

# Contents

|          |                                                                                                     |           |
|----------|-----------------------------------------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                                                                 | <b>1</b>  |
| 1.1      | Small Scale Plasticity                                                                              | 1         |
| 1.2      | White-Beam X-ray Microdiffraction as Plasticity Probe                                               | 3         |
| 1.3      | Electromigration in Metallic Interconnects                                                          | 4         |
| 1.3.1    | Electromigration Fundamentals                                                                       | 4         |
| 1.3.2    | Electromigration Degradation Mechanisms<br>in Cu Interconnects                                      | 6         |
| 1.4      | Size Effects in Crystalline Materials                                                               | 7         |
| 1.4.1    | Classical Flow-Stress Relationship:<br>The Taylor Relation                                          | 9         |
| 1.4.2    | The Nix and Gao Model of Strain Gradient Plasticity                                                 | 10        |
|          | References                                                                                          | 11        |
| <b>2</b> | <b>Synchrotron White-Beam X-ray Microdiffraction<br/>at the Advanced Light Source, Berkeley Lab</b> | <b>15</b> |
| 2.1      | Introduction                                                                                        | 15        |
| 2.2      | Beamline Components and Layout                                                                      | 16        |
| 2.3      | Scanning White-Beam X-ray Microdiffraction                                                          | 18        |
| 2.3.1    | Experimental Procedure                                                                              | 18        |
| 2.3.2    | Data Analysis Using XMAS                                                                            | 20        |
| 2.4      | Local Plasticity Probing Using Whitebeam $\mu$ XRD                                                  | 28        |
| 2.4.1    | Crystal Bending, Polygonization and Rotation                                                        | 29        |
| 2.4.2    | Quantitative Peak Study                                                                             | 31        |
|          | References                                                                                          | 34        |
| <b>3</b> | <b>Electromigration-Induced Plasticity in Cu Interconnects:<br/>The Length Scale Dependence</b>     | <b>37</b> |
| 3.1      | Introduction                                                                                        | 37        |
| 3.2      | Background                                                                                          | 38        |
| 3.3      | Experimental                                                                                        | 39        |

|          |                                                                                                                                      |           |
|----------|--------------------------------------------------------------------------------------------------------------------------------------|-----------|
| 3.4      | Results and Discussion . . . . .                                                                                                     | 40        |
| 3.4.1    | Microstructure of the Cu Interconnect Lines . . . . .                                                                                | 40        |
| 3.4.2    | Evolution of Cu Grains During Electromigration . . . . .                                                                             | 42        |
| 3.4.3    | Electromigration-Induced Plasticity: The Linewidth Effects . . . . .                                                                 | 44        |
| 3.4.4    | Electromigration-Induced Plasticity: The Directionality . . . . .                                                                    | 46        |
| 3.4.5    | Correlation Between In-Plane Texture and Occurrence of Plasticity . . . . .                                                          | 48        |
| 3.4.6    | The Out-of-Plane Crystallographic Texture of the Cu Lines . . . . .                                                                  | 50        |
| 3.5      | Conclusions . . . . .                                                                                                                | 51        |
|          | References . . . . .                                                                                                                 | 52        |
| <b>4</b> | <b>Electromigration-Induced Plasticity in Cu Interconnects: The Texture Dependence . . . . .</b>                                     | <b>53</b> |
| 4.1      | Introduction . . . . .                                                                                                               | 53        |
| 4.2      | Background. . . . .                                                                                                                  | 54        |
| 4.2.1    | Electromigration-Induced Plasticity in Metallic Interconnects. . . . .                                                               | 54        |
| 4.2.2    | Microstructural Characterization of Cu Lines Manufactured by AMD . . . . .                                                           | 55        |
| 4.2.3    | Influence of Dielectrics on Mechanical Stresses and Plastic Deformation . . . . .                                                    | 56        |
| 4.3      | Experimental. . . . .                                                                                                                | 58        |
| 4.4      | Results and Discussions . . . . .                                                                                                    | 59        |
| 4.4.1    | EM-Induced Plasticity: Directionality and Extent. . . . .                                                                            | 59        |
| 4.4.2    | Influence of Dielectrics . . . . .                                                                                                   | 62        |
| 4.4.3    | Proposed Correlation: Texture Versus EM-Induced Plasticity . . . . .                                                                 | 63        |
| 4.5      | Conclusions . . . . .                                                                                                                | 66        |
|          | References . . . . .                                                                                                                 | 66        |
| <b>5</b> | <b>Industrial Implications of Electromigration-Induced Plasticity in Cu Interconnects: Plasticity-Amplified Diffusivity. . . . .</b> | <b>69</b> |
| 5.1      | Introduction . . . . .                                                                                                               | 69        |
| 5.2      | Background. . . . .                                                                                                                  | 70        |
| 5.2.1    | Dislocation Cores as Fast Diffusion Paths in Metallic Interconnects . . . . .                                                        | 70        |
| 5.2.2    | Electromigration Reliability Assessment Methodology: Black's Law . . . . .                                                           | 72        |
| 5.3      | Plasticity-Amplified Diffusion in Electromigration . . . . .                                                                         | 73        |
| 5.3.1    | Density of Core Dislocations ( $\rho_{core}$ ): Extent of Plasticity . . . . .                                                       | 74        |
| 5.3.2    | Effect of Grain Boundary Diffusion: Effective $D_{core}$ . . . . .                                                                   | 76        |

|          |                                                                                                                      |            |
|----------|----------------------------------------------------------------------------------------------------------------------|------------|
| 5.3.3    | The Extra Dependency on $J$ —The Plasticity Effect . . . . .                                                         | 82         |
| 5.4      | Conclusions . . . . .                                                                                                | 84         |
|          | References . . . . .                                                                                                 | 85         |
| <b>6</b> | <b>Indentation Size Effects in Single Crystal Cu as Revealed<br/>by Synchrotron X-ray Microdiffraction . . . . .</b> | <b>87</b>  |
| 6.1      | Introduction . . . . .                                                                                               | 87         |
| 6.2      | Background. . . . .                                                                                                  | 88         |
| 6.3      | Experimental. . . . .                                                                                                | 89         |
| 6.4      | Results and Discussion . . . . .                                                                                     | 91         |
| 6.4.1    | Mapping of Laue Peak Streaking on Individual<br>Indents. . . . .                                                     | 91         |
| 6.4.2    | Comparison of Laue Peak Streaking for Different<br>Indentation Depths. . . . .                                       | 93         |
| 6.4.3    | Quantitative Analysis of Laue Peak Streaking-Based<br>GND Density . . . . .                                          | 94         |
| 6.4.4    | Hardness Measurement and Revised Nix and Gao's<br>GND Density . . . . .                                              | 95         |
| 6.4.5    | Strain Gradient Plasticity Analysis. . . . .                                                                         | 96         |
| 6.5      | Conclusions . . . . .                                                                                                | 99         |
|          | References . . . . .                                                                                                 | 99         |
| <b>7</b> | <b>Smaller is Stronger: Size Effects in Uniaxially Compressed<br/>Au Submicron Single Crystal Pillars . . . . .</b>  | <b>103</b> |
| 7.1      | Introduction . . . . .                                                                                               | 103        |
| 7.2      | Background. . . . .                                                                                                  | 104        |
| 7.3      | Experimental. . . . .                                                                                                | 105        |
| 7.3.1    | Thin Film of Au on Single Crystal Cr Substrate . . . . .                                                             | 105        |
| 7.3.2    | Fabrication and Uniaxial Compression of Submicron<br>Au Pillar . . . . .                                             | 106        |
| 7.3.3    | White-Beam X-ray Microdiffraction Experiment . . . . .                                                               | 107        |
| 7.4      | Results and Discussion. . . . .                                                                                      | 108        |
| 7.4.1    | Diffraction Intensity Mapping: Pillar Location<br>Identification. . . . .                                            | 108        |
| 7.4.2    | Stress-Strain Behavior of Pillar Uniaxial Compression . . . . .                                                      | 110        |
| 7.4.3    | Laue Diffraction Peak Shapes: Undeformed Versus<br>Deformed. . . . .                                                 | 110        |
| 7.4.4    | Limitation of the Technique: Quantitative Analysis<br>of GND Density . . . . .                                       | 112        |
| 7.4.5    | Dislocation Starvation and Dislocation<br>Nucleation-Controlled Plasticity. . . . .                                  | 113        |
| 7.5      | Conclusions . . . . .                                                                                                | 114        |
|          | References . . . . .                                                                                                 | 115        |
| <b>8</b> | <b>Conclusions . . . . .</b>                                                                                         | <b>117</b> |

<http://www.springer.com/978-981-287-334-7>

Probing Crystal Plasticity at the Nanoscales

Synchrotron X-ray Microdiffraction

Budiman, A.

2015, IX, 118 p. 64 illus., 52 illus. in color., Softcover

ISBN: 978-981-287-334-7