

Woodhead Publishing Series in Electronic and Optical Materials:
Number 29

Ultrasonic transducers

Materials and design for sensors,
actuators and medical applications

Edited by
K. Nakamura

Oxford Cambridge Philadelphia New Delhi

© Woodhead Publishing Limited, 2012

Contents

<i>Contributor contact details</i>	<i>xiii</i>
<i>Woodhead Publishing Series in Electronic and Optical Materials</i>	<i>xvii</i>
<i>Preface</i>	<i>xxi</i>
Part I Materials and design of ultrasonic transducers	1
1 Piezoelectricity and basic configurations for piezoelectric ultrasonic transducers S. COCHRAN, University of Dundee, UK	3
1.1 Introduction	3
1.2 The piezoelectric effect	4
1.3 Piezoelectric materials	13
1.4 Piezoelectric transducers	20
1.5 Summary, future trends and sources of further information	31
1.6 References	33
2 Electromagnetic acoustic transducers G. HÜBSCHEN, Fraunhofer Institute for Non-Destructive Testing (IZFP), Germany	36
2.1 Introduction	36
2.2 Physical principles	36
2.3 Lorentz-force-type transducers	41
2.4 Magnetostriction-type transducers	60
2.5 Conclusion	66
2.6 References	66
3 Piezoelectric ceramics for transducers K. UCHINO, The Pennsylvania State University, USA and Office of Naval Research – Global, Japan	70
3.1 The history of piezoelectrics	70
3.2 Piezoelectric materials: present status	88
3.3 References	114

v

vi	Contents	
4	Thin-film PZT-based transducers M. K. KUROSAWA, Tokyo Institute of Technology, Japan	117
4.1	Introduction	117
4.2	PZT deposition using the hydrothermal process	118
4.3	Applications using the bending and longitudinal vibration of the d_{31} effect	127
4.4	Thickness-mode vibration, d_{33}	140
4.5	Epitaxial film	150
4.6	Conclusions	151
4.7	References	151
5	High-Curie-temperature piezoelectric single crystals of the $\text{Pb}(\text{In}_{1/2}\text{Nb}_{1/2})\text{O}_3\text{-Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ ternary system Y. YAMASHITA, Toshiba Research Consulting Corporation, Japan and Y. HOSONO, Toshiba Corporation, Japan	154
5.1	Introduction	154
5.2	PIMNT ceramics	157
5.3	PIMNT single crystals grown by the flux method	163
5.4	PIMNT single crystals grown by the Bridgman method	165
5.5	Recent research into PIMNT single crystals and their applications	175
5.6	Future prospects and tasks	177
5.7	Conclusions	179
5.8	References	180
	Part II Modelling and characterisation of ultrasonic transducers	185
6	Modelling ultrasonic-transducer performance: one-dimensional models S. COCHRAN and C. E. M. DÉMORÉ, University of Dundee, UK and C. R. P. COURTNEY, University of Bristol, UK	187
6.1	Introduction	187
6.2	Transducer performance expressed through the wave equation	188
6.3	Equivalent electrical circuit models	195
6.4	The linear systems model	202
6.5	Examples	205
6.6	Summary, future trends and sources of further information	216
6.7	References	218

7	The boundary-element method applied to micro-acoustic devices: zooming into the near field A. BAGHAJ-WADJI, RMIT University, Australia	220
7.1	Introduction	220
7.2	The acoustic wave equation: shear horizontal vibrations	221
7.3	Construction of infinite-domain Green's functions	224
7.4	Near-field analysis	239
7.5	Normalization of the field variables	249
7.6	Determining the asymptotic expansion terms for $\eta \rightarrow 0$	250
7.7	Future trends	258
7.8	Key references for further reading	260
7.9	Acknowledgements	261
7.10	References	261
8	Electrical evaluation of piezoelectric transducers K. NAKAMURA, Tokyo Institute of Technology, Japan	264
8.1	Introduction	264
8.2	Equivalent electrical circuit	265
8.3	Electrical measurements	267
8.4	Characterization of piezoelectric transducers under high-power operation	271
8.5	Load test	274
8.6	Summary	275
8.7	References	276
9	Laser Doppler vibrometry for measuring vibration in ultrasonic transducers M. JOHANSMANN and G. WIRTH, Polytec GmbH, Germany	277
9.1	Introduction	277
9.2	Laser Doppler vibrometry for non-contact vibration measurements	278
9.3	Characterization of ultrasonic transducers and optimization of ultrasonic tools	286
9.4	Enhanced LDV designs for special measurements	303
9.5	Conclusion and summary	312
9.6	References	312
10	Optical visualization of acoustic fields: the schlieren technique, the Fresnel method and the photoelastic method applied to ultrasonic transducers K. YAMAMOTO, Kansai University, Japan	314
10.1	Introduction	314

viii	Contents	
10.2	Schlieren visualization technique	314
10.3	Fresnel visualization method	320
10.4	Photoelastic visualization method	323
10.5	References	327
Part III Applications of ultrasonic transducers		329
11	Surface acoustic wave (SAW) devices K. HASHIMOTO, Chiba University, Japan	331
11.1	Introduction	331
11.2	Interdigital transducers (IDTs)	332
11.3	Transversal SAW filter	351
11.4	SAW resonators	362
11.5	Conclusions	371
11.6	References	371
12	Airborne ultrasound transducers D. A. HUTCHINS, University of Warwick, UK and A. NEILD, Monash University, Australia	374
12.1	Introduction	374
12.2	Basic design principles	375
12.3	Transducer designs for use in air	381
12.4	Radiated fields in air	385
12.5	Applications	392
12.6	Future trends	402
12.7	Sources of further information and advice	403
12.8	Acknowledgements	403
12.9	References	404
13	Transducers for non-destructive evaluation at high temperatures M. KOBAYASHI and C.-K. JEN, Industrial Materials Institute, Canada	408
13.1	Transducers for non-destructive evaluation at high temperatures	408
13.2	Sol-gel composite ultrasonic transducers	411
13.3	Structural-health monitoring demonstration	422
13.4	Process-monitoring demonstration	433
13.5	Conclusions	440
13.6	Sources of further information	441
13.7	References	441

14	Analysis and synthesis of frequency-diverse ultrasonic flaw-detection systems using order statistics and neural network processors J. SANJIE and E. ORUKLU, Illinois Institute of Technology, USA	444
14.1	Introduction	444
14.2	Ultrasonic flaw-detection techniques	445
14.3	Neural network detection processor	456
14.4	Flaw-detection performance evaluation	460
14.5	System-on-a-chip implementation – a case study	465
14.6	Future trends	472
14.7	Conclusions	473
14.8	Further information	474
14.9	References	474
15	Power ultrasonics: new technologies and applications for fluid processing J. A. GALLEGRO-JUÁREZ, Spanish National Research Council (CSIC), Spain	476
15.1	Introduction	476
15.2	New power ultrasonic technologies for fluids and multiphase media	478
15.3	Application of the new power ultrasonic technology to processing	490
15.4	Conclusions	513
15.5	Acknowledgements	514
15.6	References	514
16	Nonlinear acoustics and its application to biomedical ultrasonics P. A. LEWIN, Drexel University, USA and A. NOWICKI, Polish Academy of Sciences, Poland	517
16.1	Introduction	517
16.2	Basic aspects of nonlinear acoustic wave propagation and associated phenomena	518
16.3	Measurements of and advances in the determination of B/A	519
16.4	Advances in tissue harmonic imaging	523
16.5	Nonlinear acoustics in ultrasound metrology	531
16.6	Nonlinear wave propagation in hydrophone probe calibration	534
16.7	Nonlinear acoustics in therapeutic applications	538
16.8	Conclusions	539
16.9	Acknowledgements	540
16.10	References	540

x	Contents	
17	Therapeutic ultrasound with an emphasis on applications to the brain P. D. MOURAD, University of Washington, USA	545
17.1	Introduction and summary	545
17.2	Fundamentals of propagation and absorption of ultrasound	547
17.3	Acoustic attenuation as absorption plus scattering	548
17.4	Physical and chemical processes engendered by medical ultrasound	549
17.5	Bubble formation and growth	551
17.6	Inertial cavitation and associated material stresses	554
17.7	Mechanical index	554
17.8	Diagnostic ultrasound	555
17.9	Therapeutic ultrasound	560
17.10	Ultrasound-facilitated delivery of drugs and antibodies into the brain	563
17.11	Neuromodulation by ultrasound	566
17.12	Conclusion	567
17.13	References	568
18	Microscale ultrasonic sensors and actuators A. RAMKUMAR and A. LAL, Cornell University, USA	572
18.1	Introduction: ultrasonic horn actuators	572
18.2	Advantages of silicon-based technology	574
18.3	Silicon ultrasonic horns	580
18.4	Sensor integration and fabrication of silicon horns	584
18.5	Planar electrode characterization	586
18.6	Piezoresistive strain gauges	592
18.7	Applications: tissue penetration force reduction	597
18.8	Applications: cardiac electrophysiological measurement	602
18.9	Applications: microscale tissue metrology in testicular sperm extraction (TESE) surgery	606
18.10	Conclusions	614
18.11	References	615
19	Piezoelectric and fibre-optic hydrophones A. HURRELL, Precision Acoustics Ltd, UK and P. BEARD, University College London, UK	619
19.1	Introduction	619
19.2	General hydrophone considerations	620
19.3	Piezoelectric hydrophones	626
19.4	Fibre-optic hydrophones	641
19.5	Summary	671
19.6	References	673

20	Ultrasonic motors K. NAKAMURA, Tokyo Institute of Technology, Japan	677
20.1	Introduction	677
20.2	Standing-wave ultrasonic motors	678
20.3	Traveling-wave ultrasonic motors	694
20.4	Ultrasonic motor performance	700
20.5	Summary and future trends	702
20.6	References	703
	<i>Index</i>	705