

SOLID-STATE SCIENCES

B. Lüthi

Physical Acoustics in the Solid State

 Springer

B. Lüthi

Physical Acoustics in the Solid State

With 188 Figures



Springer

Professor Bruno Lüthi
Physikalisches Institut
Universität Frankfurt
D-60054 Frankfurt
E-mail: luethi@physik.uni-frankfurt.de

Series Editors:

Professor Dr., Dres. h. c. Manuel Cardona
Professor Dr., Dres. h. c. Peter Fulde*
Professor Dr., Dres. h. c. Klaus von Klitzing
Professor Dr., Dres. h. c. Hans-Joachim Queisser
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany
* Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Strasse 38
01187 Dresden, Germany

Professor Dr. Roberto Merlin
Department of Physics, 5000 East University, University of Michigan
Ann Arbor, MI 48109-1120, USA

Professor Dr. Horst Störmer
Dept. Phys. and Dept. Appl. Physics, Columbia University, New York, NY 10027 and
Bell Labs., Lucent Technologies, Murray Hill, NJ 07974, USA

ISSN 0171-1873

ISBN 3-540-22910-8 Springer Berlin Heidelberg New York

Library of Congress Control Number: 2004111958

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media.
springeronline.com

© Springer-Verlag Berlin Heidelberg 2005
Printed in Germany

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Production and Typesetting: PTP-Berlin Protago-TeX-Production GmbH, Germany
Cover concept: eStudio Calamar Steinen
Cover production: *design & production* GmbH, Heidelberg

Printed on acid-free paper SPIN: 10980897 57/3141/YU - 5 4 3 2 1 0

Preface

This book gives an up to date survey of acoustic effects in the Solid State. After a review of the different experimental techniques and an introduction to the theory of elasticity, emphasizing the symmetry aspects, applications are given for the different fields of condensed matter physics. These applications include metals and semiconductors, superconductivity, unstable magnetic moments including heavy fermion physics, magnetism, structural and magnetic phase transitions, low dimensional systems, amorphous systems and symmetry related experiments. The main emphasis is on more recent developments not covered in books written 30 years ago. Actually, acoustic experiments have been performed in all modern fields of solid state physics.

Acknowledgments

Various chapters of the book were read by different colleagues: Wolfram Brenig, Peter Fulde, Ute Löw, Bernd Wolf and Sergei Zherlitsyn. I would like to thank them for their helpful remarks and constructive criticism. Part of the book was written while the author was staying at the Max Planck Institutes in Dresden. I would like to thank Frank Steglich and Peter Fulde for the hospitality and many discussions. Much of the work presented here has been developed with students, postdoctoral fellows and colleagues. I would like to thank all of them for their contributions, their help and for sharing their insights. Finally I would like to thank Bernd Wolf for his help during all stages of the project, in particular with the figures. I also would like to thank Carolyne and Malcolm Agnew for their help on the final layout in the L^AT_EX version.

Frankfurt am Main, July 2004

Bruno Lüthi

Contents

1	Introduction	1
2	Experimental Techniques	5
2.1	Transducer	6
2.2	Sound Velocity and Attenuation, Experimental Techniques	7
2.2.1	Simple Ultrasonic Set-Up	7
2.2.2	Relative Sound Velocity and Attenuation Changes	9
2.2.3	Ultrasonics at Very Low Temperatures	11
2.2.4	Absolute Sound Velocity Measurements	12
2.2.5	Resonant Ultrasound Spectroscopy, RUS	14
2.2.6	Vibrating Reed Technique	16
2.3	Phonon Echoes	16
2.4	Ultrasonics in Pulsed Magnetic Fields	17
2.5	Surface Acoustic Wave Generation and Detection	20
2.6	Microwave Ultrasonics	21
2.7	Brillouin Scattering	23
2.8	Thermal Expansion and Magneto-striction, Thermal Conductivity	25
2.8.1	Thermal Expansion and Magneto-striction	25
2.8.2	Thermal Conductivity	25
3	Elasticity	27
3.1	Strains, Stresses and Elastic Constants	27
3.2	Symmetry Aspect	32
3.3	Third Order Elastic Constants	36
3.4	Elastic Stability, Elastic Isotropy	37
3.5	Surface Acoustic Waves, SAW	39
3.6	Lattice Dynamics	44
3.6.1	Phonon Dispersion	44
3.6.2	Debye Theory of Lattice Dynamics	45
4	Thermodynamics and Phase Transitions	47
4.1	Thermodynamic Potentials	47
4.2	Background Elastic Constant and Attenuation	49
4.2.1	Background Elastic Constant, Thermal Expansion and Specific Heat	49

4.2.2	Sound Dissipation Due to Phonons in Insulators.....	52
4.3	Landau Theory, Strain-Order Parameter Coupling.....	52
4.3.1	Landau Theory for Second Order Phase Transitions ..	53
4.3.2	Scaling Relations	54
4.3.3	Landau Theory for a First Order Phase Transition....	55
4.3.4	Strain-Order Parameter Coupling	56
4.3.5	Fluctuation Effects	59
4.3.6	Landau-Khalatnikov Theory	60
4.4	Ginzburg Criterion and Marginal Dimensionality	62
4.5	Adiabatic and Isothermal Quantities	63
5	Acoustic Waves in the Presence of Magnetic Ions	67
5.1	Strain-Magnetic Ion Interaction	67
5.1.1	Magnetic Interactions	68
5.1.2	Single Ion-Strain Interaction.....	70
5.1.3	Exchange Striction	72
5.2	Thermodynamic Functions for 4f-Rare Earth Ions in the Presence of Crystal Fields	73
5.2.1	Specific Heat and Thermal Expansion.....	75
5.2.2	Magnetic Susceptibility and Elastic Constants	77
5.2.3	Other Experimental Methods to Determine Magneto-elastic Coupling Constants	80
5.2.4	Magneto-elastic Coupling Constants	80
5.3	Susceptibilities with Interactions	82
5.4	External and Internal Strains	83
5.5	Paramagnetic Spin-Phonon Interaction for 3d-Transition Metal Ions in Crystals	87
5.6	Nuclear Acoustic Resonance	91
6	Ultrasonics at Magnetic Phase Transitions	93
6.1	Magnetic Phase Transition	94
6.1.1	Spin-Phonon Coupling Mechanism	94
6.1.2	Critical Attenuation Coefficient	95
6.1.3	Sound Velocity Effects near Magnetic Phase Transitions	101
6.2	Spin Reorientation Phase Transition	103
6.3	Sound Propagation in the Spin-Density Wave Anti-ferromagnet Chromium	106
7	Ultrasonics at Structural Transitions	109
7.1	Charge Order	110
7.2	Cooperative Jahn-Teller Effect and Quadrupolar (Orbital) Transition	119
7.2.1	Case of Transition Metal Compounds	121
7.2.2	Case of Rare Earth Compounds	125
7.2.3	Case of Actinide Compounds	139

7.2.4	Effective Quadrupole-Quadrupole Interaction	144
7.2.5	Summary	146
7.3	Ferro-elastic and Martensitic Phase Transitions	147
7.4	Other Structural Phase Transitions	151
7.4.1	Piezo-distortive Ferro-electrics	151
7.4.2	Other Non-electronic Compounds	151
7.4.3	Strain Is Not Order Parameter	152
7.4.4	Conclusion	156
8	Metals and Semiconductors	157
8.1	Deformation Potential Coupling	157
8.2	Elastic Constants and Ultrasonic Attenuation, Case of $ql_e < 1$	159
8.2.1	Electronic Redistribution Mechanism	159
8.2.2	Alpher-Rubin Effect in Magnetic Fields	164
8.3	Ultrasonic Propagation, Case of $ql_e > 1$	166
8.3.1	Ultrasonic Attenuation and Dispersion	166
8.3.2	Geometric Resonances	167
8.4	Magneto-acoustic Quantum Oscillations	169
8.4.1	Theory	169
8.4.2	Applications	172
8.5	Ultrasonics in Semiconductors and Semimetals	177
8.5.1	Inter-valley Scattering Effect	177
8.5.2	Acousto-electric Effect	177
8.5.3	Sound Wave Amplification in Piezoelectric Semiconductors	178
8.5.4	Ultrasonic Amplification in Bismuth	179
9	Unstable Moment Compounds	181
9.1	Experimental Characterisation	183
9.1.1	Mixed Valence Compounds	183
9.1.2	Kondo Alloys and Kondo Lattices	184
9.2	Electron-Lattice Coupling in Mixed-Valence Systems	187
9.3	Electron-Phonon Coupling in Heavy Fermion Systems	196
9.3.1	Introduction	196
9.3.2	Kondo Volume Collapse	198
9.3.3	Special Sound Propagation Effects for Large Ω	199
9.3.4	Scaling Approach for the Temperature Dependence of Thermal Quantities	202
9.3.5	Sound Wave Effects in Magnetic Fields, Meta-magnetic Transition	213
9.3.6	Non-Fermi Liquid Effects	219
10	Ultrasonics in Superconductors	223
10.1	Introduction	223
10.2	Electron-Strain Coupling in Superconductors	225

10.2.1 Elastic Constants	226
10.2.2 Ultrasonic Attenuation	227
10.3 Conventional Superconductors	229
10.4 High Temperature Superconductors	237
10.5 Sound Wave Interaction with the Flux Line Lattice	241
10.6 Ultrasonic Surface Wave Attenuation in Superconductors	246
10.7 Unconventional Superconductivity	247
10.7.1 Heavy Fermion Superconductivity	249
10.7.2 Other Unconventional Superconductors	264
10.7.3 Other Methods to Probe the Energy Gap Structure	267
10.7.4 Summary	268
11 Coupling to Collective Excitations	271
11.1 Plasmons and Helicons	271
11.1.1 Dielectric Tensor	271
11.1.2 Plasma Polariton	272
11.1.3 Helicons and Alfven Waves	274
11.1.4 Helicon-Phonon Interaction	275
11.2 Magneto-elastic Waves	277
11.2.1 Ferromagnetic Spinwaves with Dipolar Interaction	277
11.2.2 Magneto-static Modes	279
11.2.3 Spinwave-Phonon Interaction	280
11.2.4 Magneto-elastic Gap	282
11.2.5 Experiments with Magneto-elastic Waves in a Ferrimagnet	284
11.2.6 High Power Level Effects	286
11.2.7 Sound Wave Experiments in Anti-ferromagnets	286
12 Ultrasonics in Low Dimensional Spin and Electronic Peierls-Systems	291
12.1 Magnetic Properties of Low Dimensional Spin Systems	293
12.1.1 Uniform Chain	293
12.1.2 Dimerized Chains	295
12.2 Temperature Dependence of Elastic Constants in Low Dimensional Spin Systems	300
12.2.1 Temperature Dependence of Elastic Constants in Quasi One-Dimensional Spin Systems	300
12.2.2 Case of Two-Dimensional Dimer Spin Systems	303
12.3 Magnetic Field Effects	309
12.4 Thermal Conductivity in Low Dimensional Spin Systems	319
12.5 Peierls and Spin Peierls Effects	323
12.6 Perovskite-Type Layer-Structure Materials	326
12.7 Bose-Einstein Condensation of Magnons in TiCuCl_3	328
12.8 Conclusion	328

13 Symmetry Effects with Sound Waves	331
13.1 Magnetic Field Induced Symmetry Breaking	332
13.2 Rotationally Invariant Magneto-elastic Effects	335
13.3 Magneto-acoustic Birefringence Effects	340
13.3.1 Voigt–Cotton–Mouton Geometry	341
13.3.2 Faraday Geometry	343
13.4 Acoustical Activity	346
13.5 Non-reciprocal Surface Acoustic Wave Effects	347
13.6 Surface Acoustic Wave Effects in the Integral and Fractional Quantum Hall Effect	351
14 Ultrasonic Propagation in Tunneling Systems	357
14.1 Crystalline Systems	357
14.2 Amorphous Systems	360
14.3 Recent Developments	363
14.4 Spin-Glass	364
14.5 Quasi-crystals	364
15 Conclusion and Outlook	367
Appendix	369
A Mass Systems and Units	369
B Wave Equation for Sound Waves	371
C Elastic Constants and Symmetry Strains for the Crystal Classes	373
D g-Factor, Steven's Factors, CEF Operators	375
D.1 3d and 4f Ions: Landé g_J Factor, Steven's Factors	375
D.2 Cubic CEF and Quadrupolar Operators	376
E Ultrasonic Attenuation in Metals	377
F Free Energy of Electrongs	379
G Order–Disorder Phase Transition	381
References	383
Index	419
Index of Materials ...	423

1 Introduction

Books on physical acoustics are numerous. A series of volumes on "Physical Acoustics, Principles and Methods" by W.P. Mason [1.1] and later editors have been available since 1964. In addition, there are monographs on the same topics: "Ultrasonic Methods in Solid State Physics" by Truell et al. [1.2], "Physical Ultrasonics" by Beyer and Letcher [1.3], "Microwave Ultrasonics in Solid State Physics" by Tucker and Rampton [1.4]. But since these latter books were written more than 30 years ago, it is time to present a new account of the field.

The precise aim of this book is to present a modern account of the field. The emphasis is also slightly changed. The aspects of traditional elasticity theory are only treated briefly since they can be found in the books and treatises mentioned above and in books devoted solely to elasticity. Examples of such books are Love [1.5], Kolsky [1.6] and the standard texts on theoretical physics such as Landau Lifshitz [1.7] etc. Physical acoustics embraces the measurements of ultrasonic velocity and attenuation. The elastic constants can be gained from the ultrasonic velocities. The elastic constants are thermodynamic derivatives, the second derivative of the free energy with respect to the strains. Therefore, they are connected with the atomic and molecular bonding in the crystal. They are important, together with the specific heat and thermal expansion, for the equation of the state of a material. On the other hand the attenuation, as a transport coefficient, is connected with dissipation. It is affected by defects and inhomogeneities of the solid and more fundamentally by conduction electrons, inner (f-)electrons, thermal phonons and other relaxation processes.

This book aims to show what can be learnt about "solid state physics" using ultrasonic waves. Therefore the main objects of investigation are fields such as electron-phonon coupling in metals and semiconductors, ultrasonic effects in superconductors, spin-phonon interaction in paramagnetic and magnetic systems, phonon coupling to collective excitations and sound propagation effects near phase transitions. Of course, modern aspects of all these effects are specially treated at the expense of older treatments. The symmetry aspects are emphasized whenever possible.

Since the late 1960s and early 1970s, new fields in solid state physics have appeared. Examples are "low dimensional physics", including "low dimensional spin physics", or "unconventional superconductivity", or new types of

structural phase transitions like “charge ordering” and “cooperative Jahn–Teller transitions” or “mixed valency and heavy fermions” and finally the exciting field of two-dimensional electron systems, including the quantum Hall effect, and others. These new topics, in which ultrasonics has also played an important role, will be treated in detail. In semiconductors, there are the heterostructure materials GaAs/GaAlAs which exhibit integer and fractional quantum Hall effects. For the latter case, surface acoustic waves played an important role in characterising ground and excited states. Finally much work has been done in characterising non-crystalline solids with ultrasound. The important experiments done with ultrasonics for tunneling state systems in various materials, crystalline and non-crystalline, such as glasses will be discussed briefly.

All these new topics listed can be put together under the title “highly correlated electronic systems”. Whereas in former years in Solid State Physics, single particle phenomena were mainly studied, in recent years the focus has shifted to correlated electronic systems. It is therefore important to know what can be learned about these systems with ultrasonic methods. Various chapters in this book focus especially on this topic (Chaps. 7, 9, 10, 12–14).

On viewing the table of contents, it can be seen that virtually all sections of solid state physics occur in this book, indicating that acoustic techniques play an important role in this part of physics. It should also be mentioned what has been left out of this book. From the title of the book, it is clear that of the whole area of condensed matter physics it is only the solid state which is being treated. Important fields, like the liquid state, have been left out. In the liquid state, there are various subjects where ultrasonics plays an important role: Liquid Helium as He^4 or He^3 . In these quantum liquids, acoustic experiments played a decisive role in determining and interpreting the different phases (see e.g. Vollhardt and Wölfle [1.8]). Another important field in the liquid state is that of liquid crystals, where ultrasonics again made important contributions in the so-called nematic, cholesteric and smectic liquid crystals (see e.g. Stephen and Straley [1.9], de Gennes and Prost [1.10]). Other topics related to ultrasonics and microwave acoustics are the different methods of studying transport properties with the use of ballistic heat pulses. This technique has widespread applications, especially for well-characterised insulators. Contact with this field will be rare. Reviews on these topics are Wolfe [1.11]), Bron [1.12].

Non-dissipative sound attenuation in solids – i.e. sound scattering from imperfections like grain boundaries or diffraction losses from diffraction effects from the transducers or due to nonparallellicity of the crystal or due to mode conversion on the surface etc. – will only be mentioned occasionally. Also dislocation damping in all its different manifestations (point defect relaxation, Snoek relaxation, Zener relaxation, dislocation motion or eddy current effects) have been investigated in the early treatises and will not be covered in this text. See for the latter effects e.g. Nowick and Berry [1.13]).

The cgs-Gauss mass system is mostly used in this book since in the solid-state physics literature this mass system is used. Changes to the SI system or tables for units can be found in Appendix A.

An introduction to the field is given in the first three chapters. Experimental techniques are described in Chap. 2. The emphasis is especially on new developments that have not been covered in previous books on ultrasonics cited above. These new developments are e.g. resonant ultrasonic spectroscopy, ultrasonics in high pulsed magnetic fields, high resolution Brillouin scattering. Chapter 3 introduces elasticity emphasizing the symmetry aspects which are not covered in other books. Chapter 4 presents the necessary background of thermodynamics with the thermodynamic potentials and functions. The Landau theory of phase transitions and the range of its validity is also presented. The following Chaps. 5–14 cover the full range of the various applications in solid state physics.

This book is intended for all those who want to know what can be learned from ultrasonics about the solid state. I hope to give an updated account of this field. Graduate students and researchers in the field of physical acoustics or related fields, should also benefit from this book. Since the whole outlook of the book is based on Solid State Physics some books on this topic are listed for the reader: "Solid State Physics" by Ashcroft and Mermin [1.14], "Festkörperphysik" by Ibach and Lüth [1.15], "Introduction to Solid State Physics" by Kittel [1.16]. Recently a "Handbook of Elastic Properties of Solids, Liquids and Gases" (Editors: M. Levy, H.E. Bass, R.R. Stern) appeared placing emphasis on measuring methods and surveys on quite different materials (elements, novel materials, building materials). The outlook of this handbook is quite different to the one given in the present book.

2 Experimental Techniques

A discussion follows on the various experimental techniques used for ultrasonic investigations. In the last few decades, considerable progress has been made in the field of high resolution sound velocity and sound attenuation measurements. A wide variety of different methods are used in this field. A distinction can be made between techniques which use transducers and others which are contact free methods. To the latter ones belong the vibrating reed technique and the Brillouin scattering. Numerous books and review articles describe all these topics.

In the low frequency regime, where the sound wavelength is of the dimension of the specimen, the elastic moduli (Young's modulus E and shear modulus G) can be determined by a c.w. resonance method or by measuring flexural and torsional oscillations. At audio frequencies the vibrating reed technique is most frequently applied (Read et al. [2.1]). A brief account of this technique is given in Sect. 2.2.5. In the ultrasonic regime, the elastic constants c_{ij} can be determined by using pulse or c.w. techniques (Truell et al. [2.2], Bolef and Miller [2.3], Fuller et al. [2.4]). The most widely used method to measure sound velocity and attenuation is the pulse superposition technique or variations of it (Truell et al. [2.2], Fuller et al. [2.4]). A particularly interesting method is the shape resonance technique, also called resonant ultrasound spectroscopy (RUS), suitable for small crystals and low symmetry crystals (Migliori and Sarrao [2.5]). This technique will be discussed together with phase sensitive sound velocity and attenuation measurements in Sect. 2.2. In Sect. 2.3 a short account of phonon echoes will be given. In Sect. 2.4 ultrasonics in pulsed high magnetic field will be described. Apart from the low frequency and the ultrasonic regime, sound waves can also be generated in the microwave region (Tucker and Rampton [2.6]). A method which was used for various applications is the excitation of microwave sound at surfaces in microwave cavities. This will be discussed in Sect. 2.6. The excitation and detection of acoustic surface waves SAW will be discussed in Sect. 2.5. Finally, in Sect. 2.7, the Brillouin scattering will be mentioned. Thermal expansion and magneto-striction experiments are important to determine the length changes with temperature or magnetic field. Apart from this they are important thermodynamic functions in their own right. The experimental technique for these quantities and for measuring thermal conductivity will be discussed in Sect. 2.8. We begin with a discussion of ultrasonic transducers in Sect. 2.1.

2.1 Transducer

Several techniques are in use to generate and to detect ultrasonic waves. The most common one is to use piezoelectric transducers. But also magnetostrictive transducers or electromagnetic generation and detection of sound can be used in special cases. A brief review of the different techniques to generate and detect sound waves follows and some review articles where more details can be found are named.

With the strains and stresses defined in Chap. 3, the piezoelectric effect gives a stress-strain electric field relation

$$T_i = c_{ik}\varepsilon_k - e_{ij}E_j. \quad (2.1)$$

Here we use already the contracted Voigt notation, see Sect. 3.1 (11 \rightarrow 1, 22 \rightarrow 2, 33 \rightarrow 3, 23 \rightarrow 4, 13 \rightarrow 5, 12 \rightarrow 6) for the stress tensor T_{ij} and the strain tensor ε_{ij} . c_{ij} are the elastic constants and e_{ik} the piezoelectric stress coefficients. The inverse relation reads

$$\varepsilon_i = s_{ik}T_k + d_{ij}E_j \quad (2.2)$$

with s_{ik} a component of the compliance tensor. The piezoelectric matrix in contracted notation is given by (e_{ij}) with $i = 1, 2, 3$ (3 directions) and $j = 1, \dots, 6$ (six components of the stress tensor). For quartz (SiO_2) it has the form

$$[e_{ij}] = \begin{pmatrix} e_{11} - e_{11} & 0 & e_{14} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -e_{14} & -2e_{14} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

with $e_{11} = 0.171C/\text{m}^2$, $e_{14} = 0.0403C/\text{m}^2$ with C dimension of Coulomb (Appendix A). For LiNbO_3 the corresponding components read:

$$[e_{ij}] = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & -e_{22} \\ -e_{22} & e_{22} & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix}$$

with $e_{15} = 3.65C/\text{m}^2$, $e_{22} = 2.39C/\text{m}^2$, $e_{31} = 0.31C/\text{m}^2$, $e_{33} = 1.72C/\text{m}^2$ (Ogi et al. [2.7]).

For an X -cut quartz an electric field in the x -direction produces a strain in the same direction, therefore producing longitudinal waves. With the parameters for quartz, the longitudinal elastic constant $c_{11} = 8.6 \times 10^{11} \text{erg}/\text{cm}^3$, the piezoelectric constant $e_{11} = 0.171 \frac{C}{\text{m}^2}$ and with a typical applied electric field value of $E_x = 10 \text{V}/\text{mm}$, the stress is given by $T_1 = e_{11}E_x = 1.71 \text{CV}/\text{m}^3$ and the strain by $\varepsilon_1 = \varepsilon_{xx} = T_1/c_{11} = 0.2 \times 10^{-6}$ - a rather small strain. This would be the maximum strain for a longitudinal sound wave in the x -direction for the typical applied ac electric field. Likewise, shear waves may be generated with a Y -cut crystal. The purest shear mode with a minimum of

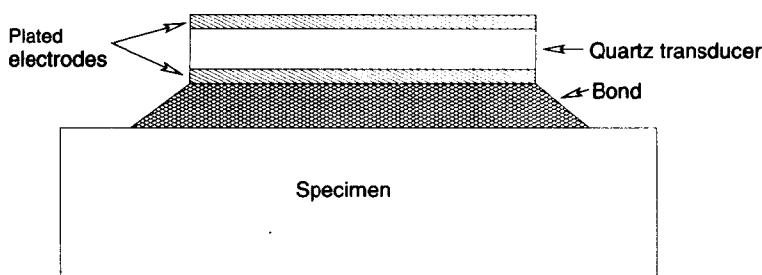


Fig. 2.1. Transducer-Bond-Specimen arrangement

coupling to other modes is the so-called AC-cut quartz crystal, a cut rotated by 31° about the x -axis.

Further details on these transducers can be found in Mason [2.8]. Another transducer material is LiNbO_3 with larger piezoelectric coupling constants as shown above. With these transducers, the resonance frequency or odd integer multiples thereof are used.

In addition, there are piezoelectric polymer foils with high efficiency. They can be used non-resonantly over a large frequency range. They are especially suited for longitudinal waves. All these transducers have to be bonded to the specimen with plane parallel polished faces (see Fig. 2.1). Thiokol LP, GE cement, Nonaq or UHU cement can be used as bond materials. If thin film technology is used, transducers, such as ZnO or CdS, can be evaporated or sputtered directly on to the specimen without a bond in between. Details on this fabrication technology can be found in Foster [2.9]. This thin film technique is also important for surface acoustic waves as discussed in Sect. 2.5. Problems arising with the different types of transducers for measuring ultrasonic velocity and attenuation are discussed in Sect. 2.2.

Apart from piezoelectric transducers, there have been studies also on magneto-strictive transducers and on electromagnetic generation of ultrasound. The latter ones have been carried out in metals, ferromagnets and various magnetic materials. Since these techniques have little technical application, no further details are given here but some relevant reviews are: Dobbs [2.10], Buchelnikov and Vasil'ev [2.11], Gorodetsky et al. [2.12].

2.2 Sound Velocity and Attenuation, Experimental Techniques

2.2.1 Simple Ultrasonic Set-Up

A simple ultrasonic system for producing stress waves is now discussed. In Fig. 2.1 we show the transducer-sample system. The (piezoelectric) transducer with electrodes on both sides is bonded to the specimen with parallel

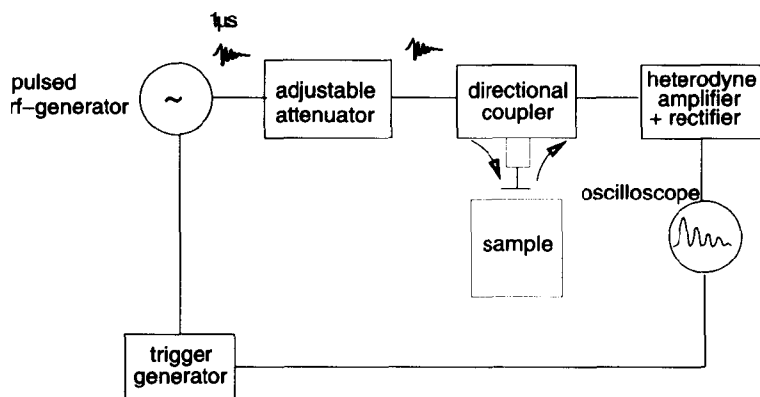


Fig. 2.2. Ultrasonic system to measure sound velocity and attenuation

end faces. For the choice of bond materials see Sect. 2.1. A pulsed electromagnetic signal of $\sim 1 \mu\text{s}$ duration, operating at the fundamental frequency of the transducer or at one of its odd harmonics, is applied across the transducer. With the piezoelectric effect, a stress wave is produced which propagates through the specimen.

In the single transducer arrangement of Fig. 2.2, the same transducer acts as a receiver. Upon reflection on the surface, a small amount of energy is converted back to an electric pulse. The major part of the pulse is reflected and propagates further, producing an ultrasonic echo pattern as shown e.g. in Fig. 2.5a. The converted electric pulse is amplified (with homodyne or heterodyne amplifiers) and shown on the oscilloscope. To investigate a wide frequency range, transducers can be used on both opposite faces of the sample (emitter and receiver) – this does not need a directional coupler. In the following, we discuss phase sensitive devices to measure ultrasonic velocity and attenuation with high accuracy.

A distinction can be made between pulse echo techniques and cw-techniques. In the latter case, the transmitting transducer is driven continuously and a resonant response is observed at frequencies which correspond to $L = n\frac{\lambda}{2}$ with L the sample length and λ the wavelength of the sound. The ultrasonic wave velocity is determined from the resonant frequencies with transducer corrections included. The attenuation follows from the quality factor Q of the resonance signals. In the following, we discuss a special phase-sensitive ultrasonic set-up, absolute sound velocity measurements, the so-called Resonant Ultrasonic Spectroscopy (RUS) and the vibrating reed technique.