Contents

Preface *xi*

Part I Fundamentals of Liquid Metal *1*

1 Introduction *3*
1.1 The Discovery and Development History of Liquid Metal *3*
1.1.1 A Vindication for Mendeleev's Prediction *4*
1.1.2 Gallium's Applications in the Semiconductor Industry *5*
1.1.3 Tackling Fundamental Problems in Fuel in Energy Science *5*
1.2 Liquid Metal Family *6*
1.3 Overview of Liquid Metal *8*
References *13*

2 Structure and Physical Properties of Liquid Metal *15*
2.1 Structure of Liquid Metal *16*
2.1.1 Monocomponent Liquid Metal *16*
2.1.2 Monophasic Liquid Metal Alloy *22*
2.1.3 Biphasic Liquid Metal Mix *24*
2.2 Low Melting Point of Liquid Metal *26*
2.2.1 Zinc Group Metals *26*
2.2.2 Alkali Metals *27*
2.2.3 Post-transition Metals *27*
2.2.4 Liquid Metal Alloys *27*
2.3 Rheological Properties of Liquid Metal *29*
2.3.1 Basic Rheology Property of Liquid Metal *29*
2.3.2 Effect of Oxide Surface *30*
2.3.3 Effect of the Formation of Composite *31*
2.4 Electrical Conductivity of Liquid Metal *34*
2.4.1 Resistance Change at Melting Point *34*

2.4.2 Temperature Dependency *36*
2.4.3 Resistance of Liquid Alloy *37*
2.5 Thermal Property of Liquid Metal *37*
2.5.1 Pure Liquid Metal *37*
2.5.2 Liquid Metal Alloy *39*
2.5.3 Effect of Oxide Surface *39*
2.6 Surface Properties of Liquid Metal *40*
2.6.1 High Surface Energy *41*
2.6.1.1 Surface Tension *41*
2.6.1.2 Nonreactive Surface Wetting *42*
2.6.2 High Surface Activity *44*
2.6.2.1 Surface Internalization *44*
2.6.2.2 Surface Oxidation *46*
2.6.3 Ordered Surface State *47*
2.7 Liquid Metal in Other Dimensions *49*
2.7.1 One-Dimensional Liquid Metal *49*
2.7.1.1 Ga *50*
2.7.1.2 In *50*
2.7.1.3 Sn *51*
2.7.1.4 Pb *52*
2.7.1.5 Sb *53*
2.7.1.6 Bi *53*
2.7.2 Two-Dimensional Liquid Metal *53*
2.7.2.1 Ga *54*
2.7.2.2 In *54*
2.7.2.3 Sn *56*
2.7.2.4 Pb *56*
2.7.2.5 Sb *56*
2.7.2.6 Bi *57*
2.8 Conclusion *58*
References *59*

3 Preparation of Liquid Metal *71*
3.1 Introduction *71*
3.2 Preparation of Liquid Metal Droplets *72*
3.2.1 Liquid-Phase Preparation *73*
3.2.2 Vapor-Phase Preparation *77*
3.2.3 Others *79*
3.3 Preparation of Liquid Metal Nanowires *81*
3.3.1 Catalyst-Assisted Methods *82*
3.3.2 Catalyst-Free Methods *83*
3.3.3 Others *84*
3.4 Preparation of Liquid Metal Nanosheets *86*
3.5 Conclusion and Prospect *90*
References *93*

4 External Field Tuning of Liquid Metal *99*
4.1 Introduction *99*
4.2 Electrical Field Tuning *101*
4.2.1 Electric-Induced Locomotion *101*
4.2.2 Electric-Induced Deformation *107*
4.3 Magnetic Field Tuning *114*
4.3.1 Magnetic-Induced Deformation *114*
4.3.2 Magnetic-Induced Locomotion *116*
4.3.3 Magnetic-Tuned Properties *122*
4.4 Chemical Tuning *125*
4.4.1 Chemical-Induced Deformation *125*
4.4.2 Chemical-Induced Locomotion *130*
4.4.3 Chemical-Tuned Properties *134*
4.5 Force Field Tuning *136*
4.6 Others *139*
4.7 Conclusion and Prospect *145*
References *146*

Part II Emergent Applications of Liquid Metal *153*

5 Liquid Metal as a New Reaction Medium *155*
5.1 Introduction *156*
5.2 Nanomaterial Synthesis *157*
5.2.1 Current Status of Nanomaterial Synthesis *157*
5.2.2 Liquid Metal-Assisted Synthesis of Zero-Dimensional Nanomaterials *158*
5.2.3 Liquid Metal-Assisted Synthesis of One-Dimensional Nanomaterials *159*
5.2.4 Liquid Metal-Assisted Synthesis of Two-Dimensional Nanomaterials *161*
5.2.4.1 Liquid Metal for the Two-Dimensional Growth of Materials *162*
5.2.4.2 Liquid Metal-Assisted Growth Behavior Control *178*
5.2.4.3 Liquid Metal-Assisted Sliding Transfer *191*
5.3 Alloy Preparation *192*
5.3.1 Current Progress of Alloy Preparation *193*
5.3.2 Liquid Metal-Assisted Preparation of Alloy *194*
5.3.2.1 Liquid Metal-Assisted Structure Formation *194*
5.3.2.2 Liquid Metal-Assisted Morphology Formation *197*
5.4 Conclusion and Prospect *201*
References *203*

6 Constructing Techniques of Liquid Metal-Based Architectures *217*
6.1 Introduction *217*
6.2 Injection *219*

6.2.1 Direct Injection *219*
6.2.2 Vacuum Filling *222*
6.3 Imprinting *225*
6.4 Mask-Assisted Deposition *227*
6.5 Direct Writing *231*
6.5.1 Inkjet Printing *232*
6.5.2 Micro-extrusion Printing *234*
6.6 Laser Ablation *243*
6.7 External Field Guiding *243*
6.7.1 Magnetic Field-Guided Patterning *243*
6.7.2 Electric Field-Guided Patterning *246*
6.8 Others *248*
6.9 Conclusion and Prospect *252*
References *255*

7 Liquid Metal Toward Flexible Electronics *263*
7.1 Introduction *263*
7.2 Traditional Materials for Flexible Electronics *264*
7.2.1 Elementary Substances and Inorganic Materials *264*
7.2.2 Organic Materials *266*
7.2.3 Composite Materials *267*
7.3 Advantages of Liquid Metals *268*
7.4 Construction Strategies for Liquid Metal-Based Flexible Electronics *269*
7.5 Typical Flexible Electronics Based on Liquid Metals *270*
7.5.1 Stretchable Conductors *272*
7.5.2 Stretchable Circuit Elements *276*
7.5.3 Stretchable Antennas *281*
7.5.4 Soft Sensors *284*
7.5.5 Others *293*
7.6 Conclusion and Prospect *296*
References *298*

8 Liquid Metal for Biomedicine *309*
8.1 Introduction *310*
8.2 Therapeutics *310*
8.2.1 The Potential of Liquid Metal for Therapeutics *310*
8.2.2 Drug Delivery *311*
8.2.3 Hyperthermia Therapy *314*
8.2.3.1 Magnetic Hyperthermia *315*
8.2.3.2 Photothermal Therapy *317*
8.2.3.3 Radio-frequency Hyperthermia *322*
8.2.3.4 Chemothermal Therapy *323*
8.2.4 Microwave Dynamic Therapy *324*
8.2.5 Electrochemical Therapy *325*
8.2.6 Embolotherapy *326*

8.3 Biomedical Imaging *328*
8.3.1 X-ray Imaging *328*
8.3.1.1 Angiography *329*
8.3.1.2 Computed Tomography *330*
8.3.2 Photoacoustic Imaging *331*
8.4 Biomimetics *332*
8.4.1 Reversible Bone Cement *334*
8.4.2 Flexible Exoskeleton *336*
8.4.3 Nerve Connector *337*
8.5 Biodevices *341*
8.5.1 Biosensor *341*
8.5.2 Implantable Electrode *346*
8.5.3 Microfluidic Pump *348*
8.6 Conclusion and Prospect *351*
References *352*

9 Liquid Metal for Energy *361*
9.1 Introduction *361*
9.2 Liquid Metal as Electrodes *362*
9.2.1 Design Principle *363*
9.2.1.1 Advantages of Liquid Metal Electrodes *363*
9.2.1.2 Potential Liquid Metal Candidates *365*
9.2.1.3 Wetting Behavior *366*
9.2.2 High-temperature Liquid Metal Electrodes *368*
9.2.2.1 Metal–metal Design *368*
9.2.2.2 Metal–nonmetal Design *370*
9.2.3 Room-temperature Liquid Metal Electrodes *371*
9.2.3.1 Ga-based Metal Anodes *371*
9.2.3.2 Na–K Alkali Metal Anodes *373*
9.2.3.3 Others *376*
9.3 Liquid Metal as Coolants *378*
9.3.1 Traditional Nuclear Application *378*
9.3.1.1 Liquid Alkali Metal *379*
9.3.1.2 Liquid Heavy Metal *380*
9.3.2 Advanced Electronic Cooling *381*
9.3.2.1 Proposition of Liquid-metal Coolants *382*
9.3.2.2 Design of Hybrid Coolants *385*
9.3.2.3 Optimization of Cooling Systems *390*
9.4 Liquid Metal as Catalysis *392*
9.5 Conclusion and Prospect *396*
References *397*

Index *403*