Internal Friction and Mechanical Spectroscopy

Edited by
R. Schaller and D. Mari

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Internal Friction and Mechanical Spectroscopy

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D. Mari

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Selected, peer reviewed papers from the
16th International Conference on
Internal Friction and Mechanical Spectroscopy
(ICIFMS-16)
July 3-8, 2011, Lausanne, Switzerland

Edited by

R. Schaller and D. Mari

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Preface

The papers collected in this special issue of Solid State Phenomena, which have been accepted after peer reviewing, are the outcome of the 16th International Conference on Internal Friction and Mechanical Spectroscopy, ICIFMS-16, held on July 3 – 8, 2011, in Lausanne, Switzerland.

The Symposium brought together 110 scientists coming from 22 countries to share their results in the area of mechanical energy dissipation and elastic properties of crystalline and non-crystalline solid materials. The scientific program was composed of 7 invited lectures, 65 oral talks and 30 posters.

Two special talks were given in remembrance of Prof. P. G. Bordoni and Prof A. S. Nowick by Prof. F Mazzolai and Prof. D. Beshers, respectively. Prof. Bordoni, who died in 2009, discovered in 1949 the low temperature anelastic relaxation, which is now known as the Bordoni relaxation and the origin of which was correctly attributed by Bordoni to dislocations. The 1953 review article of Prof Nowick, "Internal Friction in Metals" brought him widespread recognition at an early age. In 1972 the iconic monograph "Anelastic Relaxation in Crystalline Solids, written with Brian S. Berry, established Nowick's position as the leading expositor.

As customary with previous conferences of this series, distinguished scientists were awarded the gold medal Zener prize for their outstanding contributions to the advancement of knowledge in the field of elasticity and anelasticity of materials. They were:

Fabio Mazzolai of University of Perugia, Italy
Gérard Gremaud of EPFL, Lausanne, Switzerland

The present proceedings of ICIFMS-16 aim at attracting newcomers to this field of research to appreciate the potentiality of anelastic methodologies in the investigation of advanced materials and new phenomena. On the other hand scientist already involved in the field may find in this issue ideas and stimuli to built new experiments and theories.

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A Tribute to Piero Giorgio Bordoni

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Professional Career

Piero Giorgio Bordoni passed away on September 19, 2009 at the age of 94. He was born in Rome on July 18, 1915. Graduated in electrical Engineering in 1937 from Rome University, Piero Giorgio Bordoni started his scientific activity as fellow at the Elettrotechnical Institute Galileo Ferraris in Tourin, where he spent one year working in the acoustic laboratory. Then, beginning in 1938, he was recruited as researcher by the Institute of Electroacoustics founded by the physicist and senator of the Italian Republic Orso Mario Corbino. Soon after, during his four years military service (during the World War II), he was the chief of the acoustic laboratory of the Areonautical "Genio" in Guidonia, little town located near Rome. In the last two years of his military service he developed the acoustically triggered torpedo for the Italian Navy.

Fig.1. P. G. Bordoni, Laurea "honoris causa", Perugia 1988.

At the end of the World War II, beginning in 1942, he resumed his position as researcher at the Institute O. M. Corbino, where he remained until 1949. Thereafter he was appointed as assistant professor of Rational Mechanics at the Engineering Faculty of Rome University.

In 1954 P. G. Bordoni obtained the chair of Mathematical Physics at Pisa University, where he also directed the astronomical observatory.

In 1962 he was appointed by Rome University "La Sapienza" as professor of Rational Mechanics at the Faculty of Engineering, where also his father Ugo had been an eminent professor of Technical Physics.

In the early period, the scientific activity of P. G. Bordoni was predominantly technological in nature as it was addressed towards the development of electro-acoustical devices such as transducers and detectors. However, he was fascinated by fundamental research and pretty soon started investigating, from a physical point of view, the acoustical behavior of materials as a function of temperature, and he was indeed a pioneer in Italy in this field.

In 1948 P. G. Bordoni had a CNR fellowship for a study visit to United States, where he spent eight months working at MIT in the low temperature laboratory directed by Prof. Slater. Before going there, P. G. Bordoni built up his own apparatus in Rome and had it shipped to USA. After a short initial period of work on the instrumentation he started collecting data on the low temperature elastic and anelastic properties of lead, copper, silver and aluminum. These measurements, which were made possible by the availability of large amounts of liquid helium at the Slater's laboratory, were, actually, a continuation of those he had initiated in Rome at higher temperatures. In figure 2 Bordoni is seen working at MIT.

These measurements led him to the discovery of the low temperature anelastic relaxation [1-3], now known as Bordoni relaxation, the origin of which was correctly attributed by Bordoni to dislocations. It is amazing that a single scientist could in those difficult times, immediately after the Second World War, provides at the same time the overall needed instrumentation, the experimental data and their interpretation.

Returned to Italy P. G. Bordoni continued his work on the anelastic properties of fcc [4-8] and to a lesser extent of hexagonal [9] and bcc [10] metals at the O. M. Corbino Institute, where his principal collaborators, from 1958 to 1964, were Mario Nuovo, Livio Verdini and to a lesser extent Fausta Fanti. Over this period of time Bordoni had a number of students: Paolo Emilio Giua, Luciano Palmieri, Mariella Borgucci Verani, Fabio Massimo Mazzolai, Gaetano Cannelli, Giovanni Bosco Cannelli. They helped him to carry out programs on dislocations, dislocation-hydrogen inter-actions and thermoelastic Zener relaxation. Some of them have continued their activity in the field of anelasticity in solids.

After 1964 P. G. Bordoni left the Istitute O. M. Corbino and was mostly involved in teaching and writing a textbook of Rational Mechanics as well as in actively promoting the research work of his university assistants and colleagues: B. Forte, P. Benvenuti, F. Nappo, C. Risito, G. Andreassi, G. Maschio and C. Valente.

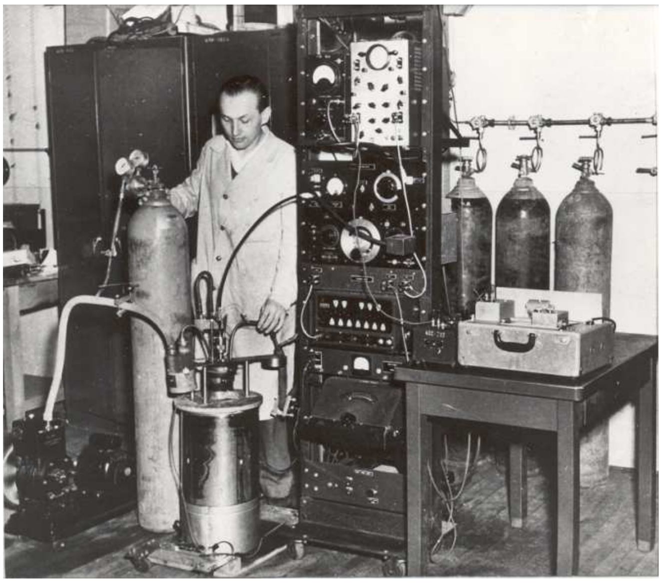

Fig.2. P. G. Bordoni at MIT, USA, 1948.

In 1968 Rosario Cantelli, coming from Seeger's team in Stuttgart, joined the Physical Acoustics Group, at that time composed of M. Nuovo, G. Cannelli and myself of O. M. Corbino Institute. In the meantime the research activity had been addressed towards anelasticity in hydrides (Zener effect) and towards H diffusion (Gorsky effect).

P. G. Bordoni came back from mathematics to solid state physics in 1980 and we investigated, together with F. A. Lewis (Belfast), H-dislocation interaction in Pd and Zener effect in Pd hydrides [10, 11]. In the last period of his activity Bordoni was involved with the problem of deducing the time relaxation spectrum from IF peaks and creep relaxation curves [12].

In 1988 P. G. Bordoni received a laurea *"Honoris Causa"* in physics from the University of Perugia in recognition of his achievements in the field of solid state physics, and in 1993 the *Zener gold medal* in Rome. In fig. 1 Bordoni is giving his speech in the occasion of the "Laurea honoris causa" ceremony in the historical hall of the doctorate at Perugia University.

The Scientist

P. G. Bordoni was an outstanding experimentalist, able to design and construct his own apparatus and to carry out the experiments according to rigorous methodologies. To these capabilities he joined a strong mathematical background that allowed him to read and write theoretical papers easily. He had a strong personality and competence, thus, did not need to be authoritarian to be followed in his intuitions and suggestions. Admiration and friendship were the sentiments he inspired in his collaborators and scholars.

The Man

He was a brilliant person knowing ancient history, music, art and languages, including Latin and old Greek. He could talk for hours about many different topics in a spontaneous way, never giving the impression that he was willing to show his cultural superiority. He had the sense of humor never appearing sad or in bad mood. His cutting irony was that of an acute observer of the multiform facets of life and events. This ability let him to be a keen poet. He wrote a number of sonnets, in Roman Dialect in the style of the famous roman poet Gioacchino Belli. He was such a complex personality that I consider a privilege having known him, and this also explains the great love, lasting more than sixty years, that his wife Emma had for him.

Bordoni Relaxation

As it is well known Bordoni relaxation has been and still is one of the most extensively investigated anelastic effects, both experimentally and theoretically. Comprehensive reviews on the subject are now available and the interested reader is referred to them [14, 15].

P. W. Mason was the first to elaborate a structural model of the Bordoni Relaxation based on stress-assisted motions from one energy valley to another of rigid dislocation segments running parallel to close packed directions [16]. This model was unable to account for some of the major features of Bordoni relaxation such as its activation energy. The overwhelming theoretical achievements on Bordoni relaxation, as it is well known, are due to Alfred Seeger [17-19] in Stuttgart, who elaborated the now generally accepted model, based on thermally activated generation (and diffusion) of double kinks along dislocation segments running parallel to closed packed lattice directions. A number of alternative models of Bordoni relaxation have also been proposed over the years based on motions of dislocation geometrical kinks, dislocation dipoles and dislocation jogs. However, for one reason or another, these models failed to explain the main features of the Bordoni relaxation, thus, they have been abandoned. Also the initial double kink generation model of Seeger [17] required some refinements [18, 19], mainly in the aim of accounting for the wide spectrum of the relaxation times and for the dependence of the peak height on strain amplitude.

With respect to Snoek and Gorsky relaxations, whose structural models involve simple mathematics, thus allowing their use for accurate determinations of certain physical quantities, such as jump frequencies, diffusion coefficients and concentrations of heavy and light interstitials (O, C, N, H, D and T), Bordoni relaxation model imply complex mathematics and only partially known quantities. Thus, it has been more difficult to use it to derive fundamental quantities concerning the dislocation network. However, Bordoni relaxation appears to be the only mean available to prove and measure Peierls stress σ_P, even though one of the last problems to be solved has been the discrepancy between the value of σ_P , as determined from Bordoni relaxation $(10^{-3}\mu<\sigma_P<10^{-4}\mu)$, and the critical resolved shear stress derived from plasticity measurements $(\sigma_P \cong 10^{-5}\ \mu)$.

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Arthur Stanley Nowick, an Intellectual Appreciation

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Abstract. We present Nowick's scientific background, professional development, principal achievements, and an assessment of his career.

Introduction

Arthur Stanley Nowick, my colleague and friend for more than half a century, died on July 20, 2010 at age 86 of heart arrhythmia while swimming near his home in Newport Beach, California. He had been less active in recent years, more so after he moved to southern California, it was nevertheless characteristic that he was active when he lost his hold on life. It is a pleasure, if melancholy, and a privilege to have this opportunity to review and meditate on the meaning of his life's work. I want to make the case that this meaning is more than transient, that there is a permanence that calls now for recognition.

Art was the leading researcher and expositor in the field of internal friction for many years. His 1953 review article, "Internal Friction in Metals" [1] brought him widespread recognition at an early age. In 1972 the iconic monograph "Anelastic Relaxation in Crystalline Solids" [2], written with Brian S. Berry, established Nowick's position as the leading expositor. An active participant in what is now recognized as the first International Conference held at Brown University in Providence, Rhode Island in 1956, he was Chairman of the second Conference at Ithaca, NY in 1961. He had proposed to me that we jointly organize the fourth at Columbia in 1969, but then he found that Charles Elbaum at Brown was well along with a similar project, so we joined forces and did a good deal of the mailing work. He was the medalist at the ninth International Conference in Beijing in 1989, although he was unable to attend. (The organizers of the twelfth International Conference in Buenos Aires in 1999 arranged to have a Zener gold medal formed for him, although again he was not there, and I brought it back to New York for him. My brief case was stolen off my baggage cart at Kennedy airport on my return, but the thief was well known to the police who were watching him, so I had the case returned as soon as I reported the loss, and the medal was delivered safely.) To the attendants at the sixteenth International Conference, I want to say that he was one of us.

His work was also significant for the related fields of diffusion and crystallography, and a few others. In all there appear to have been over two hundred papers, several reports and patents, and four books. One recognition that he has, by the nature of the thing, not received is a summary of his life's work. This paper makes a brief attempt at filling the need.

Career Milestones

Nowick received an A.B. (Physics) from Brooklyn College in 1943, an A.M. (Physics) from Columbia University in 1948, and a Ph.D. (Physics) from Columbia in 1950. His first professional position was Instructor, University of Chicago (1949-1951) – we would now call this a post-doctoral research position. He became an independent researcher when he moved to Yale University as Assistant Professor of Metallurgy where he was soon promoted to Associate Professor (1951-1957). He left Yale to become Head, Metallurgy Group, IBM Research Center (1957-1966), and finally returned to academia as Professor of Metallurgy at Columbia University in 1966. Under Nowick's leadership, the Metallurgy program soon changed to Materials Science and Engineering. He also established, and for many years was Chair of, the Interdepartmental Committee on Solid State Science and Engineering. Toward the end of his career he was named Henry Marion Howe Professor. After his retirement in 1993 he continued to work at Columbia until about 2003, but gradually became more involved with the program at the U. of California, Irvine, as a Visiting Researcher (2001-2010). A Fellow of The Metallurgical Society of AIME, and also of The American Physical Society, he delivered the David Turnbull Lectureship of the Materials Research Society (1994) entitled "The Golden Age of Crystal Defects" [3] from which I have drawn some personal reminiscences . A more extensive obituary appeared in the Bulletin of the Materials Research Society [4].

Internal Friction before Nowick

Our account starts with the publication [5] of the thesis of S.L. Quimby who later became the thesis advisor of Arthur Nowick. Quimby introduced the composite oscillator in primitive form, and made measurements of material properties with it.

Quimby's own graduate students in succession introduced improved versions, and soon the composite oscillator became a significant research tool. Three outstanding students who used this tool were W. F. Brown, Jr., T. A. Read, and A. S. Nowick. There were interactions among these, and with the other formative influence in Nowick's career, Clarence Zener. Brown's thesis [6] presented, in addition to important experimental data, a theory of the macro-eddy current damping in a cylinder in longitudinal vibration, perhaps the first successful theoretical treatment of a damping mechanism. Zener, though, was only a few months behind with a series of papers [7-9] that began by developing a theory of internal friction based on thermoelastic coupling. However, the fifth of the series [9] recognized that the thermoelastic theory and the macro-eddy current theory are both diffusive theories, and used the thermoelastic theory as a guide to generalize Brown's theory to arbitrary shapes. These papers established Zener as the leading practitioner of that part of internal friction governed by linear differential equations.

Nowick's Early Career

Essential to this account, but omitted from the standard summaries of his career, is that after graduating from Brooklyn College during World War II, he held two junior positions connected with the war. First, he taught physics to army personnel receiving technical training at Johns Hopkins University and second, he worked for the National Advisory Committee on Aeronautics (NACA) at their Aircraft Engine Research Laboratory in Cleveland, Ohio. In addition to being a co-author on an internal report on oxidation of cast iron in engines, he joined with Eugene S. Machlin to produce two papers on creep. Machlin joined the Columbia Metallurgy faculty in the early 1950's and was later instrumental in bringing Nowick to Columbia as a colleague. One of those papers, "Dislocation Theory as Applied by N.A.C.A. to the Creep of Metals" [10], brought Nowick into contact with the future field of his thesis. The abstract begins: "An equation for the steady-state rate of creep of pure annealed polycrystalline metals is derived through dislocation theory and the theory of rate processes." The paper has been cited repeatedly over the years, at least four times in the last decade.

Nowick has told [3] how, newly enrolled in graduate school, he was reading recent papers looking for a promising thesis topic, already knowing about dislocations but mindful of criticisms about glibness in many discussions. "With such skepticism in mind, I sought a PhD thesis topic in 1946 and came across a study of internal friction of copper and zinc by T. A. Read [11,12] carried out in S. L. Quimby's laboratory at Columbia University. [Read showed] that there exists a strongly amplitude-dependent internal friction that is very sensitive to the application of stresses well below the yield point of the material. This behavior suggests that a real manifestation of dislocation motion is involved. Since I was a student at Columbia, I decided to study this phenomenon in the same laboratory where Read's work was done."

Nowick continued: “Together with Quimby, who was a master of meticulous measurement, I explored the effects of many variables, especially of frequency and temperature, on the damping phenomenon [13]. Most importantly, we showed that this amplitude-dependent damping was independent of frequency, suggesting a mechanism of hysteresis in which dislocations break away from pinning points.” That suggestion is now universally accepted.

Development

While Nowick was a graduate student with Quimby, Zener moved to the University of Chicago, published a slender volume, “Elasticity and Anelasticity” [14] and started a notable experimental program. Having done well with Quimby, It was only natural for Nowick to obtain an appointment to the other leading laboratory, Zener’s, arriving late in 1949. Less than two years later seminal publications on a variety of topics began appearing. At Chicago and at Yale, his development may be characterized as steady broadening with deepening. We will trace this development by reviewing selected papers.

When Nowick arrived in Zener’s laboratory, late in 1949, he was well prepared to make the most of the opportunity. Zener had discovered an internal friction peak in α-brass back in 1943, had speculated about it, and then moved on; he had also developed an atomistic theory of diffusion which gave explicit values for the diffusion constant at infinite temperature, the pre-exponential factor D_0. Nowick seized on these disparate facts to bring new understanding in several ways.

First, he found and used the acceleration of the Zener relaxation on quenching [15] to demonstrate that diffusive defects, probably vacancies, were involved in the Zener relaxation itself. This paper triggered a decade of work using quenching to detect vacancies. Second, he carried out the first thorough study of the Zener relaxation and its dependence on concentration and temperature in equilibrated specimens [16] illuminating discussions of the temperature variation of diffusion coefficients. Third, he used the theoretical values of D_0 to call in to question [17] much published data on diffusion coefficients, suggesting that short-circuit diffusion paths, such as grain boundaries, had distorted many reports. The extrapolated data for solid solutions often gave a pre-exponential factor much lower than Zener’s theoretical value. Nowick suggested that this was attributable both to the relatively narrow range of temperatures available for extrapolation and to short circuit diffusion along interfaces in the specimens. As other laboratories sought new data on single crystals without such interfaces, Nowick’s name soon became familiar, and then was celebrated when the suggestion turned out to be correct.

When Nowick left Chicago and Zener for Yale in1951 he chose to continue the study of metals, but also, influenced by the writings of Frederick Seitz, started a program on alkali halides [3] which became a lifelong project, His long collaboration with Brian Berry commenced during this time, when Berry was a postdoctoral fellow. The group at Yale continued the study of the Zener relaxation, and eventually, during Nowick’s IBM years, gave a full phenomenological description. Work on the Zener peak continued until 1962 [18], but even today no theory has yet come forth.

He also carried on collaborative research with scientists in nearby laboratories. One collaboration that paid off handsomely was that with Ralph Feder at the Frankford Arsenal of the U. S. Army in Philadelphia. Their paper “Use of thermal expansion measurements to detect lattice vacancies near the melting point of pure lead and aluminum” [19] was the pioneering effort, with precision sufficient only to conclude that the effect probably existed, doubt that was later erased by Balluffi and Simmons by whose names experiments of this type are usually known. Later Nowick and Feder, united at IBM, used laser techniques [20] to improve the experiment much further.

At Yale Nowick completed the review article which appeared in Progress in Metal Physics 4 [1] That number sold out rapidly; while volumes 1-3 and 5-7 were available for some time afterward; I believe that it was Art’s article that made the difference. The article covered point defects, dislocations, and domain walls, that is, both the Zener and Quimby fields of inteerest. Reasonably complete, systematic and easy to read, it soon became the standard. Neither Quimby nor Zener was as good a writer; so Art became the up and coming spokesman for the field.

Two studies, one at Chicago, the second at Yale, gave evidence that Nowick himself learned to be a "master of meticulous measurement" as he called Quimby. The first, on discontinuous precipitation in aluminum-zinc alloys [21] involved a complex system of irregularly distributed precipitates which gave rise to a damping that continually increased with temperature and probably was the basis for an invitation to talk on "Stress relaxation across interfaces" [22] at the ASM annual seminar in 1951, a signal honor for one so young. The second, on transient electrical effects of plastic deformation in sodium chloride crystals, with D. B. Fischbach [23] devised a number of penetrating and clarifying experiments and sorted deftly through a number of possible explanations to reach the satisfying conclusions that the increase in conductivity on deformation (the Gyulai-Hartly effect) is attributable to the break-up of vacancy complexes by moving dislocations, while a small charge flow after deformation is traceable to the creep of charged dislocations.

IBM: Maturation

The move to IBM affected Nowick's work in several ways. As one might expect, it brought him into contact with urgent technological developments and he, and his group, responded with a number of innovations and patents. We mention two which were important advances in materials science, and both were in collaboration with Siegfried Mader as well as others. Both were also examples enlarging the scope of the principle that most useful materials are not in equilibrium states but rather in long-lived metastable states; their preparation always involves throwing the material into a shorter lived nonequilibrium state which then decays into the desired one. The paper "Metastable alloys of Cu-Co and Cu-Ag thin films …" [24] demonstrated that co-depositing metals by vacuum evaporation on to a cold substrate (80 K) is considerable more effective than quenching from the liquid for the production of nonequilibrium phases. A later paper using the same technique, "Metastable Co-Au alloys …", reported the discovery of an amorphous ferromagnet [25].

The early 60's saw two momentous, and related, turns in Nowick's research program. Experimentally, his student R.W. Dreyfus observed two kind of relaxation due to dopant-vacancy dipoles in NaCl, first dielectric relaxation [26] and then, with Laibowitz at IBM, anelastic relaxation [27]. The thought was that knowing both the dielectric and the anelastic relaxation behavior would facilitate identification of the atomic structure of the defect responsible. This approach requires an additional step, that of verifying that the anelastic and dielectric relaxations involve the same defect, but it undoubtedly increases the power of the experimenter.

The theory needed to use this enhanced experimental approach was elaborated by Nowick in conjunction with W. R. Heller in a series of three long papers [28-30] that used group theory to sort out the possible macroscopic symmetries of electric and elastic dipoles in crystals. These were "Anelasticity and stress-induced ordering of point defects in crystals," (1963), "Dielectric and anelastic relaxation of crystals containing point defects," (1965) and, "Dielectric and anelastic relaxation of crystals containing point defects. II," (1967). The three papers ran to a total of 161 pages, effectively a monograph.

Columbia: full flower

The return to academia in 1966 enabled a focus on a mature program based on the Nowick-Heller theory. We mention three more papers. "Dielectric relaxation due to the aluminum-sodium defect in α-quartz" [31] with M. W. Stanley, in 1969, marked Nowick's entry into the study of a new type of material, one with very important uses, notably as the beating heart of standards of frequency.

Nowick extended the theory in 1970 [32] to include defect interactions among several different species with differing symmetries, showing how to obtain expressions for the various relaxations times in terms only of the symmetries of the crystal and of the interacting defects.

One paper distinctly outside the general program was "Piezoelectric properties of bone as functions of moisture content" [33] with Gloria Reinish. In this and other papers, Reinish and Nowick established the possibility of reproducible results with this difficult topic, which has now an appreciable literature. Beyond this point, the number of papers becomes too great to deal with, the number of excellent students too large to mention individuals, and the distinctions too fine for this review. Most of these later papers were on defects in cubic ionic crystals, but protonic conduction also appeared.

However the four books which appeared from 1972 onwards each merit special attention. The group theoretical approach noted above became, in greatly simplified form, one of the distinguishing features of Nowick's first book "Anelastic Relaxation in Crystalline Solids", [2] which capped the first part of his career. As was true of his first review article, the book has appreciable coverage of the relaxations involving dislocations and magnetic domain walls, and touches briefly on hysteretic motions of these large-scale imperfections that are strictly outside the scope of anelastic. Its combined breadth and depth have rightly made it the leading presentation of the field.

Two books which Nowick co-edited, "Diffusion in Solids: Recent Developments," (1975, with J.J. Burton) and "Diffusion in Crystalline Solids" (1984, with G.E. Murch) had a wide influence on the broader field of diffusion. While he did not himself do diffusion measurements as such, he kept in touch with developments after his early successes in the field.

His final book, "Crystal Properties via Group Theory," (1995) is really an independent foray into a topic related to, but not the same as, his previous work. The preface to "Crystal Properties" challenges a classic work, J. F. Nye's "Physical Properties of Crystals," [36] emphasizing a passage on p. 122 of Nye's book which states: "Group theory as applied in the above publications does not reveal which moduli are independent but only the total number of independent ones." Nowick's claim for his own work is that it does show how to reveal which moduli are independent and further "that the use of group theory lends elegance and beauty to what would otherwise be dull calculations." Therefore this book is truly an advance over the position of Nye and the crystallographic works using group theory that Nye relied on. Nowick also goes further than Nye by treating matter tensors up to rank 6.

Overview

Nowick's main effort, which grew in importance during the 1960's to be his lifetime goal, was to find a material system that would substantiate the full Nowick-Heller theory of elastic and dielectric relaxations by exhibiting all the possible modes of relaxation and permit specification of the local symmetry. In this effort, he was ultimately frustrated; I am not aware of any one system being fully worked out. Nevertheless, his last full paper, "Electrical relaxations: Simple versus complex ionic systems" [37] has a very broad sweep. If he aspired to extend his reach to still broader horizons, we must acknowledge and celebrate the grandeur of that vision, recognize that it was improbable that any one person should accomplish that goal, and pass on that challenge. The study of mechanical and dielectric loss mechanisms supplies, and will supply, knowledge not obtainable in any other way, knowledge essential to our advancing understanding of materials.

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CHAPTER 2:

Invited Talks

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Studies of Condensed Matter at Low Temperatures by Ultrasonic and Other Mechanical Spectroscopies

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Abstract. In the second half of the twentieth century and in the first decade of the twenty first century, many new phenomena came to light in the fields of condensed matter and of materials properties' at low temperatures. A few examples of these phenomena are: the plasticity and the behavior of dislocations in solid helium -4 (a quantum solid), "high" temperature superconductivity, occurrence of superfluid flow in solid helium ("supersolid"), and, Bose-Einstein condensation of cold atoms. In this presentation descriptions and some discussions are given on the role played in these studies by ultrasonic and other forms of mechanical spectroscopy.

Introduction

Studies of materials and, more generally, matter at low temperatures have been motivated over time by a large variety of interests, ranging from engineering applications and all the way to fundamental physics. To classify these interests it is helpful to divide the temperature range referred to as "low" temperature into the following regions:

1) From below the liquefaction of nitrogen (about 67K) to below the liquefaction of helium-4 (about4K),
2) From about 4K to about 1K,
3) From about 1K to about 10^{-7} K.

A few examples are given here to illustrate the salient features and properties of matter that are characteristic of the temperature regions listed above.

In each of these regions different motivations predominated. In the first region, for example, studies extend from phase transitions such as liquefaction and melting-freezing of noble gases, structural changes in solids, mechanical properties of solids in regard to plastic deformation mechanisms and development of materials for practical applications.

In the second region one enters the domain of observable quantum mechanical effects in macroscopic size systems. Among these are "quantum" solids. These solids are characterized by weak interactions among their constituent atoms. This manifests itself to the extent that the kinetic energy of atomic motions exceeds the potential energy of binding, or in quantum mechanical terms, by a large amplitude of zero point particle displacements. Thus, they remain liquid under their own vapor pressure to the lowest attainable temperatures, approaching absolute zero. Also, Solidification requires the application of considerable, temperature-dependent pressure. As an example, helium-4 at temperatures approaching 0K requires a pressure near 25 atmospheres to solidify.

The most prominent of the quantum solids are the two isotopes of helium, namely helium-3 and the more common helium-4. The properties of Solid helium-4 have been studied extensively in the context of thermodynamic, structural and mechanical properties of quantum solids and, in addition, for general studies of the solid state, as a model "material" available with exceptionally high purity, such as concentrations of helium-3 as low as 10^{-13}. (Helium-3 is the only "impurity" in liquid or solid helium at these temperatures and pressures considered here, all the other elements having solidified at much higher temperature.)

In this and the third temperature region very important phase transitions occur involving Bose-Einstein Condensation, BEC, which was predicted in the 1920s to occur in highly rarefied gasses at very low temperatures, where atoms obeying Bose statistics (bosons) would condense into a single