



Veikko Lindroos  
Markku Tilli  
Ari Lehto  
Teruaki Motooka

# HANDBOOK OF SILICON BASED MEMS MATERIALS AND TECHNOLOGIES

# Contents

|                                       |    |
|---------------------------------------|----|
| Preface . . . . .                     | ix |
| List of Contributors . . . . .        | xi |
| Overview by Tapani Ryhänen . . . . .  | xv |
| Impact of Silicon MEMS—30 years after |    |

## **PART I: Silicon as MEMS Material**

*Edited by Markku Tilli*

|                                                                       |            |
|-----------------------------------------------------------------------|------------|
| <b>1. Properties of Silicon . . . . .</b>                             | <b>3</b>   |
| <i>Markku Tilli and Atte Haapalinna</i>                               |            |
| <b>2. Czochralski Growth of Silicon Crystals . . . . .</b>            | <b>19</b>  |
| <i>Olli Anttila</i>                                                   |            |
| <b>3. Properties of Silicon Crystals . . . . .</b>                    | <b>37</b>  |
| <i>Jari Paloheimo</i>                                                 |            |
| <b>4. Oxygen in Silicon . . . . .</b>                                 | <b>59</b>  |
| <i>Eero Haimi</i>                                                     |            |
| <b>5. Silicon Wafers: Preparation and Properties . . . . .</b>        | <b>71</b>  |
| <i>Markku Tilli</i>                                                   |            |
| <b>6. Epi Wafers: Preparation and Properties . . . . .</b>            | <b>89</b>  |
| <i>Douglas J. Meyer</i>                                               |            |
| <b>7. Thick-Film SOI Wafers: Preparation and Properties . . . . .</b> | <b>107</b> |
| <i>Jari Mäkinen</i>                                                   |            |
| <b>8. Silicon Dioxides . . . . .</b>                                  | <b>137</b> |
| <i>Simo Eränen</i>                                                    |            |

## **PART II: Modeling in MEMS**

*Edited by Teruaki Motooka and Risto Nieminen*

|                                                                         |            |
|-------------------------------------------------------------------------|------------|
| <b>9. Multiscale Modeling Methods. . . . .</b>                          | <b>151</b> |
| <i>Teruaki Motooka</i>                                                  |            |
| <b>10. Manufacture and Processing of MEMS Structures. . . . .</b>       | <b>157</b> |
| <i>Miguel Gosálvez</i>                                                  |            |
| <b>11. Mechanical Properties of Silicon Microstructures . . . . .</b>   | <b>179</b> |
| <i>Maria Ganchenkova and Risto Nieminen</i>                             |            |
| <b>12. Electrostatic and RF-Properties of MEMS Structures . . . . .</b> | <b>221</b> |
| <i>Ilkka Tittonen and Mika Koskenvuori</i>                              |            |
| <b>13. Optical Modeling of MEMS . . . . .</b>                           | <b>239</b> |
| <i>Timo Aalto and Juuso Olkkonen</i>                                    |            |
| <b>14. Gas Damping in Vibrating MEMS Structures . . . . .</b>           | <b>259</b> |
| <i>Timo Veijola</i>                                                     |            |

### **PART III: Measuring MEMS**

*Edited by Veli-Matti Airaksinen*

|                                                                                              |            |
|----------------------------------------------------------------------------------------------|------------|
| <b>15. Introduction to Measuring MEMS</b> . . . . .                                          | <b>283</b> |
| <i>Veli-Matti Airaksinen</i>                                                                 |            |
| <b>16. Silicon Wafer and Thin Film Measurements.</b> . . . .                                 | <b>289</b> |
| <i>Veli-Matti Airaksinen</i>                                                                 |            |
| <b>17. Optical Measurement of Static and Dynamic Displacement in MEMS.</b> . . . .           | <b>299</b> |
| <i>David Horsley</i>                                                                         |            |
| <b>18. MEMS Residual Stress Characterization: Methodology and Perspective</b> . . . . .      | <b>305</b> |
| <i>Kuo-Shen Chen and Kuang-Shun Ou</i>                                                       |            |
| <b>19. Strength of Bonded Interfaces.</b> . . . .                                            | <b>317</b> |
| <i>Örjan Vallin and Kerstin Jonsson</i>                                                      |            |
| <b>20. Focused Ion and Electron Beam Techniques</b> . . . . .                                | <b>323</b> |
| <i>Oliver Wilhelm, Steve Reynjens, Brandon Van Leer, Paul Anzalone and Lucille Giannuzzi</i> |            |
| <b>21. Oxygen and Bulk Microdefects in Silicon</b> . . . . .                                 | <b>327</b> |
| <i>Hele Savin and Veli-Matti Airaksinen</i>                                                  |            |

### **PART IV: Micromachining Technologies in MEMS**

*Edited by Helmut Seidel*

|                                                                        |            |
|------------------------------------------------------------------------|------------|
| <b>22. MEMS Lithography.</b> . . . .                                   | <b>333</b> |
| <i>Sami Franssila and Santeri Tuomikoski</i>                           |            |
| <b>23. Deep Reactive Ion Etching.</b> . . . .                          | <b>349</b> |
| <i>Franz Laermer, Sami Franssila, Lauri Sainiemi and Kai Kolari</i>    |            |
| <b>24. Wet Etching of Silicon</b> . . . . .                            | <b>375</b> |
| <i>Miguel Gosálvez, Irena Zubel and Eeva Viinikka</i>                  |            |
| <b>25. Porous Silicon Based MEMS</b> . . . . .                         | <b>409</b> |
| <i>Gerhard Müller, Alois Friedberger and Kathrin Knese</i>             |            |
| <b>26. Atomic Layer Deposition in MEMS Technology.</b> . . . .         | <b>433</b> |
| <i>Riikka Puurunen, Hannu Kattelus and Tuomo Suntola</i>               |            |
| <b>27. Metallic Glass</b> . . . . .                                    | <b>447</b> |
| <i>Parmanand Sharma and Akihisa Inoue</i>                              |            |
| <b>28. Surface Micromachining</b> . . . . .                            | <b>473</b> |
| <i>Christina Leinenbach, Hannu Kattelus and Roy Knechtel</i>           |            |
| <b>29. Silicon Based BioMEMS: Micromachining Technologies.</b> . . . . | <b>489</b> |
| <i>Abhinav Bhushan and Cristina Davis</i>                              |            |

### **PART V: Encapsulation of MEMS Components**

*Edited by Ari Lehto and Heikki Kuisma*

|                                                            |            |
|------------------------------------------------------------|------------|
| <b>30. Introduction to Encapsulation of MEMS</b> . . . . . | <b>501</b> |
| <i>Heikki Kuisma</i>                                       |            |
| <b>31. Silicon Direct Bonding</b> . . . . .                | <b>505</b> |
| <i>Kimmo Henttinen and Tommi Suni</i>                      |            |
| <b>32. Anodic Bonding</b> . . . . .                        | <b>513</b> |
| <i>Adriana Cozma Lapadatu and Henrik Jakobsen</i>          |            |
| <b>33. Glass Frit Bonding</b> . . . . .                    | <b>521</b> |
| <i>Roy Knechtel</i>                                        |            |

|                                                                                       |            |
|---------------------------------------------------------------------------------------|------------|
| <b>34. Metallic Alloy Seal Bonding . . . . .</b>                                      | <b>533</b> |
| <i>Wolfgang Reinert and Peter Merz</i>                                                |            |
| <b>35. Bonding of CMOS Processed Wafers . . . . .</b>                                 | <b>543</b> |
| <i>Roy Knechtel</i>                                                                   |            |
| <b>36. Non-destructive Bond Strength Testing of Anodic Bonded Wafers . . . . .</b>    | <b>551</b> |
| <i>Roy Knechtel</i>                                                                   |            |
| <b>37. Wafer-Bonding Equipment. . . . .</b>                                           | <b>555</b> |
| <i>Viorel Dragoi and Paul Lindner</i>                                                 |            |
| <b>38. Encapsulation by Film Deposition. . . . .</b>                                  | <b>569</b> |
| <i>Rob Candler</i>                                                                    |            |
| <b>39. Via Technologies for MEMS . . . . .</b>                                        | <b>575</b> |
| <i>Kimmo Henttinen</i>                                                                |            |
| <b>40. Outgassing and Gettering . . . . .</b>                                         | <b>585</b> |
| <i>Antonio Bonucci, Andrea Conte, Marco Moraja, Giorgio Longoni and Marco Amiotti</i> |            |
| <b>41. Dicing of MEMS Devices. . . . .</b>                                            | <b>601</b> |
| <i>Scott Sullivan</i>                                                                 |            |
| <b>42. Hermeticity Tests. . . . .</b>                                                 | <b>607</b> |
| <i>Wolfgang Reinert and Dirk Kähler</i>                                               |            |
| <br>Appendix 1: Common Abbreviations and Acronyms . . . . .                           | <br>617    |
| Appendix 2: Nanointendation Characterization of Silicon and MEMS Materials . . . . .  | 623        |
| <i>P. Zachariasz, K. Brudziński, K. Gronicz, S. Nagao and R. Nowak</i>                |            |
| Index. . . . .                                                                        | 629        |