

# Contents

|          |  |           |
|----------|--|-----------|
| <b>1</b> | <b>When is a material stable?</b>                                | <b>1</b>  |
| 1.1      | Concept  | 1         |
| 1.2      | Introduction   | 1         |
| 1.3      | Definitions  | 2         |
| 1.4      | The first law of thermodynamics                                  | 4         |
| 1.5      | The second law of thermodynamics                                 | 5         |
| 1.6      | Closed systems and heat reservoirs                               | 12        |
| 1.7      | The Helmholtz free energy  | 13        |
| 1.8      | The Gibbs free energy  | 14        |
| 1.9      | Chemical potentials  | 15        |
| 1.10     | The Gibbs-Duhem equation   | 16        |
| 1.11     | The Gibbs phase rule   | 17        |
| 1.12     | Closing remarks  | 18        |
|          | Further reading  | 18        |
| <b>2</b> | <b>Phase diagrams</b>  | <b>19</b> |
| 2.1      | Introduction   | 19        |
| 2.2      | Free energy - composition curves                                 | 21        |
| 2.3      | From free energy - composition curves to the equilibrium state   | 22        |
| 2.4      | Phase diagram for complete miscibility                           | 25        |
| 2.5      | Phase diagrams for limited solubility in the solid state         | 26        |
| 2.6      | Closing remarks  | 28        |
|          | Further reading  | 29        |
| <b>3</b> | <b>Restless motion</b>   | <b>30</b> |
| 3.1      | Concept  | 30        |
| 3.2      | Evidence of restless atomic motion                               | 30        |
| 3.3      | Fluctuations and thermally activated processes                   | 31        |
| 3.4      | Brownian motion  | 33        |
| 3.5      | The fluctuation-dissipation theorem                              | 34        |
| 3.6      | Some other manifestations of restless atomic motion in materials | 37        |
|          | Further reading  | 39        |
| <b>4</b> | <b>Defects</b>   | <b>40</b> |
| 4.1      | Concept  | 40        |
| 4.2      | Change in materials  | 40        |
| 4.3      | Point defects  | 41        |
| 4.4      | Dislocations   | 46        |
| 4.5      | Grain boundaries   | 50        |
|          | Further reading  | 51        |



|           |  |     |
|-----------|--|-----|
| <b>5</b>  | <b>Symmetry</b>  | 52  |
| 5.1       | Concept  | 52  |
| 5.2       | Introduction   | 52  |
| 5.3       | Conservation laws  | 54  |
| 5.4       | Physical properties of crystals                              | 55  |
| 5.5       | Topological defects  | 57  |
| 5.6       | Quasicrystals  | 58  |
|           | Further reading  | 64  |
| <b>6</b>  | <b>Quantum behaviour</b>                                     | 65  |
| 6.1       | Concept  | 65  |
| 6.2       | The size and identity of atoms                               | 65  |
| 6.3       | The double slit experiment                                   | 66  |
| 6.4       | Identical particles, the Pauli exclusion principle and spin  | 71  |
| 6.5       | Consequences of the Pauli exclusion principle                | 72  |
| 6.6       | Tunnelling   | 76  |
| 6.7       | Thermal properties of solids                                 | 76  |
| 6.8       | Quantum diffusion  | 79  |
| 6.9       | Closing remarks  | 80  |
|           | Further reading  | 80  |
| <b>7</b>  | <b>Small is different</b>                                    | 81  |
| 7.1       | Concept  | 81  |
| 7.2       | Introduction   | 81  |
| 7.3       | Quantum dots   | 83  |
| 7.4       | Catalysis  | 86  |
| 7.5       | Giant magnetoresistance                                      | 86  |
| 7.6       | Closing remarks  | 93  |
|           | Further reading  | 93  |
| <b>8</b>  | <b>Collective behaviour</b>                                  | 94  |
| 8.1       | Concept  | 94  |
| 8.2       | More is different  | 94  |
| 8.3       | Three examples of processes involving multiple length scales | 96  |
|           | Further reading  | 101 |
| <b>9</b>  | <b>Materials by design</b>                                   | 102 |
| 9.1       | Concept  | 102 |
| 9.2       | Introduction   | 102 |
| 9.3       | Microstructure   | 103 |
| 9.4       | An example: replacing the 'nickel'                           | 105 |
| 9.5       | Self-assembly  | 105 |
| 9.6       | Smart materials  | 111 |
| 9.7       | Closing remarks  | 113 |
|           | Further reading  | 113 |
| <b>10</b> | <b>Metamaterials</b>   | 114 |
| 10.1      | Concept  | 114 |



|           |   |            |
|-----------|---|------------|
| 10.2      | Introduction  | 114        |
| 10.3      | An example: a metamaterial for elastic waves          | 115        |
| 10.4      | Electromagnetic metamaterials and negative refraction | 118        |
| 10.5      | Invisibility cloaks                                   | 122        |
| 10.6      | Closing remarks                                       | 123        |
|           | Further reading                                       | 124        |
| <b>11</b> | <b>Biological matter as a material</b>                | <b>125</b> |
| 11.1      | Concept   | 125        |
| 11.2      | What is life?   | 125        |
| 11.3      | Active matter   | 127        |
| 11.4      | Synthetic biology                                     | 131        |
| 11.5      | Closing remarks                                       | 131        |
|           | Further reading                                       | 132        |
|           | <b>Index</b>  | <b>133</b> |