

# Contents

---

## Part I Instrumental

---

### 1 The Polymers

<i>D. Fink</i> .....	3
1.1 General Considerations.....	3
1.1.1 General Remarks and Temperature Dependence.....	6
1.1.2 Electrical Polymer Properties .....	11
1.2 Favored Polymers .....	13
1.2.1 Polyolefines.....	13
1.2.2 Polyethers .....	15
1.2.3 Polyesters .....	16
1.2.4 Polyvinyls .....	16
1.2.5 Polyimides .....	17
1.2.6 Polysulfones .....	19
1.2.7 Polysilanes .....	19
1.2.8 Polysiloxanes .....	20
1.3 Special Polymer Groups of Technological Interest.....	21
1.3.1 Resists for Lithography .....	21
1.3.2 Conducting Polymers .....	23
1.3.3 Biopolymers and Tissue-Equivalent Polymers .....	25
1.4 Fillers and Additives in Commercial Polymers.....	27
1.5 Water in Polymers.....	27
1.6 Organometals .....	29

### 2 Ion Accelerators

<i>M. Behar and D. Fink</i> .....	35
2.1 Ion Implanters .....	36
2.1.1 Electrostatic Accelerators .....	37
2.2 High-frequency Accelerators .....	39
2.2.1 Linear Accelerators .....	39
2.2.2 Cyclotrons .....	39
2.2.3 Synchrotrons .....	40
2.3 Production of Molecular and Cluster Ions .....	40
2.4 Microparticle Accelerators .....	42
2.5 Ion Microbeams .....	42

2.6	Radioactive Sources and Nuclear Reactors .....	42
2.7	Target Chambers .....	43
<b>3 Experimental Techniques</b>		
	<i>D. Fink and V. Hnatowicz</i> .....	47
3.1	Determination of Implantation and Damage Profiles in Polymers .....	47
3.1.1	One-Dimensional Depth Profiles of Implanted Ions .....	47
3.1.2	Nuclear Analytic Techniques for Depth Profiling .....	48
3.1.3	Three-Dimensional Distributions of Implanted Ions in Polymers .....	61
3.1.4	Determination of Radiation Damage in Polymers .....	66
3.2	Determination of Chemical Changes in Irradiated Polymers .....	68
3.3	Determination of Structural Changes in Irradiated Polymers .....	78
3.4	Determination of Macroscopic Properties of Irradiated Polymers .....	101
3.4.1	Changes in Mechanical Properties .....	101
3.4.2	Changes in Thermal Properties .....	102
3.4.3	Changes in Optical Properties .....	103
3.4.4	Changes in Electrical Properties .....	103
3.4.5	Changes in Magnetic Properties .....	104
3.5	Visualization of Individual Ion Tracks in Polymers .....	105
3.5.1	Transmission Electron Microscopy .....	105
3.5.2	Scanning Electron Microscopy .....	106
3.5.3	Scanning Probe Microscopy .....	106
3.6	Conclusion .....	107

---

## Part II Mechanism of Ion–Matter Interaction

---

### 4 Mechanisms of Particle–Polymer Interaction

	<i>M. Behar and D. Fink</i> .....	119
4.1	Particle–Particle Interaction .....	119
4.1.1	Basis Expressions .....	119
4.1.2	Nuclear Potentials .....	120
4.1.3	Elastic Collisions .....	120
4.1.4	Resonances .....	121
4.1.5	Inelastic Collisions .....	121
4.1.6	Reactions with Neutrons .....	121
4.2	Energy-Loss Processes of Ions in Matter .....	123
4.2.1	Nuclear Stopping Power .....	123
4.2.2	Electronic Stopping Power .....	128
4.2.3	Special Cases .....	131
4.2.4	The Energy Loss Straggling .....	135

4.3	Range Distributions .....	138
4.3.1	Regular Ion Ranges and Range Stragglings .....	138
4.3.2	Transport Theory .....	140
4.3.3	Range-Profile Determination by a Diffusional Model .....	141
4.3.4	Analytic Approach for High Energies .....	143
4.3.5	Monte-Carlo Range-Profile Simulation .....	144
4.3.6	Comparison of Range Codes .....	146
4.3.7	Experimental Range Distributions of Ions in Polymers ....	146
4.4	Damage Distributions .....	154
4.4.1	Ion-Beam Damage of Polymers .....	154
4.4.2	Experimentally Determined Damage Distributions .....	155
4.4.3	Damage of Polymers by Fast Neutrons .....	160
4.5	Ballistic Sputtering and Mixing .....	162

## 5 Ion Tracks in Polymers

<i>D. Fink</i> .....	171
5.1 Ion-Track Formation .....	171
5.1.1 Early Events of Ion-Track Formation: Projectile Charge State and Track Electrons .....	172
5.1.2 Electronic Ionization and Excitation along the Ion Trajectory: The $\delta$ -ray Model .....	173
5.1.3 Conversion of Electronic Excitation to Atomic Motion ....	175
5.1.4 Distributions of Deposited Energy Density along Tracks ...	178
5.1.5 Damage Cross-Sections and Ion-Track Radii .....	179
5.1.6 Diffusional Approach for Ion-Track Description .....	184
5.1.7 Phase Transitions in Tracks .....	186
5.1.8 Cluster Ion Impact onto Polymers .....	186
5.1.9 Impact of Energetic Ions onto Molecular Clusters .....	188
5.1.10 Statistical Track Distributions .....	189
5.2 Electronic Sputtering .....	190
5.3 Interface Mixing by High-Energy Ion Beams .....	193
5.4 Does There Exist a Universal Scaling for Polymer Modifications? .....	193
5.5 Response of Polymers to Perturbations .....	200

## 6 Surface Tracks and Cratering in Polymers

<i>R.M. Papaléo</i> .....	207
6.1 Introduction .....	207
6.2 Morphology and Metrology of Surface Tracks .....	208
6.3 Cratering Formation and Molecular Dynamics Simulations .....	214
6.4 Dependence on the Angle of Incidence .....	217
6.5 Stopping Power and Velocity Dependence of Surface Tracks .....	218
6.5.1 Crater Volumes versus Total Sputtering Yields .....	222

## XII Contents

6.6	Surface Tracks and Material Properties.....	223
6.6.1	Dependence on Molecular Weight and Viscoelastic Behavior .....	224
6.6.2	Late Relaxation of Surface Tracks and the Glass Transition .....	227
6.6.3	Surface Tracks and Structural-Relaxation Times of Polymers.....	230
6.7	The Nature of the Ejecta: Electronic Sputtering .....	232
6.7.1	Theoretical Aspects .....	232
6.7.2	Mass Spectrometry of Sputtered Particles .....	234
6.7.3	Probing Early Physics and Chemistry of Ion Tracks: Velocity Distributions. and Disappearance Cross-Sections of Fragment Ions .....	237
6.7.4	Carbon-Cluster Emission from Polymers .....	242
6.8	Closing Remarks .....	244

## 7 Ion-Beam Radiochemistry

<i>D. Fink</i> .....	251
7.1 Radiochemical Modification of the Molecular Level .....	251
7.1.1 General Considerations .....	251
7.1.2 Radicals .....	255
7.1.3 Rules-of-thumb for Radiochemical Changes .....	256
7.1.4 Dissolution and Etching.....	258
7.1.5 Peculiarities of Swift Heavy-Ion Radiochemistry .....	259
7.1.6 Electronically and Collisionally Induced Radiochemical Reactions .....	263
7.1.7 Effects at Higher Fluences .....	268
7.2 Special Cases .....	269
7.2.1 Polypropylene (PP).....	269
7.2.2 Polycarbonate (PC) .....	270
7.2.3 Polyethylene (PE) .....	272
7.2.4 Polyethylene Terephthalate (PET).....	272
7.2.5 Polyether Ether Ketone (PEEK) .....	276
7.2.6 Cellulose Nitrate (CN) .....	277
7.2.7 Cellulose Acetates .....	277
7.2.8 Polystyrene (PS) .....	278
7.2.9 Polymethyl Methacrylate (PMMA) .....	279
7.2.10 Fluoroplastics.....	284
7.2.11 Sulfur-Containing Polymers.....	285
7.2.12 Polyimide (PI) .....	287
7.2.13 Polyallyl Diglycoll (PADC) .....	290
7.2.14 Silicon-Based Polymers .....	290
7.3 Cluster-Ion Radiochemistry .....	295
7.4 Ion-Induced Polymerization and Depolymerization .....	295
7.5 Irradiation-Induced Chemical Surface Activation .....	296
7.6 Oxidation and Corrosion of Ion-Irradiated Polymers .....	298

**8 Modifications on the Molecular and Supramolecular Level**

<i>D. Fink, V. Hnatowicz, and P. Yu. Apel</i> .....	309
8.1 Microstructural Changes: An Overview .....	309
8.2 Influence of Ion Irradiation on Polymeric Crystallinity .....	312
8.3 Changes in Free Volume and Density .....	319
8.3.1 Instrumental Detection Capabilities .....	319
8.3.2 Results of Free-Volume Examinations: Low-Energy Ion Irradiation .....	321
8.3.3 Results of Free-Volume Examinations: High-Energy Irradiation .....	323
8.4 High-Fluence Polymer Irradiation .....	325
8.4.1 The Stages of Polymer Decay .....	325
8.4.2 Cluster Formation and Carbonization .....	332
8.4.3 Structural Changes of Irradiated Silicon-Based Polymers .....	340

**9 Macroscopic Changes  
in Ion-Irradiated Polymers**

<i>V. Hnatowicz and D. Fink</i> .....	349
9.1 Changes in Mechanical Properties .....	349
9.1.1 Bulk Changes .....	349
9.1.2 Surface Changes .....	350
9.2 Changes in Chemical Resistance .....	356
9.3 Changes in Optical Properties .....	358
9.3.1 Refractive Index and Absorption .....	358
9.3.2 Luminescence Degrading .....	361
9.4 Changes in Electrical Properties .....	364
9.4.1 Polymeric Conductivity .....	364
9.4.2 Dielectric Properties .....	371
9.4.3 Piezoelectricity .....	373
9.4.4 Ferroelectricity .....	373
9.5 Changes in Thermal Properties .....	374
9.6 Polymer Heating by Ion Impact .....	375

---

**Part III Concluding Remarks**

---

**10 Remaining Open Questions**

<i>D. Fink and R.M. Papaléo</i> .....	385
10.1 New Materials for Ion-Irradiation Studies .....	385
10.2 New Techniques for Examination of Ion-Irradiated Polymers .....	385
10.3 The Physics of Energy Transfer: Stopping and Range .....	386
10.4 The Physics of Energy Transfer: Mixing and Damage .....	386
10.5 Surface Effects in Polymer Irradiation .....	386
10.6 Radiochemical Polymer Modifications .....	387

XIV     Contents

10.7	Structural Changes After Ion Impact .....	388
10.8	Macroscopic Changes After Ion Irradiation .....	388
10.8.1	Mechanical Properties .....	388
10.8.2	Thermal Properties .....	388
10.8.3	Electrical Properties .....	388
10.8.4	Optical Properties .....	389
10.9	A Final Remark .....	389
<b>Appendix A</b> .....		391
<b>Index</b> .....		395



<http://www.springer.com/978-3-540-04027-9>

Fundamentals of Ion-Irradiated Polymers

Fink, D. (Ed.)

2004, XV, 406 p., Hardcover

ISBN: 978-3-540-04027-9