MODERN ELECTROPLATING
CONTRIBUTORS

JOSEPH A. ABYS,  Lucent Technologies, Electroplating Chemicals and Services, Staten Island, NY

GEORGE A. DI BARI,  INCO, Saddle Brook, NJ

JACK W. DINI,  Lawrence Livermore National Laboratory, Livermore, CA

TAKAYUKI HOMMA,  Department of Applied Chemistry, Waseda University, Tokyo, Japan

MASANOBU IZAKI,  Department of Inorganic Chemistry, Osaka Municipal Technical Research Institute, Osaka, Japan

MANFRED JORDAN,  Dr. Ing. Mas Schlötter GmbH & Co. KG, Galvanotechnik, D-73304 Geisling/Steige, Germany

MASARU KATO,  Central Research Laboratory, Kanto Chemical Company, Soka Saitama-ken, Japan

PAUL A. KOHL,  Georgia Institute of Technology, School of Chemical Engineering, Atlanta, GA

SHINICHI KOMABA,  Department of Applied Chemistry, Waseda University, Tokyo, Japan

N. V. MANDICH,  HBM Electrochemical Company, Lansing, IL

TOSHIYUKI MOMMA,  Department of Applied Chemistry, Waseda University, Tokyo, Japan

IZUMI OHNO,  Tokyo Institute of Technology, Department of Metallurgical Engineering, Tokyo, Japan

YUTAKA OKINAKA,  Advanced Research Center for Science and Engineering, Waseda University, Tokyo

TETSUYA OSAKA,  Department of Applied Chemistry, Waseda University, Tokyo, Japan

MILAN PAUNOVIC,  IBM T.J. Watson Research Center, Yorktown Heights, NY

MORDECHAY SCHLESINGER,  Department of Physics, University of Windsor, Windsor Ontario, Canada

T. E. SCHLESINGER,  Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA
CONTRIBUTORS

DEXTER D. SNYDER, General Motors Research and Development Center, Warren, MI

DONALD L. SNYDER, ATO Tech, Cleveland, OH

DENNIS R. TURNER, 59 Susan Drive, Chatham, NJ

MICA TOMKIEWICZ, Department of Physics, Brooklyn College of SUNY, Brooklyn, NY

ROLF WEIL, 47 Carteret Street, West Orange, NJ

RENÉ WINAND, Department of Metallurgy and Electrochemistry, University of Bruxelles, Bruxelles, Belgium

TOKIHKO YOKOSIMA, Department of Applied Chemistry, Waseda University, Tokyo, Japan

YUN ZHANG, Lucent Technologies, Electroplating Chemicals and Services, Staten Island, NY
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fundamental Considerations</td>
<td>Milan Paunovic, Mordechay Schlesinger, and Rolf Weil</td>
</tr>
<tr>
<td>2</td>
<td>Electrodeposition of Copper</td>
<td>Jack W. Dini</td>
</tr>
<tr>
<td>3</td>
<td>Electrodeposition of Nickel</td>
<td>George A. Di Bari</td>
</tr>
<tr>
<td>4</td>
<td>Electrodeposition of Gold</td>
<td>Paul A. Kohl</td>
</tr>
<tr>
<td>5</td>
<td>Electroless and Electrodeposition of Silver</td>
<td>Mordechay Schlesinger</td>
</tr>
<tr>
<td>6</td>
<td>Tin and Tin Alloys for Lead-Free Solder</td>
<td>Yun Zhang and Joseph A. Abys</td>
</tr>
<tr>
<td>7</td>
<td>Electrodeposition of Chromium</td>
<td>N. V. Mandich and Donald L. Snyder</td>
</tr>
<tr>
<td>8</td>
<td>Electrodeposition of Lead and Lead Alloys</td>
<td>Manfred Jordan</td>
</tr>
<tr>
<td>9</td>
<td>Electrodeposition of Tin-Lead Alloys</td>
<td>Manfred Jordan</td>
</tr>
<tr>
<td>10</td>
<td>Electrodeposition of Zinc and Zinc Alloys</td>
<td>René Winand</td>
</tr>
<tr>
<td>11</td>
<td>Electrodeposition of Iron and Iron Alloys</td>
<td>Masanobu Izaki</td>
</tr>
<tr>
<td>12</td>
<td>Electrodeposition of Palladium and Palladium Alloys</td>
<td>Joseph A. Abys and Conor A. Dullaghan</td>
</tr>
</tbody>
</table>
PREFACE

In planning this new edition of Modern Electroplating, we have realized from the start that it would be impossible to include in one volume both the fundamental aspects and the technology itself. For this reasons we have decided to publish the recent developments in the science of deposition in a separate volume titled Fundamentals of Electrochemical Deposition. That volume was published in November 1998. Therefore, the present volume includes only a brief summary of fundamental technological advancements, and this is presented in the first, introductory chapter.

Since the last edition of Modern Electroplating in 1975, electrochemical deposition has evolved from an ill-defined area, as the Preface to the previous edition calls it, into an exact science. This development is, in the first place, seen as responsible for the ever-increasing number and widening types of applications of this branch of practical science and engineering.

The most significant developments in any field of science or technology in general, and in electrochemistry in particular, are made by those only who possess a good understanding of the fundamental aspects of the discipline, which in this case is electrochemical deposition. We, the editors, found it necessary and highly desirable to seek and present to the reader a companion volume that, for all intents and purposes, makes essentially a completely new contribution and not just a revised version of the earlier editions. Thus, for the sake of illustration, the present edition includes a chapter devoted to the electrodeposition of semiconductors. Another deals with environmental issues. Last, but not least, in this connection, neither of the editors nor the vast majority of the contributors were associated with any of the earlier editions.

Technological areas in which the possession of technical knowledge of electroplating is found to be essential include all aspects of electronics; macro-, micro-, and nano-optics; opto-electronics; and sensors of most types. In addition, a number of key industries, such as the automotive industry, employ methods of electroplating. This is so even when other methods such as evaporation and sputtering CVD (chemical vapor deposition) are an option. Electroplating is therefore often used for reasons of economy and/or convenience.

This volume is divided into 26 chapters. After a three-part introductory chapter by Paunovic, Schlesinger, and Weil come 13 chapters dealing with the electrodeposition of copper (Dini), nickel (DiBari), gold (Kohl), silver (Schlesinger), tin (Abys et al.), chromium (Snyder et al.), lead and alloys (Jordan), tin-lead alloys (Jordan), zinc and alloys (Winand), iron and alloys (Izaki), palladium and alloys (Abys et al.), nickel and cobalt alloys (DiBari), and semiconductors (T. E. Schlesinger). Closing this series of chapters is one on deposition on nonconductors (Schlesinger), and conductive polymers (Osaka et al.). Next come 6 chapters dealing with electroless deposition of copper (Paunovic), nickel (Schlesinger), cobalt (Osaka), palladium and platinum (Ohno), gold (Okinaka), and electroless alloys.
(Ohno). Finally, 4 chapters close the book, and these are on preparation for deposition (Dexter Snyder), manufacturing technologies (Turner), manufacturing control (Turner), and environmental considerations (Tomkiewicz).

In the preface to *Fundamentals of Electrochemical Deposition* we stated that it may be considered a lucky coincidence that this volume is published close to the time that copper interconnection technology is introduced in the microelectronic industry. This is still the case. There has been a truly revolutionary change from physical to electrochemical techniques in the production of microconductors on silicon, and developments in electrochemical deposition are bound to generate and maintain in the twenty-first century an increased interest and urgent need for up-to-date information regarding the technology. The present volume together with the *Fundamentals* volume should be of great help in understanding these advancements.

The chapters were written by different authors and so differences in style and approach will be evident. We the editors have tried to smooth those differences without changing the basic message present in each chapter. We also intend this volume to be a useful reference for practitioners of deposition as well as for individuals who are about to enter this modern ever-evolving field of practical knowledge. For this reason each chapter is complete and may be read and consulted separately, and certainly the book can be read in any order.

Our thanks and heartfelt gratitude go to many members of the Electrochemical Society and in particular to those of the Electrodeposition Division. Our thanks also go to our respective families for their patience and understanding during the hectic long hours we spent in preparing this volume.

**Mordechay Schlesinger**

*Windsor Ontario, Canada*

**Milan Paunovic**

*Yorktown Heights, New York*
The Electrochemical Society Series

Corrosion Handbook
Edited by Herbert H. Uhlig

Modern Electroplating, Third Edition
Edited by Frederick A. Lowenheim

Modern Electroplating, Fourth Edition
Edited by Mordechay Schlesinger and Milan Paunovic

The Electron Microprobe
Edited by T. D. McKinley, K. F. J. Heinrich, and D. B. Wittry

Chemical Physics of Ionic Solutions
Edited by B. E. Conway and R. G. Barradas

High-Temperature Materials and Technology
Edited by Ivor E. Campbell and Edwin M. Sherwood

Alkaline Storage Batteries
S. Uno Falk and Alvin J. Salkind

The Primary Battery (in Two Volumes)
Volume I Edited by George W. Heise and N. Corey Cahoon
Volume II Edited by N. Corey Cahoon and George W. Heise

Zinc-Silver Oxide Batteries
Edited by Arthur Fleischer and J. J. Lander

Lead-Acid Batteries
Hans Bode
Translated by R. J. Brodd and Karl V. Kordesch

Thin Films-Interdiffusion and Reactions
Edited by J. M. Poate, M. N. Tu, and J. W. Mayer

Lithium Battery Technology
Edited by H. V. Venkatasetty

Quality and Reliability Methods for Primary Batteries
P. Bro and S. C. Levy
Techniques for Characterization of Electrodes and Electrochemical Processes  
Edited by Ravi Varma and J. R. Selman

Electrochemical Oxygen Technology  
Kim Kinoshita

Synthetic Diamond: Emerging CVD Science and Technology  
Edited by Kari E. Spear and John P. Dismukes

Corrosion of Stainless Steels  
A. John Sedriks

Fundamentals of Electrochemical Deposition  
Milan Paunovic and Mordechay Schlesinger

Semiconductor Wafer Bonding: Science and Technology  
Q.-Y. Tong and U. Göscle

Uhlig’s Corrosion Handbook, Second Edition  
Edited by R. Winston Revie
Conversion Factors

1 centimeter (cm) = 0.934 inch (in.)
1 millimeter (mm) = 0.0394 inch (in.)
1 micrometer (µm, micron) = 0.0394 mil = 39.37 microinch (µ in.)
1 square decimeter (dm²) = 15.5 square inch (in.²) = 0.1076 square foot (ft²)
1 square centimeter (cm²) = 0.155 square inch (in.²)
1 square millimeter (mm²) = 0.00155 square inch (in.²)
1 kilogram (kg) = 2.205 pound (lb)
1 gram (g) = 0.0353 ounce (oz) avoirdupois = 0.0321 ounce Troy
1 liter (l) = 0.264 gallon U.S. (gal) = 0.220 gallon British
1 ampere per square decimeter (A/dm²) = 9.29 ampere per square foot (A/ft²) – see chart
1 gram per liter (g/l) = 0.133 ounce per gallon, U.S. (oz/gal) – see chart
1 kilogram per square millimeter (kg/mm²) = 1.422 pounds per square inch (lb/in.², psi) – see chart;
strictly, unit should be kilogram-force, or kgf/mm²; in S.I. units, 1 kgf/mm² = 9.806×10⁶ newton/square meter (N/m²) = 9.806 MN/m²; 1 N/m² = 1 Pa (pascal)

Approximate Conversion Factors for Mental Calculation (accurate to 10% or better)

<table>
<thead>
<tr>
<th>To convert from</th>
<th>To</th>
<th>Do this</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/dm²</td>
<td>A/ft²</td>
<td>Multiply by 10</td>
</tr>
<tr>
<td>A/dm²</td>
<td>A/in.²</td>
<td>Divide by 15 (multiply by 2, divide by 30)</td>
</tr>
<tr>
<td>Celsius (Centigrade)*</td>
<td>Fahrenheit, F</td>
<td>Multiply by 9/5 (1.8) and add 32</td>
</tr>
<tr>
<td>g/l</td>
<td>oz/gal</td>
<td>Divide by 7.5 (multiply by 4, divide by 30)</td>
</tr>
<tr>
<td>kg/mm²</td>
<td>lb/in.² (psi)</td>
<td>Multiply by 1500</td>
</tr>
<tr>
<td>mm</td>
<td>inch</td>
<td>Divide by 25 (multiply by 4, divide by 100)</td>
</tr>
<tr>
<td>micrometers (m)</td>
<td>mil</td>
<td>Divide by 25 (multiply by 4, divide by 100)</td>
</tr>
</tbody>
</table>

*Exact.
Graphical Conversions

(1 A/dm² = 9.29 A/ft²)  
(1 g/l = 0.133 oz/gal)  
(1 kg/mm² = 1422 psi)
MODERN ELECTROPLATING