经典电介质科学丛书

Classic Dielectric Science Book Series

CDSBS

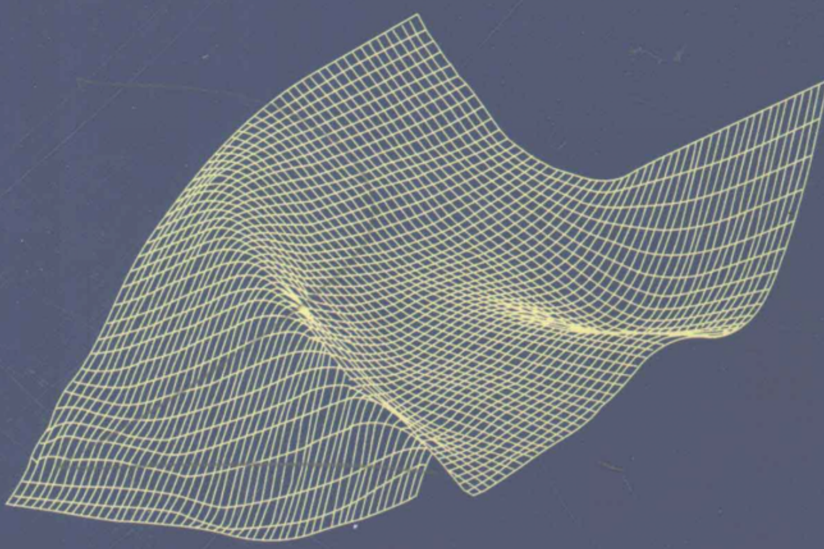
丛书主编 姚熹 (Yao Xi, Series Editor)

固体中的介电弛豫

Dielectric Relaxation in Solids

（影印版）

〔英〕 A. K. 琼克 (A. K. Jonscher) 著



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Dielectric Relaxation in Solids

本书内容简介：

本书是研究固体中介电弛豫现象的专著，被电介质领域的许多研究者奉为经典。作者提出在所有固体介质中存在普适的分数指数弛豫定律，其观点在学术界经历了从不被理解到广泛接受的曲折过程。书中介绍了介质极化的基础知识和介电函数的表述方法，在此基础上讨论了几种理想化模型的动态响应特征，结合频域响应和时域响应的多种实验现象，总结提出了介电弛豫的多体普适模型。全书行文流畅、简明扼要，可作为物理、电子、材料、电气等相关专业的教师、研究生和科研人员的参考书。精读此书有助于深入、全面地理解电介质、半导体、电池及其他电子元器件测量中的实验结果。

本书作者简介：

A. K. 琼克（A. K. Jonscher,1922 – 2005），生于波兰华沙，1949 年在伦敦大学玛丽皇后学院以一级荣誉学士学位毕业，并在该校Harry Tropper教授的指导下于1952 年获得博士学位，1951 年起在GEC研究实验室工作，从事半导体器件物理原理方面的研究工作，1962 年以 Reader 身份加入伦敦大学切尔西学院，1965 年成为固态电子学教授，1987 年成为伦敦大学皇家霍洛威与贝德福德斯学院荣誉教授，1990 年受邀为 IEEE “普适介电响应”杰出怀特海荣誉讲席。琼克教授在介电弛豫研究方面具有很深的造诣，他于 1983 年和 1996 年分别出版的学术专著《固体中的介电弛豫》和《普适弛豫定律》，在国际学术界享有盛誉。

丛书主编简介：

姚熹，1935年生于中国江苏苏州，1957年毕业于交通大学电机系，1982 年获美国宾夕法尼亚州立大学固态科学博士学位，1957年至今在西安交通大学任教，1984 年起任西安交通大学教授。姚熹教授 1989 年当选国际陶瓷科学院首批院士，1991 年当选中国科学院院士，2002 年当选美国陶瓷学会会士，2007 年因在“电子陶瓷科学和工程创新方面做出了杰出贡献”当选美国国家工程院外籍院士。

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内容提要

本书是研究固体中介电弛豫现象的专著，被电介质领域的许多研究者奉为经典。作者提出在所有固体介质中存在普适的分数指数弛豫定律，其观点在学术界经历了从不被理解到广泛接受的曲折过程。书中介绍了介质极化的基础知识和介电函数的表述方法，在此基础上讨论了几种理想化模型的的动态响应特征，结合频域响应和时域响应的多种实验现象，总结提出了介电弛豫的多体普适模型。

全书行文流畅、简明扼要，可作为物理、电子、材料、电气等相关专业的教师、研究生和科研人员的参考书。精读此书有助于深入、全面地理解电介质、半导体、电池及其他电子元器件测量中的实验结果。

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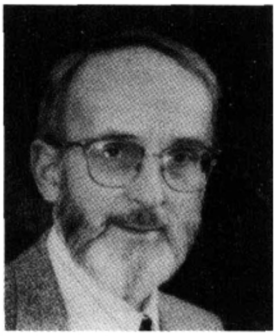
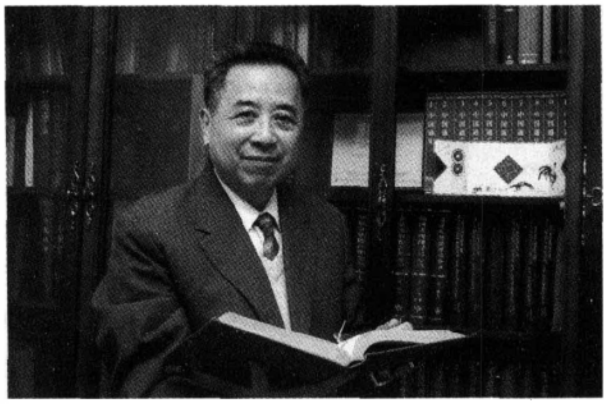
作者简介
ABOUT THE AUTHOR



A. K. 琼克,(A. K. Jonscher,1922－2005),生于波兰华沙,1949 年在伦敦大学玛丽皇后学院以一级荣誉学士学位毕业,并在该校 Harry Tropper 教授的指导下于 1952 年获得博士学位,1951 年起在 GEC 研究实验室工作,从事半导体器件物理原理方面的研究工作,1962 年以 Reader 身份加入伦敦大学切尔西学院,1965 年成为固态电子学教授,1987 年成为伦敦大学皇家霍洛威与贝德福德斯学院荣誉教授,1990 年受邀担纲 IEEE“普适介电响应”杰出怀特海荣誉讲席。琼克教授在介电弛豫研究方面具有很深的造诣,他于 1983 年和 1996 年分别出版的学术专著《固体中的介电弛豫》和《普适弛豫定律》,在国际学术界享有盛誉。

A. K. Jonscher (1922 － 2005) was born in Warsaw, Poland. He received the B.Sc. degree in 1949 with 1st Class Honours in Electrical Engineering at Queen Mary College, University of London and obtained Ph.D. in 1952 under the late Professor Harry Tropper, leader of the wellknown Dielectrics Laboratory there. In 1951 he joined the staff of GEC Research Laboratories in Wembley, later named Hirst Research Centre, where he worked on physical principles of semiconductor devices. In 1960 appeared his monograph *Principles of Semiconductor Device Operation*. He joined Chelsea College, University of London, in 1962 as Reader and became Professor of Solid State Electronics in 1956. He became increasingly interested in the properties of dielectrics, with special emphasis on the "universality" of relaxation processes. In 1983 appeared his monograph *Dielectric Relaxation in Solids*. With the dissolution in 1987 of the Chelsea Dielectrics Group as a result of the recent reorganization of the University of London, he joined Royal Holloway and Bedford New College as Emeritus Professor and leader of a research group working on relation processes in a wide range of systems. In 1990 he was invited to give the prestigious Whitehead Memorial Lectureship of IEEE under the title "The Universal Dielectric Response". In 1996 appeared his monograph *Universal Relaxation Law*. Professor Jonscher is the author of some 150 papers and has supervised fifty Ph.D. theses, and has a international reputation in his study of dielectric relaxation.

丛书主编简介
ABOUT THE SERIES EDITOR



姚熹，1935年生于中国江苏苏州。1957年毕业于交通大学电机系，1982年获美国宾夕法尼亚州立大学固态科学博士学位。1957年至今在西安交通大学任教，1984年起任西安交通大学教授。1989年当选国际陶瓷科学院首批院士。1991年当选中国科学院院士。2002年当选美国陶瓷学会会士。2007年因“在电子陶瓷科学和工程创新方面做出了杰出贡献”当选美国国家工程院外籍院士。

Yao Xi was born in Suzhou, Jiangsu, China, in 1935. He graduated from the department of electrical engineering, Jiaotong University in 1957, and received his Ph.D. of solid state science from the Pennsylvania State University in 1982. He has been a professor of Xi'an Jiaotong University since 1984. Dr. Yao was elected as an Academician in the first election of the World Academy of Ceramics in 1989. He was also elected as a Member of the Chinese Academy of Sciences in 1991 and a Fellow of the American Ceramic Society in 2002. In 2007, Prof. Yao was elected to be Foreign Associate of the National Academy of Engineering (USA) for his "contributions to the science and engineering innovations for electroceramics".

Preface to the Classic Dielectric Science Book Series

Fifty years ago, I was sitting in a class at Jiaotong University in Shanghai, China taking a course called "DIELECTRIC PHYSICS" lectured by the late Professor Chen Jidan. I was one of the thirty students sitting in his class taking the course. This was the first time DIELECTRIC study was introduced to Chinese Universities. Since then, dielectric study became one of the major concerns of the science and technology community of China in developing its electrical and electronic engineering. Fifty years past, thousands of students, graduate students, professors, scientists and engineers have been engaged in the studies and applications of dielectrics in this country. In the past fifty years, the Xi'an Jiaotong University, Shanghai Jiaotong University, Electronic Science and Technological University, Shandong University, Zhongshan University, Sichuan University, Nanjing University, Tongji University and the Shanghai Institute of Ceramics, the Beijing Institute of Physics of the Chinese Academy of Sciences were heavily involved in dielectric studies and gave their various contributions to the development of dielectric study in China. Now, China is probably one of the most important countries in dielectric studies among the list of the ex Soviet Union and the United Kingdom. Late Professor Chen was the pioneer and founder of DIELECTRIC studies in China. The staidness, sureness and solemnness of his academic attitude are the invaluable treasure of the Chinese dielectric community. I would like to take the chance of writing this preface to pay my sincere respect to the late Professor Chen.

However, as a branch of solid state science, the advancement of dielectric science is not well satisfied as widely expected. Our basic understanding on the electro-physical process within real dielectrics beyond the classical electro-magnetic theory is still rather poor. For example, the way how the charge assemblies respond to the external stimuli of electric field and the way of the communication and interaction among charge assemblies in real dielectrics are yet to be explored. Our understanding on local field, defects, inhomogeneous, space charges in real dielectric materials is to be profounded. As to the structure-property relationship of dielectric materials is still rather superficial. We are still struggling on how to calculate the dielectric constants of alkali-halogen crystals, water and other high dielectric constant materials. In contrast with other fields of solid state science such as metal, semiconductor and magnetics, dielectrics are probably the worst understood arena of solid state materials. The current status of dielectric science is not satisfied at all. Big efforts should be taken to catch up with the development of modern science and technology in this 21st century.

China is probably the country having the largest community of dielectric study in the world. Many of the old generation have devoted their career life focused on dielectrics in the past several decades. Next generation of dielectric study is now getting more mature and stronger. They have got better training and better working condition than their old generation. The Chinese dielectric community should be able to render more contribution to the advancement of dielectric science. However, dielectric science is now not yet in the main stream of solid state science. Many of the important publications were published twenty to sixty years ago in English. The first published book by P. Debye, Polar Molecules, was published in 1928. These important classics are not easily available to young scholars nowadays. To promote the dielectric studies in China, Electronic Materials Research Laboratory at Xi'an Jiaotong University proposed a publication project to introduce the most important classical publications on dielectrics from abroad and publish them in China, subjected to the consent of their original publishers. I am very pleased that the Xi'an Jiaotong University Press (XJTU Press) kindly agrees to support the publication project of Classical Dielectric Science Book Series (CDSBS). We will carefully select the subjects and topics based on our best knowledge and judgment to keep the CDSBS including all the important and useful publications, while still keeping it concise. Needless to say, due to the restriction of our knowledge and information, there might be pretermissions in searching and collection. Any suggestion and recommendation from the reader of the series would be highly appreciated.

I would like to take the chance to thank the Chinese publisher, the Xi'an Jiaotong University Press, for their kind support of the project and their far sighted vision in promoting academic excellence, as well as the original publishers, such as the Oxford University Press and etc. for their generous consideration to permit the publication of their books in China. Highest esteem will be dedicated to the authors of the books. We may not be able to give our thanks to them individually. We gratitude them and hope them happy and healthy. I would also acknowledge Dr. Wei Xiaoyong and Dr. Xu Zhuo as well as the editors of the book series Ms Zhao Liping and Mr. He Fengtao for their enthusiastic and hard works to promote the CDSBS project being realized.

Yao Xi

Electronic Materials Research Laboratory,
Xi'an Jiaotong University
April 20, 2006

Preface

Felix qui potuit rerum cognoscere causas†
Virgil

The quest for understanding the laws of Nature constitutes one of man's most basic urges and lies at the origin of all discovery. Another is the urge to harness the discoveries to practical ends which is the mainspring of technology. These two attributes are clearly visible in the development of the science and technology of dielectrics over the last century. In the present monograph I am primarily concerned with the first role – the understanding of the laws of dielectric relaxation – while being hopeful that beneficial consequences of this better understanding for the technology of dielectrics will follow.

A growing understanding of Nature leads to the introduction of a greater order into a previously rather confused picture and to the establishment of an organic unity in the complex range of empirically known phenomena. This unifying order produces a strong aesthetic appeal – an ordered and unified system is beautiful and the happiness to which Virgil alludes in the motto quoted above is a powerful motivation for scientific work.

This monograph proposes such a unifying and ordering treatment of the richly varied subject of dielectric relaxation. It will be left to the reader to judge the extent to which this objective is achieved.

Although I have to accept the sole responsibility for the opinions expressed in this monograph, it is my pleasure to acknowledge invaluable help from many individuals, especially from my immediate colleagues in the Chelsea Dielectrics Group. Among them I would wish to mention Professor Robert Hill whose contribution can be measured by the number of references and acknowledgements in these pages. Both he and Dr Len Dissado have developed the new many-body theory of dielectric relaxation in continuing

† Happy is he to whom it was given to understand the causes of things.

contact with the experimentalists working in our laboratory. The names of many Research Students and Visitors appear in acknowledgements, and I am particularly indebted to Mr John Pugh whose help with the development and the running of the Frequency Response Analysers in our laboratory is much appreciated.

This work would not have been possible without continuing support and understanding from successive Principals of Chelsea College – Dr Malcom Gavin, Dr David Ingram and currently Dr Charles Phelps; from the Head of the Physics Department Professor E J Burge and from my many Colleagues in the Department. Many aspects of this work were developed in close association with Professor Robert Lacoste of the Laboratoire de Génie Electrique at the Université Paul Sabatier in Toulouse. Essential material support was provided by Chelsea College, by the Science and Engineering Research Council as well as by other bodies. More detailed acknowledgements of this support, together with the account of current work in progress may be found in successive Progress Reports of the Chelsea Dielectrics Group which are available on request.

The loving understanding shown by my wife for the innumerable hours of painstaking work is also acknowledged – without it this monograph would never have seen the light of day.

Andrew K Jonscher

Chelsea Dielectrics Group

April 1983

Useful Physical Constants

magnitude of electronic charge	e	$= 1.602 \times 10^{-19}$	C
speed of light in free space	c	$= 2.998 \times 10^{8}$	ms^{-1}
permittivity of free space	ε_0	$= 10^7/4\pi c^2$	
		$= 8.854 \times 10^{-12}$	Fm^{-1}
mass of electron	m	$= 9.109 \times 10^{-31}$	kg
mass of hydrogen atom	m_H	$= 1.673 \times 10^{-27}$	kg
Boltzmann's constant	k	$= 1.381 \times 10^{-23}$	JK^{-1}
		$= 0.862 \times 10^{-4}$	eVK^{-1}
thermal energy at 300 K	kT	$\cong 1/40$	eV
Avogadro's number	L	$= 6.023 \times 10^{23}$	mol^{-1}

atomic excitation energy   1 eV $= 2.305 \times 10^4$ calorie mol^{-1}

Debye unit of dipole moment   1D $= (1/3) \times 10^{-29}$ Cm

approximately equal to charges $\pm$ e at a distance of 0.2 Å $= 2 \times 10^{-11}$m.

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PRESENTATION OF DIELECTRIC FUNCTIONS

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CHAPTER 1

INTRODUCTION

1.1 DIELECTRICS AND INSULATORS

The use of electrical insulation is as old as the science and technology of electrical phenomena; it goes back at least a century and a half, while the recognition of specifically electrostatic manifestations of electrification goes back to antiquity. Systematic investigations of dielectric properties may be traced back to the 1870's.

The accumulated experimental and theoretical material is vast and from an early stage on it was possible to discern two essentially complementary approaches to this wide-ranging subject – the study and development of insulators and of dielectrics. In this classification, insulators are materials used to prevent the flow of current where it is not desired, especially in the context of electrical and electronic engineering, and the principal interest in them lies in achieving the lowest possible electrical conduction coupled with the maximum resistance to destructive breakdown in high electric fields. Other factors such as long life, low cost, chemical inertness and the ability to withstand elevated temperatures may be added to the long list of technical specifications which must be met by modern insulating materials working sometimes under extreme external stresses. It is understandable that engineers and materials scientists searching for insulating materials suitable for specific applications were less concerned with the detailed physical mechanisms governing the behaviour of these materials, provided that their characterisation in terms of clearly defined parameters could be achieved reliably and simply. This order of priorities remains true to this day and the chief emphasis in electrical insulation science falls on the synthesis of materials and their characterisation.

By contrast with the insulation aspect, dielectric phenomena are at once more general and more fundamental – after all, insulators *are* dielectrics – and are concerned more intimately with the microscopic mechanisms of dielectric polarisation and include, especially, the transient behaviour under time-varying electric fields. Much of the available experimental evidence and a good deal of the