

Table of Contents

1. Introduction (P. Esquinazi)	1
1.1 Tunneling Systems	1
1.2 Content and Organization of the Book	3
2. Heat Release in Solids	
(A. Nittke, S. Sahling, and P. Esquinazi)	9
2.1 A Simple System with Two Levels of Energy	9
2.2 Phenomenological Theory for the Heat Release	12
2.2.1 Generalities	12
2.2.2 The Standard Tunneling Model	14
2.2.3 The Time and Temperature Dependence of the Specific Heat	18
2.2.4 Influence of a Finite Number of Tunneling Systems ..	23
2.2.5 Influence of High-Order Tunneling Processes and a Finite Cooling Rate	24
2.3 The Heat Release Within the Soft-Potential Model	27
2.3.1 The Heat Release and Specific Heat	30
2.3.2 Influence of Thermal Activation	31
2.4 Experimental Details	35
2.4.1 Quasi-static Measurements	35
2.4.2 Calorimetric Measurements	37
2.5 Experimental Results	38
2.5.1 The Time Dependence of the Heat Release	38
2.5.2 The Temperature Dependence of the Heat Release ..	44
2.5.3 Influence of Thermal Activation	45
2.5.4 Correlation Between the Heat Release and Other Low-Temperature Properties	54
2.6 Conclusion and Outlook	55
3. Crossover to Phonon-Assisted Tunneling	
in Insulators and Metals (A. Würger)	57
3.1 Introduction	57

3.2	The Spin-Boson Model	60
3.3	Polaron Transformation and Phonon Dressing	66
3.3.1	Break-Down of Perturbation Theory	67
3.3.2	Canonical Transformation	68
3.3.3	Phonon Dressing	69
3.3.4	Time Evolution	71
3.4	Crossover to Incoherent Tunneling	71
3.4.1	Noninteracting Blip Approximation	72
3.4.2	Nearest-Neighbor Blip Interactions	74
3.4.3	Time Evolution in NIBA	77
3.4.4	Two-State Dynamics Beyond NIBA	83
3.4.5	The Undressing Effect	86
3.4.6	Discussion	87
3.5	Phonon-Assisted Tunneling in Metals	91
3.5.1	Blip Expansion for Zero Asymmetry	91
3.5.2	Coherent Motion	93
3.5.3	The Incoherent Rate	94
3.5.4	Quantum Diffusion of Trapped Hydrogen in Niobium	98
3.5.5	Rate Equations for Large Asymmetry Energy	100
3.5.6	Resistance Fluctuations of Mesoscopic Wires.	103
3.5.7	Discussion	105
3.6	Phonon Dressing in Real Systems	108
3.7	Asymmetric Tunneling Systems	110
3.7.1	Projection Method	111
3.7.2	Approximations.	112
3.7.3	The Damping Kernel.....	114
3.7.4	Crossover to Relaxation	117
3.7.5	Low Temperatures: $T \ll T^*$	117
3.7.6	High Temperatures: $T \gg T^*$	118
3.7.7	How Large is the Maximum Tunnel Energy in Glasses?	119
3.7.8	Sound Propagation in Amorphous Solids Above 5 K ..	122
3.8	Two-State Dynamics for Weak Phonon Coupling	125
3.8.1	Perturbation Series	126
3.8.2	Phase Relaxation: $W(z)$	129
3.8.3	Energy Relaxation: $V(z)$	131
3.8.4	Discussion.	132
3.8.5	Mode-Coupling Approximation (MCA)	133
3.8.6	Comparison of Perturbation Theory and MCA:]	136
3.9	Summary	139
4.	Influence of Tunneling Systems on the Acoustic Properties of Disordered Solids (P. Esquinazi and R. Konig).....	145
4.1	Acoustic Properties and Tunneling Systems	145
4.2	Theoretical Remarks	147
4.2.1	Resonant and Relaxation Processes	147

4.2.2	The Standard Tunneling Model.	
	Relaxation due to Phonons	150
4.2.3	Relaxation due to Conduction Electrons	154
4.2.4	Influence of the Acoustic Intensity	161
4.2.5	'Coherent Coupling Below 100 mK	165
4.2.6	Acoustic Properties Above 1 K: Thermal Activation and Incoherent Tunneling	166
4.3	Experimental Details	168
4.3.1	Experimental Methods for Low and High Frequencies	168
4.3.2	The Vibrating Reed and Vibrating Wire Techniques	170
4.3.3	The Influence of the Clamping	174
4.3.4	Acoustic Experiments at Very Low Temperatures: Cryogenics and Sample Thermalization	176
4.4	Acoustic Properties of Amorphous Solids	178
4.4.1	Dielectrics	178
4.4.2	Normal-Conducting Amorphous Metals	185
4.4.3	Superconductors	191
4.4.4	Influence of Thermal Treatment on the Acoustic Properties of Amorphous Metals	194
4.4.5	Amorphous Thin Films	197
4.5	Acoustic Properties of Polycrystalline Metals	199
4.5.1	General Remarks	199
4.5.2	Polycrystalline Superconductors	200
4.5.3	Normal Metals. The Absence of Electron-Assisted Relaxation in Polycrystals	207
4.5.4	The Influence of Thermal Treatment	215
4.5.5	Acoustic Properties of Polycrystals at $T > 1\text{K}$	217
4.6	On the Origin of Tunneling Systems in Disordered Solids: Conclusion and Perspective	219

5. Interactions Between Tunneling Defects

in Amorphous Solids (A. L. Burin, D. Natelson,

D. D. Osheroff, and Yu. Kagan)	223
5.0.1 Dielectric and Acoustic Properties	223
5.0.2 Interaction Effects: Spectral Diffusion and Dephasing	225
5.1 Interactions and Equilibrium Properties	227
5.1.1 Standard Tunneling Model Predictions	228
5.1.2 Interactions Between Tunneling Systems: Spectral Diffusion	234
5.1.3 Theoretical Approaches to the Relaxation of Tunneling Systems	241
5.1.4 Many-Body Effects and Collective Excitations	242
5.1.5 Interaction-Stimulated Relaxation of Tunneling Systems	250

5.1.6	Equilibrium Acoustic and Dielectric Measurement Techniques	255
5.1.7	Equilibrium Acoustic and Dielectric Loss Data	258
5.1.8	Equilibrium Dielectric Saturation at Very Low Temperatures	261
5.2	Nonequilibrium Effects: Long-Time Relaxations and the Dipole Gap	263
5.2.1	Nonequilibrium Experimental Techniques.	263
5.2.2	Experimental Results	267
5.2.3	Nonequilibrium Behavior: General Remarks	277
5.2.4	Nonequilibrium Behavior Without Interactions Between Tunneling Systems	278
5.2.5	Weak Interactions: The Dipole Gap	279
5.2.6	Discussion of the Experiments	288
5.2.7	Anomalous Hysteretic Behavior and Ultralow Temperatures	292
5.3	On the Universality of the Low-Temperature Properties	295
5.3.1	Basic Facts	296
5.3.2	Significance of $1/R^3$ Interactions	297
5.3.3	The Renormalization Group Model	299
5.3.4	A Key Identity.	301
5.3.5	General Model	304
5.3.6	Tunneling Motion	309
5.3.7	Discussion of the Results.	311
5.4	Conclusion and Remarks	315

**6. Investigation of Tunneling Dynamics
by Optical Hole-Burning Spectroscopy**

(I. Maier, B. M. Kharlamov, and D. Haarer)	317
6.1	Introduction	317
6.2	Optical Spectra of Impurities in Solids	318
6.2.1	Crystals.	318
6.2.2	Amorphous Solids.	322
6.3	Basic Methods of Hole-Burning Spectroscopy	327
6.3.1	Introduction	327
6.3.2	Experimental Techniques	328
6.3.3	Technical Limitations	333
6.4	High-Barrier Versus Low-Barrier Tunneling	338
6.4.1	Photochemical Hole Burning.	338
6.4.2	Nonphotochemical Hole Burning	344
6.4.3	Hole Burning in a Model System: Benzoic Acid	347
6.4.4	Conclusion	351
6.5	Spectral Diffusion: Low-Barrier Tunneling	352
6.5.1	Spectral Diffusion	352
6.5.2	Theoretical Description of Spectral Diffusion	355

6.5.3	Equilibrium Glass Dynamics	358
6.5.4	Long-Time Equilibrium Dynamics: Nonclassical Distribution of Tunneling States	360
6.5.5	Nonequilibrium Glass Dynamics	370
6.6	Conclusion	38 6
7.	Tunneling of H and D in Metals and Semiconductors (G. Cannelli, R. Cantelli, F. Cordero, and F. Trequattrini)	389
7.1	Introduction	389
7.2	Solid Solutions of Hydrogen.	390
7.2.1	The bcc Metals V, Nb and Ta	392
7.2.2	The Rare Earths Sc, Y and Lu	393
7.2.3	Trapping of Hydrogen by Impurities	394
7.3	Experimental Techniques Revealing the Tunneling of Hydrogen	395
7.3.1	Specific Heat	395
7.3.2	Acoustic Measurements	396
7.3.3	Neutron Spectroscopy.	406
7.3.4	Nuclear Magnetic Resonance.	409
7.4	Long-Range Diffusion and Incoherent Hopping of Hydrogen in bcc Metals	411
7.4.1	Theories of Quantum Diffusion	411
7.4.2	The Gorsky Effect: Long-Range Diffusion	413
7.4.3	Hopping of Hydrogen near Interstitial Impurities	416
7.4.4	Hopping of Hydrogen near Substitutional Impurities ..	418
7.5	Coherent Tunneling and Fast Local Motion of Hydrogen.	418
7.5.1	Hydrogen Trapped by Interstitial O,N and C in Nb and Ta: A Two-Level System	418
7.5.2	Hydrogen Trapped by Substitutional Ti and Zr in Nb: Two- and Four-Level Systems	434
7.5.3	Tunneling of H in hcp Rare Earths	449
7.5.4	Motion and Delocalization of Untrapped Hydrogen in Nb, Ta and V	452
7.6	Nonclassical Motion of Hydrogen in Doped Semiconductors.	455
7.7	Conclusion	45 7
8.	Microscopic View of the Low-Temperature Anomalies in Glasses (A. Heuer)	459
8.1	Introduction	459
8.2	Phenomenological Description of the Low-Temperature Anomalies	461
8.2.1	The Tunneling Model	461
8.2.2	Determination of Tunneling Parameters from Experiments	463

XII Table of Contents

8.2.3	Soft-Potential Model	464
8.3	Double-Well Potentials in Computer Simulations	465
8.3.1	The Scope of Computer Simulations in the Present Context	465
8.3.2	Summary of Earlier Simulations	470
8.3.3	Systematic Search of Double-Well Potentials for a Model Glass	471
8.3.4	Application of Different Search Strategies	481
8.3.5	Tunneling Systems in the Presence of Impurities	484
8.3.6	Total Energy Landscape of a Glass-Forming System	487
8.4	Coupling Between Tunneling Systems and Heat Bath	493
8.4.1	Microscopic Origin of the Deformation Potential and the Velocity of Sound	494
8.4.2	Numerical Evaluation of the Deformation Potential	497
8.4.3	Relation Between the Deformation Potential and the Structure of DWP's	498
8.5	Nature of Tunneling Systems Beyond Computer Simulations	503
8.5.1	1D Model Glass	504
8.5.2	Spin Glass Like Model Glass	505
8.5.3	Simple Models of Soft Modes	507
8.6	Universality of the Low-Temperature Parameters	508
8.6.1	Corresponding States	508
8.6.2	Universal Relations for LJ Glasses	509
8.6.3	Application for Different Types of Glasses	512
8.6.4	Quantitative Universality: What Does it Express?	517
8.7	Experimental Hints about the Microscopic Nature of the Soft Modes	519
8.7.1	Relation to Strong and Fragile Glasses	519
8.7.2	Cooling Rate Dependence of TS's	520
8.7.3	The Microscopic Nature of Soft Modes in SiO₂	521
8.7.4	The Properties of Defects	521
8.7.5	Pressure Dependence	522
8.7.6	Length-Scale Dependence	523
8.8	Summary and Outlook	523

9. Beyond the Standard Tunneling Model: The Soft-Potential Model

(M. A. Ramos and U. Buchenau)	527	
9.1	Introduction	527
9.2	Tunneling States and Soft Modes in Glasses	530
9.2.1	Specific Heat	530
9.2.2	Thermal Conductivity	531
9.2.3	Coherent Neutron Scattering	532
9.2.4	Temperature Dependence of Raman and Neutron Scattering	535

9.2.5	Comparison Between Neutron and Specific-Heat Data	537
9.2.6	More Recent Neutron Data	538
9.3	The Soft-Potential Model and its Parameters	541
9.3.1	The Anharmonic Quartic Potential	541
9.3.2	Assumptions	543
9.3.3	Level Splittings and Matrix Elements	544
9.3.4	The Distribution-Limiting Thermal Strain "Ansatz"	548
9.3.5	Other Approaches	550
9.4	Predictions of the Soft-Potential Model	551
9.4.1	Tunneling Density of States in Double-Well Potentials	551
9.4.2	Vibrational Density of States	552
9.4.3	Specific Heat	555
9.4.4	Thermal Conductivity	559
9.4.5	Acoustic Attenuation	564
9.5	Conclusion and Outlook	566
References		57¹
Index		59 2