

## Volume 3

- 4.5 Ordered Mesoporous Oxides 1311
- 4.5.1 Micelle-Templated Materials 1311  
*F. Di Renzo, A. Galarneau, P. Trems, and F. Fajula*
- 4.5.1.1 Introduction 1311
- 4.5.1.2 Micellar Templates 1312
- 4.5.1.2.1 Micelles 1312
- 4.5.1.2.2 Mesophases 1315
- 4.5.1.3 Syntheses of Micelle-templated Materials 1318
- 4.5.1.3.1 Mechanisms of Formation 1318
- 4.5.1.3.2 An Introductory Example 1321
- 4.5.1.3.3  $S^+ I^-$  Synthesis with Alkyltrimethylammonium Cations 1324
- 4.5.1.3.4 Examples of Syntheses of MCM-41 and MCM-48 1336
- 4.5.1.3.5  $S^+ I^-$  Pathway with Other Cationic Surfactants 1337
- 4.5.1.3.6  $S^+ X^- I^+$  Pathway with Cationic Surfactants 1339
- 4.5.1.3.7 Synthesis with Amines 1342
- 4.5.1.3.8 Nonionic Surfactants and the  $S^0 I^0$  Pathway 1343
- 4.5.1.3.9  $(S^0 H^+)(X^- I^+)$  Synthesis Pathway with Nonionic Surfactants 1346
- 4.5.1.4 Properties and Activation 1349
- 4.5.1.4.1 Pore-size Control 1349
- 4.5.1.4.2 Doped Silicas 1352
- 4.5.1.4.3 Template Extraction 1354
- 4.5.1.4.4 Silica Surface 1356
- 4.5.1.4.5 Hydrothermal Stability 1357
- 4.5.1.4.6 Functionalization of the Surface 1359
- 4.5.1.4.7 Acidity 1360
- 4.5.1.4.8 Zeolitization of the Walls 1361
- 4.5.1.4.9 Mechanical Stability 1361
- 4.5.1.4.10 Texture 1364
- 4.5.1.5 Applications 1368
- 4.5.1.5.1 Adsorption and Separation 1368
- 4.5.1.5.2 Solid State 1369
- 4.5.1.5.3 Catalysis 1369
- 4.5.1.6 Nonsilica Materials 1372
- 4.5.1.7 Health Concerns 1380
- 4.5.1.7.1 The Health of the Users 1380
- 4.5.1.7.2 The Health of the Producers 1380
- 4.5.1.8 A Glossary of Mesoporous Materials 1381
- References 1383
- 4.5.2 Anodic Alumina 1395  
*D. Hönicke and E. Dietzsch*
- 4.5.2.1 Formation and Characterization of Anodic Alumina 1396
- 4.5.2.1.1 Barrier-type and Porous-type Alumina 1396

4.5.2.1.2	Porous Anodic Alumina by Faraday Oxidation	1397
4.5.2.1.3	Porous Alumina by Plasma-chemical Oxidation	1407
4.5.2.2	Structure and Composition of Anodic Alumina	1408
4.5.2.3	Catalytic Properties of Anodic Alumina	1410
4.5.2.4	Applications of Anodic Alumina and Derived Material	1419
	References	1427
4.6	Porous Glasses	1432
	<i>F. Janowski and D. Enke</i>	
4.6.1	Introduction and Classification	1432
4.6.2	Preparation	1434
4.6.2.1	Porous Vycor Glass (PVG)	1436
4.6.2.2	Controlled Pore Glass (CPG)	1444
4.6.2.2.1	Composition of the Initial Glass	1446
4.6.2.2.2	Phase Separation	1449
4.6.2.2.3	Leaching	1453
4.6.2.3	Open-pore Glass from Sol–Gel Processes	1456
4.6.2.4	Miscellaneous	1457
4.6.3	Characterization	1458
4.6.3.1	Structure	1458
4.6.3.2	Texture	1467
4.6.3.2.1	Pore Volume	1468
4.6.3.2.2	Pore Size	1470
4.6.3.2.3	Pore-size Distribution	1474
4.6.3.2.4	Pore Shape	1476
4.6.3.2.5	Specific Surface Area	1476
4.6.3.3	Modeling	1478
4.6.3.4	Surface Chemistry	1481
4.6.4	Properties and Handling of Porous Glasses	1489
4.6.5	Modification	1491
4.6.5.1	Surface Coating	1491
4.6.5.2	Surface Reactions	1492
4.6.5.3	Generation of Acidic Sites	1497
4.6.5.4	Composites	1503
4.6.6	Application	1507
4.6.6.1	Adsorption	1508
4.6.6.2	Ion Exchange	1510
4.6.6.3	Porous Glass Membranes	1510
4.6.6.4	Chromatography	1514
4.6.6.5	Solid-phase Biochemistry	1515
4.6.6.6	Catalysis	1517
4.6.6.7	Porous Glasses as Restricted Geometries	1521
4.6.6.8	Commercial Applications	1528
4.6.7	Final Remarks	1529
	References	1529

4.7	Other Oxides	1543
4.7.1	Silica	1543
	<i>C. Setzer, G. van Essche, and N. Pryor</i>	
4.7.1.1	Introduction	1543
4.7.1.1.1	The Formation of Silica Sols, Gels and Powders	1544
4.7.1.1.2	Surface Chemistry of Silica	1545
4.7.1.2	Silica Types: Production, Structure, Properties	1551
4.7.1.2.1	Colloidal Silicas	1551
4.7.1.2.2	Precipitated Silica	1553
4.7.1.2.3	Fumed Silica	1554
4.7.1.2.4	Silica Gel	1555
4.7.1.3	Surface Modifications	1572
4.7.1.3.1	Chemical Modifications of Silica	1572
4.7.1.3.2	Impregnation of Silicas	1573
4.7.1.3.3	Surface-enriched Co-Ion-containing Silica Gels	1574
4.7.1.4	Applications	1575
4.7.1.4.1	Chromatography	1575
4.7.1.4.2	Rheological Modification	1577
4.7.1.4.3	Cleaning, Polishing and Planarization	1581
4.7.1.4.4	Adsorption	1581
4.7.1.4.5	Matting Agents	1583
4.7.1.4.6	Ink-receptive Coatings	1583
4.7.1.4.7	Antiblocking Agents	1584
4.7.1.4.8	Reinforcing Agent	1584
4.7.1.4.9	Defoamer	1584
4.7.1.4.10	Catalyst/Catalyst Support	1584
4.7.1.4.11	Colloidal Silica for the Investment Casting of Metals	1586
	References	1586
4.7.2	Alumina	1591
	<i>P. Euzen, P. Raybaud, X. Krokidis, H. Toulhoat, J.-L. Le Loarer, J.-P. Jolivet, and C. Froidefond</i>	
4.7.2.1	Introduction	1591
4.7.2.2	Structures, Textures and Porosity	1594
4.7.2.2.1	Trihydroxides	1594
4.7.2.2.2	(Oxihydr)oxide	1595
4.7.2.2.3	Conclusion on Hydroxides	1613
4.7.2.2.4	From (Oxi)hydroxide to Transition Aluminas	1615
4.7.2.2.5	Transition Aluminas	1625
4.7.2.2.6	Alpha Alumina	1630
4.7.2.2.7	Conclusion Texture, Structure and Porosity	1632
4.7.2.3	Surface Properties	1633
4.7.2.3.1	Acido-basicity of Boehmite	1633
4.7.2.3.2	Acido-basicity of Alumina	1636
4.7.2.4	Alumina Forming	1638

4.7.2.4.1	Extrusion	1640
4.7.2.4.2	Oil-drop Coagulation	1645
4.7.2.4.3	Granulation	1648
4.7.2.4.4	Calcination	1651
4.7.2.5	Catalytic Applications	1652
4.7.2.5.1	Introduction	1652
4.7.2.5.2	Control of Acido-basicity	1653
4.7.2.5.3	Control of Textural Properties	1657
4.7.2.6	Conclusion	1667
	Acknowledgments	1667
	References	1668
4.7.3	Transition Metal Oxides	1677
	<i>M. V. Landau</i>	
4.7.3.1	Introduction	1677
4.7.3.2	Group 4: Ti, Zr, Hf	1680
4.7.3.2.1	Zirconium Oxide	1680
4.7.3.2.2	Titanium Oxide	1698
4.7.3.2.3	Hafnium Oxide	1705
4.7.3.3	Group 11: Copper Oxide	1706
4.7.3.4	Group 12: Zn, Cd	1708
4.7.3.4.1	Zinc Oxide	1708
4.7.3.4.2	Cadmium Oxide	1711
4.7.3.5	Group 3: Scandium, Yttrium, and Lanthanum Oxides	1712
4.7.3.6	Group 13: Ga, In, Tl	1715
4.7.3.7	Group 14: Ge, Sn, Pb	1716
4.7.3.7.1	Tin Oxide	1716
4.7.3.7.2	Germanium Oxide	1720
4.7.3.7.3	Lead Oxide	1721
4.7.3.8	Group 5: V, Nb, Ta	1722
4.7.3.8.1	Vanadium Oxides	1722
4.7.3.8.2	Niobium and Tantalum Oxides	1726
4.7.3.9	Group 15: Sb, Bi	1729
4.7.3.9.1	Antimony Oxide	1729
4.7.3.9.2	Bismuth Oxide	1730
4.7.3.10	Group 6: Cr, Mo, W	1731
4.7.3.10.1	Chromium Oxide	1731
4.7.3.10.2	Molybdenum Oxide	1734
4.7.3.10.3	Tungsten Oxide	1736
4.7.3.11	Group 7: Mn, Re	1738
4.7.3.11.1	Manganese Oxides	1738
4.7.3.11.2	Rhenium Oxides	1742
4.7.3.12	Group 8: Fe, Co, Ni	1743
4.7.3.12.1	Iron Oxides	1743
4.7.3.12.2	Cobalt Oxides	1746

4.7.3.12.3	Nickel Oxide	1747
4.7.3.13	Conclusions	1748
	References	1752
4.8	Carbons	1766
4.8.1	Production and Applications of Activated Carbons	1766
	<i>F. Rodríguez-Reinoso</i>	
4.8.1.1	Introduction	1766
4.8.1.2	Production	1770
4.8.1.2.1	Precursors	1771
4.8.1.2.2	Conventional Products	1774
4.8.1.2.3	Speciality Carbons	1793
4.8.1.2.4	Furnaces	1802
4.8.1.2.5	Quality Control	1803
4.8.1.2.6	Regeneration	1807
4.8.1.3	Industrial Production	1808
4.8.1.4	Applications	1809
4.8.1.4.1	Gas-Phase Applications	1809
4.8.1.4.2	Liquid-Phase Applications	1814
4.8.1.4.3	Miscellaneous Applications	1818
4.8.1.5	Market	1819
4.8.1.5.1	Consumption	1819
4.8.1.5.2	Price	1821
4.8.1.6	Conclusions	1822
	References	1822
4.8.2	Properties of Activated Carbons	1828
	<i>B. McEnaney</i>	
4.8.2.1	Introduction	1828
4.8.2.2	Carbonization	1829
4.8.2.3	The Microstructure of Activated Carbons	1831
4.8.2.4	Adsorption Forces in Activated Carbons	1834
4.8.2.5	Characterization of Activated Carbons	1836
4.8.2.6	Adsorption of Water Vapor	1839
4.8.2.7	Physical Activation	1840
4.8.2.7.1	Mechanisms of Physical Activation	1841
4.8.2.7.2	Pore Development during Physical Activation	1842
4.8.2.7.3	Comparison of Pore Development during Physical Activation using Different Activating Gases	1846
4.8.2.8	Chemical Activation	1847
4.8.2.8.1	Activation by Phosphoric Acid	1847
4.8.2.8.2	Activation by Zinc Chloride	1849
4.8.2.8.3	Activation by Potassium Hydroxide	1850
4.8.2.8.4	Comparative Studies of Chemical and Physical Activation	1852
4.8.2.9	Special Classes of Activated Carbon	1853

4.8.2.9.1	Molecular Sieve Carbons	1853
4.8.2.9.2	Microporous Carbon Membranes	1854
4.8.2.9.3	Activated Carbon Fibers, Textiles and Composites	1855
4.8.2.10	Conclusions	1857
4.8.2.11	Symbols and Abbreviations	1858
	Acknowledgements	1859
	References	1859
4.8.3	Surface Composition and Structure of Active Carbons	1863
	<i>R. Schlögl</i>	
4.8.3.1	The Electronic Structure of Carbon Surfaces	1863
4.8.3.2	The Generation of Oxygen Surface Functional Groups	1869
4.8.3.3	The Structure of Carbon-Oxygen Functional Groups	1874
4.8.3.4	Analysis of Carbon-Oxygen Functional Groups	1883
	References	1897
4.8.4	Pore Structure of Graphite, Coke and Composites	1900
	<i>J. W. Patrick and S. Hanson</i>	
4.8.4.1	Introduction	1900
4.8.4.2	Carbon Materials	1901
4.8.4.2.1	Carbon in the Form of Graphite	1902
4.8.4.2.2	Carbon in the Form of Coke	1903
4.8.4.2.3	Carbon in the Form of Carbon/Carbon Composites	1904
4.8.4.3	Textural Composition	1905
4.8.4.4	Pore Structure of Graphite	1906
4.8.4.5	Pore Structure of Cokes	1910
4.8.4.5.1	Development of Porosity during Carbonization	1910
4.8.4.5.2	Coke Porosity and Strength	1912
4.8.4.5.3	Coke Porosity and Reactivity	1914
4.8.4.5.4	Petroleum and Pitch Cokes	1915
4.8.4.6	Pore Structure of Carbon/Carbon Composites	1916
4.8.4.6.1	General Process of Composite Formation	1916
4.8.4.6.2	Characterization of Porosity in Carbon/Carbon Composites	1918
4.8.4.7	Concluding Remarks	1921
	References	1921
4.8.5	Carbon Nanotubes	1923
	<i>A. Minett, K. Atkinson and S. Roth</i>	
4.8.5.1	Introduction	1923
4.8.5.2	Single-Walled Carbon Nanotubes (SWCNT), Multiwalled Carbon Nanotubes (MWCNT), Bundles and Buckypaper	1927
4.8.5.3	Synthesis, Purification, Characterization	1934
4.8.5.4	Quantum Transport in Carbon Nanotubes	1947
4.8.5.4.1	Quantum Dot Effects	1947
4.8.5.4.2	Quantum Wire Effects	1949

- 4.8.5.4.3 Nanocylinder Effects 1950
- 4.8.5.4.4 Chirality Effects 1950
- 4.8.5.5 Industrial Applications 1952
- 4.8.5.5.1 Hydrogen Storage 1952
- 4.8.5.5.2 Field Emission 1953
- 4.8.5.5.3 Nanoelectronics 1954
- 4.8.5.5.4 Artificial Muscles 1957
- 4.8.5.5.5 Nanocomposites 1958
- 4.8.5.6 Conclusion 1959
- Acknowledgments 1960
- References 1960
  
- 4.9 Porous Polymers and Resins 1964  
*H.-P. Hentze and M. Antonietti*
- 4.9.1 Introduction 1964
- 4.9.2 History 1964
- 4.9.3 Synthetic Strategies to Porous Polymer Networks 1965
- 4.9.3.1 Gases, Liquids and Supercritical CO<sub>2</sub> for Pore Generation 1966
- 4.9.3.1.1 Spheres 1970
- 4.9.3.1.2 Monolithic Polymer Gels 1971
- 4.9.3.1.3 Sc-CO<sub>2</sub> as a Porogen 1974
- 4.9.3.2 Porous Polymers by Thermally Induced Phase Separation (TIPS) 1979
- 4.9.3.3 Porous Polymers by Immersion Precipitation and Chemically Induced Phase Separation (CIPS) 1982
- 4.9.3.4 Polymerization of High Internal Phase Emulsions (HIPE) 1983
- 4.9.3.5 Porous Polymers and Resins by Template Syntheses 1986
- 4.9.3.5.1 Molecular Imprinting 1988
- 4.9.3.5.2 Colloidal Crystal Templating 1990
- 4.9.3.5.3 Micellar Imprinting 1991
- 4.9.3.5.4 Polymerization within Sponge Phases of Bicontinuous Microemulsions 1993
- 4.9.3.5.5 Polymerization within Long-Ranged Ordered Mesophases and other Liquid Crystalline Templates 1995
- 4.9.4 Other Techniques of Porous Polymer Synthesis 2000
- 4.9.5 Functionalization of Porous Polymers 2001
- 4.9.6 Applications of Porous Polymers and Resins 2003
- 4.9.7 Conclusions and Outlook 2007
- Acknowledgments 2008
- References 2009
  
- 4.10 Aerogels 2014
- 4.10.1 Oxidic Aerogels 2014  
*T. F. Baumann, A. E. Gash, G. A. Fox, J. H. Satcher, Jr., and L. W. Hrubesh*
- 4.10.1.1 Introduction to Aerogels 2014

4.10.1.1.1	Properties	2014
4.10.1.1.2	Applications	2015
4.10.1.2	Aerogel Preparation	2015
4.10.1.2.1	Sol Formation and Gelation	2016
4.10.1.2.2	Aerogel Precursors	2018
4.10.1.2.3	Drying Processes	2021
4.10.1.2.4	Characterization	2023
4.10.1.3	Oxidic Aerogels	2024
4.10.1.3.1	Main Group Elements	2024
4.10.1.3.2	Transition Metals	2028
4.10.1.3.3	Rare Earth Metals	2030
4.10.1.3.4	Binary and Ternary Oxide Aerogels	2031
	Acknowledgments	2032
	References	2032
4.10.2	Carbon Aerogels	2037
	<i>J. Fricke and R. Petricevic</i>	
4.10.2.1	Introduction	2037
4.10.2.2	Synthesis	2038
4.10.2.2.1	Gel Formation and Drying Process	2038
4.10.2.2.2	Pyrolysis	2040
4.10.2.2.3	Fiber-Reinforced Films	2041
4.10.2.2.4	Surface Modification	2042
4.10.2.3	General Structure	2045
4.10.2.4	Properties	2047
4.10.2.4.1	Mechanical Properties	2048
4.10.2.4.2	Thermal Properties	2049
4.10.2.4.3	Electrical Properties	2051
4.10.2.4.4	Electrochemical Properties	2054
4.10.2.4.5	Gas-Transport Properties	2056
4.10.2.4.6	Optical/Infrared-Optical Properties	2058
4.10.2.5	Applications	2058
4.10.2.5.1	High-Temperature Thermal Insulation	2059
4.10.2.5.2	Electrical Double-Layer Capacitors	2059
4.10.2.5.3	Capacitive Deionization	2059
4.10.2.5.4	Fuel Cells	2060
4.10.2.5.5	Broadband Nonreflective Materials	2060
	References	2060
4.11	Miscellaneous Solids	2063
	<i>P. Llewellyn and S. Kaskel</i>	
4.11.1	Porous Silicon	2063
4.11.1.1	Introduction	2063
4.11.1.2	Preparation	2064
4.11.1.2.1	Synthesis	2064

4.11.1.2.2	Masking	2067
4.11.1.2.3	Porosity Multilayers	2068
4.11.1.2.4	Aging	2068
4.11.1.2.5	Drying	2068
4.11.1.3	Characterization	2069
4.11.1.3.1	Adsorption Properties	2069
4.11.1.3.2	X-Ray Diffraction	2071
4.11.1.3.3	Spectroscopic Methods	2072
4.11.1.3.4	Microscopic Methods	2072
4.11.1.3.5	Photoluminescence	2073
4.11.1.4	Applications	2074
4.11.2	Soils and Rocks	2074
4.11.3	Foamed Metals	2075
4.11.4	Raney Metals	2077
4.11.5	Porous Inorganic Nitrides	2078
4.11.5.1	Surface and Bulk Nitridation of Oxides	2079
4.11.5.2	Solid-State Reactions	2080
4.11.5.3	Pre ceramic Intermediates	2080
4.11.6	Other Materials	2083
4.11.7	Summary	2084
	References	2084