materials, or even a group of materials related by characteristics. Instead, it discusses a group of materials that are, in many cases, related only because they are used together in IC packages. The materials included in this group may also be discussed in other volumes in this series—*Characterization of Metals and Alloys, Characterization of Polymers*, and *Characterization of Ceramics*, for example. It is the purpose of this volume to concentrate on the characteristics of these materials that impact the

performance and reliability of IC packages and the techniques for measuring these characteristics.

The conventional approach for a text on the characterization of IC packaging materials would describe the techniques in detail and provide packaging examples. This volume takes a different perspective. It is designed to help the reader understand the important characteristics of IC packaging materials and the various techniques available for measuring them. It will enable the characterization non-specialist to select and communicate with the appropriate characterization lab. It is intended as a practical guide for engineers working in IC packaging, assembly, and reliability, as well as an application-specific reference for a graduate-level course in materials science. The chapters of this volume are based on the key characteristics and critical technological problems of IC packaging. Characterization techniques are described through examples in which the benefits and trade-offs of the techniques are demonstrated. The reader is referred to the appendix for more information on the characterization techniques. The appendix includes one-page summaries of techniques discussed in more detail in the lead volume of this series, *Encyclopedia of Materials Characterization*, and longer summaries of techniques that are unique to this volume.

Chapter 1, IC Package Reliability Testing, describes the methods for evaluating the reliability of IC packages through in-process measurements and through accelerated stress tests on finished packages. The integrity of critical internal interfaces is demonstrated to be the key factor in package reliability. Factors which affect the adhesion of the mold compound to the lead frame and die are covered in Chapter 2, Mold Compound Adhesion and Strength. These factors are difficult to measure, but some properties of the materials' surfaces, such as the wetting angle and the work of adhesion, can be measured to indirectly predict adhesion performance. The impact of mold compound adhesion on assembly operations and reliability is discussed, and future directions in mold compound development are reviewed.

Chapter 3, Mechanical Stress in IC Packages, demonstrates how the different mechanical properties of the materials within the package can lead to internal stresses during temperature cycling. Finite element modeling is used to predict these stresses, and in situ strain gauges directly measure stresses at the die surface. Chapter 4, Moisture Sensitivity and Delamination, describes how moisture absorbed from the atmosphere by the mold compound during shipping or storage can produce high stresses and severe damage to the plastic package during surface mount assembly. Acoustic microscopy is shown to be effective in detecting package cracks and delaminations nondestructively. Acoustic microscope studies indicate that delamination at the surface of the die is the primary cause of electrical failure during temperature cycling.

Chapter 5, Thermal Management, describes how the exponential rise in power densities over the past 20 years has turned thermal management into a critical design issue. Techniques for measuring the thermal properties of packaging materials are demonstrated. Chapter 6, Electrical Performance of IC Packages, discusses

the modeling techniques and test methods for predicting high-frequency IC package performance. Most IC package electrical characteristics are very dependent upon package design, as well as material properties, and can be defined only for the complete IC package configuration. Chapter 7, Solderability of Integrated Circuits, covers the various lead finishes used on IC packages and the test methods for determining solderability and for analyzing solder defects. Chapter 8, Hermeticity and Joining in Ceramic IC Packages, reviews ceramic package sealing, methods for testing hermeticity, and residual gas analysis of the package cavity. Chapter 9, Advanced Interconnect Technology, deals with solutions to performance issues that often dictate replacing discrete IC device packages with the direct interconnection of die on multi-chip module (MCM) substrates. The properties of the materials used for interconnect substrates take on a new level of importance when these materials must also perform the function of IC package.

The completion of this volume would not have been possible without the encouragement and support of the Materials Science Laboratories (MSL), which are a part of the Central Research Laboratories of Texas Instruments, Inc., in Dallas. The editors especially recognize the support of Dr. Thomas J. Shaffner, Acting Director of MSL, and Dr. Don W. Shaw, Director of MSL and Founding Director of the Texas Instruments Tsukuba Research and Development Center in Tsukuba, Japan. Throughout the completion of this volume we have enjoyed the patience and professionalism of Lee E. Fitzpatrick, the managing editor at Manning Publications. Many of the figures were created by Brett Geddes and Larry Norton, two of the computer graphics specialists in the Graphics Services group of the TI Central Research Laboratories. We greatly appreciate the contributions from our technical readers: William Sonia of Annam, Mike Lampson and Gail Heinen of Texas Instruments, and Michael Chan and Joe Stoddard of Compaq Computer Corporation. We also appreciate the expert support in library research of Marcia Schemper-Carlock of Texas Instruments.

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