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Introduction to
Metrology Applications in IC Manufacturing

Bo Su
Eric Solecky
Alok Vaid

Tutorial Texts in Optical Engineering
Volume TT101

SPIE PRESS
Bellingham, Washington USA
Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to cover many diverse fields of science and engineering. The initial idea for the series was to make material presented in SPIE short courses available to those who could not attend and to provide a reference text for those who could. Thus, many of the texts in this series are generated by augmenting course notes with descriptive text that further illuminates the subject. In this way, the TT becomes an excellent stand-alone reference that finds a much wider audience than only short course attendees.

Tutorial Texts have grown in popularity and in the scope of material covered since 1989. They no longer necessarily stem from short courses; rather, they are often generated independently by experts in the field. They are popular because they provide a ready reference to those wishing to learn about emerging technologies or the latest information within their field. The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, fiber optics, and laser technologies. Authors contributing to the TT series are instructed to provide introductory material so that those new to the field may use the book as a starting point to get a basic grasp of the material. It is hoped that some readers may develop sufficient interest to take a short course by the author or pursue further research in more advanced books to delve deeper into the subject.

The books in this series are distinguished from other technical monographs and textbooks in the way in which the material is presented. In keeping with the tutorial nature of the series, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. There is also heavy use of tabular reference data and numerous examples to further explain the concepts presented. The publishing time for the books is kept to a minimum so that the books will be as timely and up-to-date as possible. Furthermore, these introductory books are competitively priced compared to more traditional books on the same subject.

When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the science and technologies under discussion.

It is my goal to maintain the style and quality of books in the series and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

James A. Harrington
Rutgers University
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Preface

We contemplated writing a book about IC manufacturing metrology for years. Each of us in parallel recognized a gap that existed in the field of metrology and inspection. Until now, metrology (not to be confused with meteorology) had no book from the perspective of an engineer in a manufacturing and development environment in the modern IC industry. The closest we could find was a chapter called “Metrology Methods in Photolithography,” written by Laurie J. Lauchlan, Diana Nyyssonen from IBM Microelectronics, and Neal Sullivan from DEC, within a book titled *Handbook of Microlithography, Micromachining, and Microfabrication, Vol. 1* (SPIE Press, 1997). The other significant text comes from Alain Diebold, in a book titled *Handbook of Silicon Semiconductor Metrology* (CRC Press, 2001). Numerous other books, especially statistical books, briefly mention metrology in the context of gauge studies, precision-to-tolerance ratios (also called the gauge maker’s rule), and repeatability and reproducibility.

The three of us combined have been working in semiconductor IC fabs for more than two decades, specializing in metrology in semiconductor manufacturing. This book allows us to share our learning, understanding, and experiences with our fellow engineers and managers. As in other disciplines, metrology is constantly improving, enhancing, and developing to meet ever-increasing needs in today’s high-technology manufacturing.

In IC fabs, people refer to metrology equipment as process equipment tools or a fleet of tools. We will use that term in this book to mean metrology equipment or systems. Photomasks, masks, and reticles are all used to describe the photomasks used in IC manufacturing, interchangeably. Many acronyms in IC fabs are used in this book; please refer to the List of Acronyms for their exact meanings.

The contents of the book are organized not only for metrology engineers but also for other process engineers and fab managers to better understand metrology data and the uncertainties associated with those data. It also serves as a textbook for students and researchers who are interested in metrology in general or as a reference book on fundamentals and latest developments in the IC industry.

The first two chapters introduce metrology at its most basic level. The first half of Chapter 1 defines metrology, its origin, and its purpose regardless of the
field of practice. The second half of the chapter discusses measurement methods
and the measurement process and includes descriptions of operator, machine,
and what is being measured along with the evolution of manual and automated
measurements. It closes with a discussion on applications of industrial
metrology. Chapter 2 explores metrology fundamentals as they pertain to
traditional measurement system characterization and calibration. The word
“traditional” is used because this is an area where much has changed since the
1997. Chapter 3 discusses the need to improve upon the traditional forms of
measurement system characterization and calibration. Many newer concepts
are introduced here in the areas of system matching, long-term stability
monitoring, and accuracy. Chapter 4 focuses on a particular industrial
application of metrology—the semiconductor industry—that has the tightest
metrology requirements in the world. It explores areas such as the pervasiveness
and value of metrology, target design, and process control. Chapter 5 features
optical metrology measurement techniques such as ellipsometry and scattero-
metry. Chapter 6 presents charged-particle measurement techniques, with a
primary focus on scanning electron beam metrology. Chapter 7 explores other
measurement techniques not used inline in 1997, such as x-ray and in-situ
metrology. Chapter 8 discusses the limits of metrology and the evolution of
hybrid metrology. Hybrid metrology development and implementation is
another major change. Chapter 9 discusses metrology in mask making,
emphasizing the differences as compared to wafer metrology. The final chapter
closes with trends, perspectives on future metrology challenges, and other
considerations not covered in the other chapters.

Example Excel spreadsheets are provided in the accompanying CD in the
area of measurement uncertainty analysis—specifically, precision, matching
and relative accuracy. These files complement the textbook material and help
readers understand the metrology concepts better (as well as leverage these
spreadsheets in their own work, as needed).

Although there is a significant focus on the semiconductor industry, many
of the concepts can be easily applied to other industrial fields. The metrology
field has grown significantly over time, especially in the areas of semiconduc-
tor manufacturing. With this growth comes an increasing need for metrology
expertise. This book is intended to introduce a new generation to metrology
while also helping current practitioners. Almost every other major semicon-
ductor discipline, such as lithography and etch, is taught in academia; there is
very little metrology material taught currently, and we hope this book helps
spark increased academic interest.
Acknowledgments

Bo Su would like to thank his many colleagues over the past 20 years. He would also like to thank his family (Xiaoyu Chen, Brooke Su, and Brian Su) for their love and support.

Eric Solecky would like to acknowledge three metrology pioneers: Diana Nyssonen, Charles (Chas) Archie, and Bill Banke.

I first met Diana during my first few years at IBM as a new hire in my first professional assignment. I will never forget attending meetings with metrology suppliers, where Diana always knew the right questions to ask and often strongly influenced the supplier’s future directions. I thought to myself, “wouldn’t it be nice to have this ability?” As chance would have it, Diana became my mentor and taught me many valuable skills for the next few years before her passing. Also before then, Charles Archie joined IBM to lead the Advanced X-ray Lithography Facility, started developing an interest in metrology, and worked closely with Diana. Diana sensed her early passing and, as my mentor, brought Chas and me into a room and told him to take care of me, which is exactly what Chas did. I continued to learn from Chas until his retirement from IBM in 2012. He was unbelievably giving of his knowledge. If he did not know the answer to my questions (which was rare), he would think about it and always come back to me with an answer. Chas continued to mentor numerous other metrologists, and his industry influence was immense.

Bill Banke worked in IBM Burlington in the standards lab. I got to know him through Chas, and we published a few papers together. Chas and Bill pioneered the TMU accuracy metric that relied on the Mandel regression. This breakthrough served as the catalyst for the other important measurement system analysis metrics: FMP and TMP. I was very lucky to be surrounded by these metrology pioneers.

I considered publishing a book on metrology for over two years but never quite knew how to move forward. As fate would have it, being on an SPIE committee, I was selected to review a metrology book proposal from Bo Su. I reached out to Bo and explained my outline for a book comparable to his, and we had numerous
discussions. We agreed to combine his thoughts with mine and move forward together. I very much appreciate this opportunity he granted me. I reached out to Alok Vaid because I knew he could bring some great material to the table. I have a lot of respect for Alok from my interactions with him throughout the years, and he was the perfect third partner for the book. I would like to thank my family, especially my wife, Chrisanne, and son, Alex, for their support in writing this book.

Alok Vaid would like to acknowledge five industry pioneers: Chas Archie, Matthew Sendelbach, Cornel Bozdog, Olivier Vatel, and Carsten Hartig. I was fortunate enough to have crossed paths with them at different stages of my career, and each of them in their own unique way helped shape my technical expertise and grow passion for metrology. Like Eric Solecky, I was fortunate to have a chance to work with Chas Archie at IBM Fishkill for several years before his retirement. He mentored me while we worked on projects aimed at expanding the sphere of CD-SEM metrology and solving the growing concerns of gaps in reference metrology. At the same time, I also had the privilege of working with Matthew Sendelbach, who, in turn, helped grow my expertise in OCD as well as data analysis techniques that should be used to qualify various metrology techniques (e.g., TMU analysis). Together we conducted a couple of key next-generation metrology tool evaluations (that later became benchmarks) and also collaborated on and published several papers on advancements in OCD, one of which won the Best Metrology Paper award from SPIE.

I had the pleasure to know and work with Cornel Bozdog, who in my opinion is one of the best scientists in the field of optical metrology, but at the same time a very humble and charming personality. Cornel is an epitome of collaboration, and together we have been expanding and advancing the new field of hybrid metrology. Over the past years, I have learnt a lot from both him and Matthew Sendelbach and developed close friendships with them. I met Olivier Vatel a few years ago when he joined GLOBALFOUNDRIES as a senior executive in charge of the technology development group. I had several close interactions with him as he helped me develop the practice of never being satisfied with the status quo and understanding that true innovation happens when you have a motivated “team” (as opposed to silos) willing to collaborate. I also had the pleasure of working and collaborating closely with Carsten Hartig over the last decade. He has been and continues to be a technical mentor/coach who has helped me understand the fundamental capabilities and limits of various metrology techniques. I am always amazed by his deep knowledge of metrology techniques,
especially CD-SEM and OCD, and even though he is based in Germany he remains a dear friend and my go-to person for technical advice.

I would like to acknowledge my co-author of this book, Eric, who gave me this opportunity to work on this book. I have known him for several years, including at IBM Fishkill, but I got the chance to work very closely with him only recently when he moved to GLOBALFOUNDRIES. Again, I am fortunate to have an expert like him sitting right next to my desk (literally), and together we have been challenging and expanding the boundaries of metrology/process control.

Finally, I would like to acknowledge my wife and fellow semiconductor engineer, Niti Garg, who has always been at my side through good and rough times over the years. She also happens to be my internal customer (as a Process Engineer at GLOBALFOUNDRIES), and my metrology techniques along with expertise, continue to be challenged to meet sub-angstrom specifications for her etch equipment!

We would like to thank SPIE Press for supporting technical publications like ours and for the opportunity to publish this Tutorial Text. We appreciate the great help and guidance from Tim Lamkins and Scott McNeill (our book editor).

Bo Su
Eric Solecky
Alok Vaid
August 2015
### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADC</td>
<td>Automatic defect classification</td>
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<tr>
<td>ADI</td>
<td>After-development inspection</td>
</tr>
<tr>
<td>AEI</td>
<td>After-etch inspection</td>
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<tr>
<td>AFM</td>
<td>Atomic force microscope</td>
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<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
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<tr>
<td>APC</td>
<td>Advanced process control</td>
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<tr>
<td>BEOL</td>
<td>Back end of line</td>
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<tr>
<td>BMS</td>
<td>Benchmark measurement system</td>
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<td>BSE</td>
<td>Backscattered electrons</td>
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<tr>
<td>CD</td>
<td>Critical dimension</td>
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<td>CD-SEM</td>
<td>Critical-dimension scanning electron microscope</td>
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<td>CDU</td>
<td>Critical dimension uniformity</td>
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<td>CMP</td>
<td>Chemical and mechanical polishing</td>
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<td>Cp and Cpk</td>
<td>Process capability indices</td>
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<tr>
<td>CTF</td>
<td>Contrast transfer function</td>
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<tr>
<td>DOE</td>
<td>Design of experiment</td>
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<tr>
<td>DOF</td>
<td>Degree of freedom</td>
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<tr>
<td>DR</td>
<td>Design rules</td>
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<td>DRAM</td>
<td>Dynamic random access memory</td>
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<td>DUV</td>
<td>Deep ultraviolet</td>
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<tr>
<td>FEOL</td>
<td>Front end of line</td>
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<tr>
<td>FinFET</td>
<td>Fin field-effect transistor</td>
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<tr>
<td>FMP</td>
<td>Fleet measurement precision</td>
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<tr>
<td>FOV</td>
<td>Field of view</td>
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<tr>
<td>e-beam</td>
<td>Electron beam</td>
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<tr>
<td>EBI</td>
<td>Electron-beam inspection</td>
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<tr>
<td>EBR</td>
<td>Electron-beam review</td>
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<tr>
<td>EUV</td>
<td>Extreme ultraviolet</td>
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<tr>
<td>GOF</td>
<td>Goodness of fit</td>
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<tr>
<td>HAR</td>
<td>High aspect ratio</td>
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<tr>
<td>HRXRD</td>
<td>High-resolution x-ray diffraction</td>
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<tr>
<td>HVP</td>
<td>High-volume production</td>
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<tr>
<td>IC</td>
<td>Integrated circuit</td>
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<tr>
<td>IC fab</td>
<td>IC fabrication plant</td>
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<tr>
<td>IR</td>
<td>Inspection report</td>
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ITRS
LCL
LSL
MPU
MS
MSA
MTT
OAI
OCD
OPC
POR
PSA
PSM
PTR
R&R (or gauge R&R)
RAE
RET
rms
RMS
SE
SE
SEM
SIS
SMO
SNR
SoC
SPC
Spec
SRAF
SRAM
STEM
SWA
TEM
TMP
TMS
TMU
TuT
UCL
USL
WIP
XPS
XRF
XRR

International technology roadmap for semiconductors
Lower control limit
Lower spec limit
Microprocessing unit
Measurement system
Measurement system analysis
Mean to target
Off-axis illumination
Optical CD measurement technique
Optical proximity correction
Process (or product) of record
Process-stressed artifact
Phase shift masks, including attenuated (or embedded) and alternating PSM
Precision-to-tolerance ratio
Repeatability and reproducibility
Rotating analyzer ellipsometry
Resolution enhancement technique (e.g., OPC, OAI, PSM)
Root mean square
Reference measurement system
Secondary electrons (in a SEM)
Spectroscopic ellipsometry
Scanning electron microscope
Slope-induced shift
Source mask optimization
Signal-to-noise ratio
System on a chip
Statistical process control
Specifications
Subresolution assistant feature
Static random access memory
Scanning transmission electron microscope
Sidewall angle
Transmission electron microscope
Tool-matching precision
Test measurement system
Total measurement uncertainty
Tool under test
Upper control limit
Upper spec limit
Work (or wafer) in process
X-ray photoelectron spectroscopy
X-ray florescence
X-ray reflectance