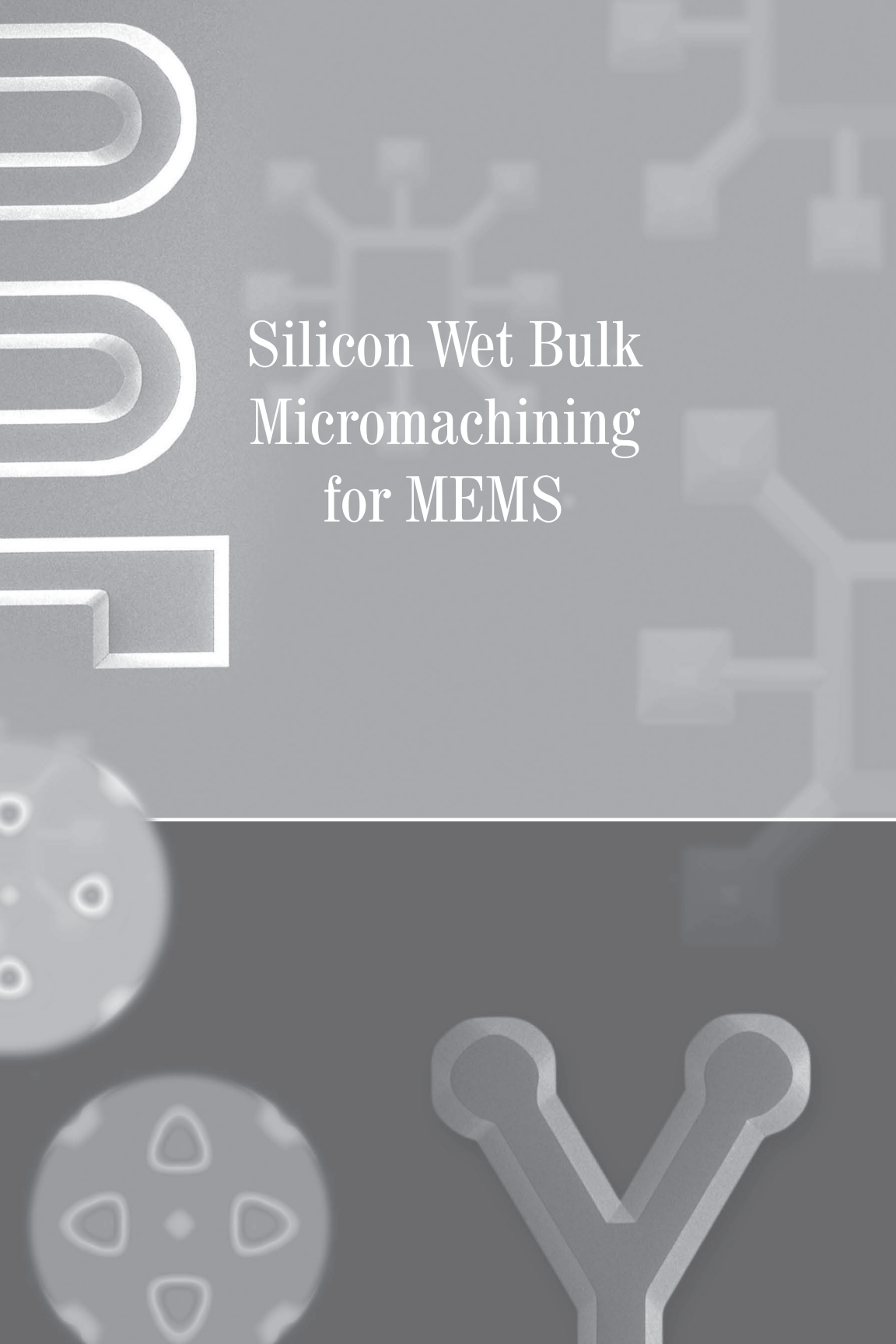


Silicon Wet Bulk Micromachining for MEMS

Prem Pal
Kazuo Sato



The background of the image features various microfluidic channel patterns. On the left side, there are large, white, 3D-rendered U-shaped and T-shaped channels. The right side and bottom of the image show a dark gray background with faint, light gray patterns of microfluidic networks, including circular chambers with internal structures and Y-shaped junctions.

Silicon Wet Bulk
Micromachining
for MEMS

Silicon Wet Bulk Micromachining for MEMS

Prem Pal
Kazuo Sato

Published by

Pan Stanford Publishing Pte. Ltd.
Penthouse Level, Suntec Tower 3
8 Temasek Boulevard
Singapore 038988

Email: editorial@panstanford.com

Web: www.panstanford.com

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Silicon Wet Bulk Micromachining for MEMS

Copyright © 2017 by Pan Stanford Publishing Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN 978-981-4613-72-9 (Hardcover)

ISBN 978-1-315-36492-6 (eBook)

Printed in the USA

Contents

<i>Preface</i>	xi
1. A Brief Introduction of the Crystal Structure	1
1.1 Introduction	1
1.2 Crystal Structure	2
1.3 Unit Cell: Primitive and Nonprimitive	4
1.4 Symmetry Operations	5
1.5 Types of Lattices	7
1.6 Index System for Crystal Planes and Directions	9
1.7 Cubic Structures	12
1.7.1 Simple Cubic or Primitive Cubic Structure	12
1.7.2 Body-Centered Cubic Structure	13
1.7.3 Face-Centered Cubic Structure	13
1.8 Stereographic Projection	14
2. Brief Overview of Silicon Wafer Manufacturing and Microfabrication Techniques	23
2.1 What Is Silicon?	23
2.2 Why Is Silicon Used as a Material for ICs and MEMS?	24
2.3 What Are Microelectromechanical Systems?	25
2.4 Wafer Manufacturing	26
2.4.1 Crystal Growth and Doping	26
2.4.2 Ingot Trimming, Grinding, and Slicing	29
2.4.3 Polishing, Cleaning, and Packaging	32
2.5 Silicon Microfabrication Processes	33
2.5.1 Wafer Cleaning	34
2.5.2 Thin-Film Formation	36
2.5.2.1 Thermal oxidation (or reactive growth)	36
2.5.2.2 Chemical vapor deposition	38
2.5.2.3 Physical vapor deposition	40
2.5.3 Photolithography	41
2.5.4 Etching	45

2.5.4.1	Silicon wet isotropic etching	48
2.5.4.2	Silicon wet anisotropic etching	49
2.5.4.3	Silicon dry etching	50
2.5.5	Local Oxidation of Silicon	54
2.5.6	Micromachining	55
2.5.6.1	Bulk micromachining	55
2.5.6.2	Surface micromachining	56
2.5.7	Doping	57
2.5.7.1	Diffusion	57
2.5.7.2	Ion implantation	60
2.5.8	Silicon Direct Wafer Bonding	62
2.5.8.1	Hydrophilic bonding	63
2.5.8.2	Hydrophobic bonding	64
3.	Isotropic Etching of Silicon and Related Materials	67
3.1	Isotropic Etching Properties	67
3.2	Isotropic Etching Solutions	68
3.3	Conditions for Isotropic Etching	71
3.4	Applications	72
4.	KOH-Based Anisotropic Etching	79
4.1	Etching in Pure KOH Solutions	79
4.1.1	The Etching Mechanism	79
4.1.2	Advantages and Disadvantages of KOH	82
4.1.3	Characterization of Etch Rate Anisotropy	84
4.1.4	Effects of KOH Concentration	88
4.1.5	Effects of Etching Temperature	90
4.1.6	Etch-Stop Technologies	92
4.1.6.1	Etch stop by heavy boron doping	93
4.1.6.2	Electrochemical etch stop	94
4.1.6.3	Use of a SOI wafer	96
4.1.7	Etched Surface Roughness	97
4.1.8	Comparison of KOH and TMAH Etching Characteristics	101
4.2	Effect of Alcohols and Surfactant Additives	106
4.2.1	Etching in KOH Solutions Saturated with Alcohols	106

4.2.1.1	Properties of KOH solutions saturated with alcohols	106
4.2.1.2	Results of etching in KOH solutions containing alcohols with one hydroxyl group	113
4.2.1.3	Results of etching in solutions containing alcohols with two hydroxyl groups (diols)	121
4.2.2	Etching in KOH Solutions with the Alcohol Concentration below Saturation	125
4.2.2.1	Effect of alcohol concentration on the course of etching	125
4.2.2.2	Using unsaturated solutions for texturing Si(100) substrates	138
4.2.2.3	Analysis of the etching mechanism in KOH solutions containing alcohols	142
4.2.3	Etching in KOH Solutions Containing Surfactants	148
5.	TMAH-Based Anisotropic Etching	163
5.1	Introduction	163
5.2	The Etching Mechanism	165
5.3	Etch Rates	165
5.3.1	Etch Rates of Various Crystallographic Planes Using the Wagon-Wheel Structure	169
5.3.2	Etch Rates of the Whole Range of Crystallographic Planes Using a Convex Hemispherical Specimen	172
5.4	Surface Morphology	174
5.5	Undercutting and Etched Profiles	178
5.6	Why Are Etching Characteristics Affected When a Surfactant Is Added to TMAH?	182
5.6.1	FTIR Measurement	184
5.6.2	Ellipsometric Measurement	187
5.6.3	The Physical Model	188
5.7	Etched Profile Control	191
5.7.1	P ⁺ Silicon Etch Stop	191
5.7.2	Electrochemical Etch Stop	192

5.7.3	Protection of Convex Corners	194
5.7.4	Effect of Mechanical Agitation	194
5.7.5	Role of the Open-Circuit Potential	195
5.8	Summary	198
6. Convex and Concave Corners in Silicon Wet Bulk Micromachining 211		
6.1	Introduction	211
6.2	Etch Rate, Underetching, and Undercutting	213
6.3	Role of Corner Undercutting in MEMS Fabrication	219
6.4	Why Does Undercutting Start at Convex Corners?	219
6.5	Etched Profiles at Sidewalls and Corners	226
6.6	Fabrication Techniques of Convex Corners	236
6.6.1	The Corner Compensation Method	236
6.6.1.1	Corner compensation geometries for a Si{100} wafer	237
6.6.1.2	Corner compensation geometries for a Si{110} wafer	262
6.6.2	Perfect Convex Corners Using Two-Step Etching Techniques	269
6.6.2.1	Sharp-edge convex corners by lithography on anisotropically etched patterns	269
6.6.2.2	Perfect convex corners using the LOCOS process	271
6.7	Summary	275
7. Alignment of Mask Patterns to Crystallographic Directions 287		
7.1	Introduction	287
7.2	Role of Precise Alignment in Wet Bulk Micromachining	288
7.2.1	Microchannels	288
7.2.2	Cantilever Beams	290
7.2.3	Diaphragms	292
7.3	Alignment Techniques	294
7.3.1	Cleaved-Edge Alignment	295
7.3.2	Pre-etched Patterns	296
7.3.2.1	Identifying crystallographic directions on a Si{100} wafer	297

7.3.2.2	Identifying crystallographic directions on a Si{110} wafer	313
7.4	Summary	320
8.	Simple to Complex Structures Using Wet Bulk Micromachining	323
8.1	Introduction	323
8.2	Cavities, Channels, and Mesa Structures	326
8.3	Microstructures with 45° Slanted Sidewalls	328
8.4	Silicon Gratings	330
8.5	Suspended Microstructures	331
8.5.1	Time-Controlled Back-Side Etching	335
8.5.2	P ⁺ Silicon	337
8.5.3	Electrochemical Etch Stop	338
8.5.4	Silicon-on-Insulator Wafers	338
8.5.5	Micromachined Cavities Sealed by Wafer Bonding	339
8.5.6	Silicon Nitride-Based SOI Wafers	339
8.6	Microstructures with Perfectly Sharp Edges and Corners	342
8.7	Suspended Microfluidic Channels	348
8.8	AFM Cantilevers	355
8.9	Microvalves and Micropumps	357
8.9.1	Microvalves	358
8.9.2	Micropumps	359
8.10	Microstructures Inside a Silicon Wafer	361
8.11	Dry-Assisted Wet Etching	368
8.12	Silicon Molds for the Fabrication of PDMS Structures	372
8.13	Complex Patterns for Very-High-Aspect-Ratio Microstructures Using Photoelectrochemical Etching	372
<i>Index</i>		383

Preface

Microelectromechanical systems (MEMS)-based sensors and actuators have become remarkably popular in the past few decades. Rapid advances have taken place in terms of both technologies and techniques of fabrication of MEMS structures. Wet chemical-based silicon bulk micromachining continues to be a widely used technique for the fabrication of microstructures used in MEMS devices. Researchers all over the world have contributed significantly to the advancement of wet chemical-based micromachining, from understanding the etching mechanism to exploring its application to the fabrication of simple to complex MEMS structures. In addition to its various benefits, one of the unique features of wet chemical-based bulk micromachining is the ability to fabricate slanted sidewalls, such as 45° walls as micromirrors, as well as freestanding structures, such as cantilevers and diaphragms. This makes wet bulk micromachining necessary for the fabrication of structures for myriad applications. Considering the importance of wet bulk micromachining in the fabrication of MEMS, all that we wanted to do is to write a deep book that can cover topics from the basic to the advanced level and can be used as a reference and as a textbook.

This book provides a comprehensive understating of wet bulk micromachining for the fabrication of simple to advanced microstructures for various applications in MEMS. It includes introductory to advanced concepts and covers research on basic and advanced topics on wet chemical-based silicon bulk micromachining. The book thus serves as an introductory textbook for undergraduate- and graduate-level students of physics, chemistry, electrical and electronics engineering, materials science, and engineering, as well as a comprehensive reference for researchers working or aspiring to work in the area of MEMS and for engineers working in microfabrication technology.

To understand the wet anisotropic etching for silicon micromachining, an elementary understanding of crystallography is essential. Hence we have included a separate chapter to cover the basics of the crystal structure and stereographic projection.

In addition, a basic understanding of microfabrication techniques employed in semiconductor industries is required in order to explore wet bulk micromachining for the fabrication of MEMS components. Therefore, a separate chapter, “Brief Overview of Silicon Wafer Manufacturing and Microfabrication Techniques,” is also included.

We gratefully acknowledge financial support from the Department of Science and Technology (Project No. SR/S3/ MERC/072/2011), India, the Japan Society for the Promotion of Science (JSPS, Fellowship ID No. L14538), and the Japan International Cooperation Agency (JICA). JICA supported Prof. Prem Pal in visiting Sato Lab (AIT Toyota) in October 2015 and Prof. Sato in visiting the Indian Institute of Technology (IIT) Hyderabad, India, in December 2015. These visits have been useful for discussing some topics covered in this book.

We sincerely thank two distinguished contributors Prof. Irena Zubel (Wrocław University, Poland) for writing Section 4.2, Chapter 4, and Mr. Sajal Sagar Singh (IIT Hyderabad, presently at the University of Michigan) for coauthoring Chapter 7. We are highly thankful to Ms. Michiko Shindo (secretary to Prof. Sato) for her assistance in obtaining permissions to reproduce a few figures from published papers. At Pan Stanford Publishing, we wish to thank Mr. Stanford Chong for inviting us to write a book on silicon bulk micromachining and his team that has helped in refining the material in this book and extended all possible support at every stage of the manuscript. We welcome comments or suggestions on this textbook by email at prem@iith.ac.in and sato@aitech.ac.jp.

Prem Pal
Kazuo Sato