Advanced Processes for 193-nm Immersion Lithography

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Preface

The benefits of using liquids in optical microscopes were first demonstrated in the 1880s. A century later, in the 1980s, experiments with immersion technology demonstrated its potential for use in modern lithography. In 2002, when 157-nm lithography was delayed by a host of technical problems, the development of 193-nm immersion lithography for use in fabricating integrated circuits gained momentum. The development of 193-nm immersion lithography (193i) occurred much faster than did any previous lithographic technology. Currently, 193i is widely used to manufacture advanced microelectronic devices at the 45-nm node. The entire transition from proof of concept to delivery of a mass production tool took only about four years.

This rapid growth was possible because of the combined efforts of all sectors of the lithography community, including the manufacturers of scanners, materials, and integrated circuits. Much of the research critical to the rapid advancement of 193i has been published in the last few years in various journals and proceedings. One of the goals of this book is to summarize this information so that those new to the field as well as current practitioners may increase their understanding of this important technology.

Thus, while actively involved in evaluating new materials, equipment, and processes for 193i imaging, Yayi Wei began writing the manuscript for this book. During the summer of 2008, Robert Brainard, a researcher developing new resist materials, joined Yayi as his coauthor to help prepare the manuscript. Their collaboration resulted in this timely monograph that presents the knowledge critical for establishing high-yield cost-effective 193i processes and materials. The text can be used as course material for graduate students of electrical engineering, material sciences, physics, chemistry, and microelectronics engineering. It can also be used to train engineers involved in the manufacture of integrated circuits.

A large portion of this book is concerned with the challenges and opportunities of water-based 193-nm immersion lithography. The first chapter provides a broad overview of 193i lithography. The second chapter describes the track where most of the processes occur. The book continues with descriptions of the interactions between the immersion fluid (water) and the resist in terms of contact angle, leaching of resist components, and topcoats. It also provides a comprehensive summary of various immersion-related defects and defect-reduction strategies. It covers topics that were originally developed in “dry” lithography and are extendable to immersion 193-nm lithography, discussing
strategies for antireflection control, shrink processes, trim processes, double exposure, double patterning, and line-edge roughness. The book concludes with a chapter describing research efforts aimed at further extensions of immersion lithography to higher numerical aperture (NA) and resolution through the development of high-index lithography. Discussion of some topics (e.g., optical theory of hyper-NA) was kept brief when well described in other monographs.

The knowledge of 193i is still growing and will continue to mature as it is used more frequently in mass production. We appreciate any suggestions from our readers on how to update this material. Your input will help us improve subsequent editions of this book.

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Without a doubt, the knowledge presented in this book was collectively generated by the entire lithography community. The authors would like to express their sincere gratitude to the individuals in this community who provided enormous support during preparation of the manuscript, both by sharing their most recent results and by suggesting improvements to the content and organization of the material. Many of the figures in this book are direct reprints from their publications.

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List of Acronyms and Abbreviations

193i 193-nm immersion lithography
193i+ high refractive index 193-nm immersion lithography
α absorption coefficient
a-C amorphous carbon
AFM atomic force microscope
alt. PSM alternating phase-shift mask
ARC antireflective coating
ArF argon fluoride
att. PSM attenuated phase-shift mask
BARC bottom antireflection coating
BEOL back end of line
BIM binary intensity mask
CA contact angle
CAR chemically amplified resist
CARL chemical amplification of resist lines
CD critical dimension
CDU critical dimension uniformity
CGS centimeter-gram-second system
CMP chemical-mechanical planarization
CNAR critical normalized aspect ratio
C-SOH carbon spin-on hard mask
CVD chemical vapor deposition
DBARC developer-soluble BARC
DE double exposure
DI deionized
DIW deionized water
DLP dynamic leaching procedure
DOE design of experiment
DOF depth of focus
DP double patterning
DRAM dynamic random access memory
DUV deep ultraviolet
E0 dose to clear
EBR edge bead removal
EDX energy dispersive x-ray spectrometry
EL exposure latitude
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ESCA</td>
<td>electron spectroscopy for chemical analysis</td>
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<tr>
<td>EUV</td>
<td>extreme ultraviolet</td>
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<tr>
<td>F&lt;sub&gt;2&lt;/sub&gt;</td>
<td>fluorine</td>
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<tr>
<td>FCCD</td>
<td>first collapse critical dimension</td>
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<td>FEM</td>
<td>focus exposure matrix</td>
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<td>FEOL</td>
<td>front end of line</td>
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<td>FIB</td>
<td>focused ion beam</td>
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<td>FOV</td>
<td>field of view</td>
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<td>FT</td>
<td>film thickness</td>
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<td>FTIR</td>
<td>Fourier transform infrared spectroscopy</td>
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<td>GBARC</td>
<td>graded bottom antireflection coating</td>
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<td>GIS</td>
<td>gas injector system</td>
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<tr>
<td>HF</td>
<td>hydrofluoric acid</td>
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<tr>
<td>HM</td>
<td>hard mask</td>
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<td>HMDS</td>
<td>hexamethyldisilizane</td>
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<td>IBR</td>
<td>intrinsic birefringence</td>
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<tr>
<td>IC</td>
<td>integrated circuit</td>
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<tr>
<td>IL</td>
<td>interferometric lithography</td>
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<td>i-line</td>
<td>365-nm wavelength lithography</td>
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<td>ILS</td>
<td>image log-slope</td>
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<tr>
<td>IMR</td>
<td>intrinsic material roughness</td>
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<tr>
<td>IR</td>
<td>infrared</td>
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<tr>
<td>ITRS</td>
<td>International Technology Roadmap for Semiconductors</td>
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<tr>
<td>KrF</td>
<td>krypton fluoride</td>
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<tr>
<td>λ</td>
<td>wavelength</td>
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<tr>
<td>LC-MS</td>
<td>liquid chromatography mass spectroscopy</td>
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<tr>
<td>LER</td>
<td>line-edge roughness</td>
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<td>LWR</td>
<td>line-width roughness</td>
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<tr>
<td>MB</td>
<td>mixing bake</td>
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<tr>
<td>MEEF</td>
<td>mask error enhancement factor</td>
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<tr>
<td>Mw</td>
<td>molecular weight</td>
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<td>NA</td>
<td>numerical aperture</td>
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<td>NAR</td>
<td>normalized aspect ratio</td>
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<td>NILS</td>
<td>normalized image log-slope</td>
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<tr>
<td>NR</td>
<td>neutron reflectometry</td>
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<tr>
<td>OAI</td>
<td>off-axis illumination</td>
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<tr>
<td>OL</td>
<td>overlay</td>
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<tr>
<td>OPC</td>
<td>optical proximity correction</td>
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<td>OPD</td>
<td>optical path difference</td>
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<td>PAB</td>
<td>post-apply bake</td>
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<td>PAG</td>
<td>photoacid generator</td>
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<td>PDB</td>
<td>post-develop bake</td>
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<td>PEB</td>
<td>post-exposure bake</td>
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<tr>
<td>PGME</td>
<td>propylene glycol monomethyl ether</td>
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<td>PGMEA</td>
<td>propylene glycol monomethyl ether acetate</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<td>----------------------------------------------------------------------------</td>
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<tr>
<td>POR</td>
<td>process of record</td>
</tr>
<tr>
<td>POU</td>
<td>point of use</td>
</tr>
<tr>
<td>ppb</td>
<td>parts-per-billion</td>
</tr>
<tr>
<td>ppt</td>
<td>parts-per-trillion</td>
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<tr>
<td>PSD</td>
<td>power spectral density</td>
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<td>PSZ</td>
<td>perhydropolysilazane</td>
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<td>PW</td>
<td>process window</td>
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<td>PWP</td>
<td>particles per wafer pass</td>
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<td>QCM</td>
<td>quartz crystal microbalance</td>
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<td>QSPR</td>
<td>quantitative structure property relationship</td>
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<td>RCA</td>
<td>receding contact angle</td>
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<td>RDA</td>
<td>resist development analyzer</td>
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<tr>
<td>RELACS</td>
<td>resolution enhancement lithography assisted by chemical shrink</td>
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<tr>
<td>RI</td>
<td>refractive index, ( n )</td>
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<td>RMS</td>
<td>root mean square</td>
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<td>rpm</td>
<td>rotation per minute</td>
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<td>SA</td>
<td>swing amplitude</td>
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<tr>
<td>SADP</td>
<td>self-aligned double patterning</td>
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<tr>
<td>SAFIER</td>
<td>shrink assist film for enhanced resolution</td>
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<td>SBR</td>
<td>stress birefringence</td>
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<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
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<tr>
<td>Si-BARC</td>
<td>silicon-containing bottom antireflection coating</td>
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<tr>
<td>SIMS</td>
<td>secondary-ion mass spectroscopy</td>
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<td>Si-SOH</td>
<td>silicon spin-on hard mask</td>
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<tr>
<td>SOC</td>
<td>spin-on carbon</td>
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<td>SSQ</td>
<td>silsesquioxane</td>
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<td>SWA</td>
<td>sidewall angle</td>
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<td>TARC</td>
<td>top antireflective coating</td>
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<tr>
<td>TC</td>
<td>topcoat</td>
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<tr>
<td>TE</td>
<td>transverse electric</td>
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<tr>
<td>( T_g )</td>
<td>glass transition temperature</td>
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<td>TGP</td>
<td>thermal gradient plate</td>
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<tr>
<td>TM</td>
<td>transverse magnetic</td>
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<td>TMAH</td>
<td>tetramethylammonium hydroxide</td>
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<td>TOF-SIMS</td>
<td>time of flight–secondary-ion mass spectroscopy</td>
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<td>UCP</td>
<td>ultra-casting predispense</td>
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<td>UPW</td>
<td>ultrapure water</td>
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<td>VUV</td>
<td>vacuum ultraviolet</td>
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<td>WEE</td>
<td>wafer edge exposure</td>
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<td>WEXA</td>
<td>water extraction and analysis</td>
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<td>watermark</td>
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<td>XPS</td>
<td>x-ray photoelectron spectroscope</td>
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