经典电介质科学丛书
Classic Dielectric Science Book Series
丛书主编　姚　熹(Yao Xi, Series Editor)

电介质与波

Dielectrics and Waves

（影印版）

〔美〕亚瑟·冯·希佩尔 (Arthur von Hippel) 著

西安交通大学出版社
XI'AN JIAOTONG UNIVERSITY PRESS

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late pra fessor of etectr
founder and director of the Laborator y for Iusu ution *Research*,
and Institute Professor at the Mansathusett. Enstitut of *Technology* (*MIT*)

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Xi'an Jiaotong University Press

内容提要

本书为世界著名材料科学家，已故美国麻省理工学院教授亚瑟·冯·希佩尔为具有中等程度物理、电子与材料背景的大学理工科学生所写的一本经典教材，内容涵盖宏观与微观两方面知识内容，前一部分主要讨论电磁场在介质中传播、反射以及波导、谐振腔与等效电路处理等基础知识与应用技术，后一部分主要深入介质内部，以有效场、极化机理、原子分子结构等微观机构与电磁响应联系等角度展开讨论，也引申到铁电与铁磁材料。本书内容涉及物理、化学和电气工程等诸多研究领域的知识要点，内容广博，是电介质领域发展过程中难以逾越的一座里程碑式、具有永恒价值的重要著作。

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图书在版编目(CIP)数据

电介质与波＝Dielectrics and Waves：英文/(美)希佩尔(Hippel, A. V.)著. 影印本. —西安：西安交通大学出版社，2011.8
(经典电介质科学丛书/姚熹主编)
ISBN 978 - 7 - 5605 - 3997 - 3

Ⅰ.①电… Ⅱ.①希… Ⅲ.①电介质-英文 ②电磁波-英文 Ⅳ.①O48 ②O441.4

中国版本图书馆 CIP 数据核字(2011)第 145919 号

书　　名　电介质与波(Dielectrics and Waves)
著　　者　亚瑟·冯·希佩尔(Arthur von Hippel)
责任编辑　贺峰涛　魏晓勇

出版发行　西安交通大学出版社
(西安市兴庆南路 10 号　邮政编码 710049)
网　　址　http://www.xjtupress.com
电　　话　(029)82668357　82667874(发行中心)
(029)82668315　82669096(总编办)
传　　真　(029)82669097
印　　刷　西安交通大学印刷厂

开　　本　850mm×1 168mm　1/16　**印张**　19.25　**字数**　474 千字
版次印次　2011 年 8 月第 1 版　2011 年 8 月第 1 次印刷
书　　号　ISBN 978 - 7 - 5605 - 3997 - 3/O・371
定　　价　48.00 元

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作者简介
ABOUT THE AUTHOR

亚瑟·冯·希佩尔(1898－2003),德裔美国材料学家与物理学家,介电、铁磁与铁电材料和半导体材料研究的先驱,二战时期雷达技术奠基人之一。1924 年获德国哥廷根大学物理学博士学位。1936 年起任教于麻省理工学院,从事高电压气体放电研究。1940 年创立绝缘研究实验室,该实验室很快成为该领域最具有影响力的研究与教育中心。二战时期同麻省理工学院辐射实验室合作,与其同事开发了雷达技术。因其发现钛酸钡的铁电与压电性能而在学术界享有盛誉。上世纪五十年代他提出分子工程概念。1959 年出版专著《分子科学与分子工程》一书,预测了纳米分子器件制造的可能性。1977 年他成为美国材料研究协会最高奖——冯·希佩尔奖的第一届得主。该奖项以他的名字命名,获奖即标志着在材料科学研究中取得了享誉国际的卓著成果。

Arthur von Hippel (1898－2003) was a German American materials scientist and physicist. He was a pioneer in the study of dielectrics, ferromagnetic and ferroelectric materials, and semiconductors and was a codeveloper of radar during World War II. He received his Ph. D. in physics from the University of Göttingen in 1924. He became an assistant professor at the Massachusetts Institute of Technology in 1936. In 1940 he founded the Laboratory for Insulation Research, which soon became one of the most important research and education centers in this area in the world. Together with MIT's Radiation Lab, von Hippel and his collaborators helped to develop radar technology during the war. He became famous also for his discovery of ferroelectric and piezoelectric properties of barium titanate ($BaTiO_3$). He was the author of the pioneering book *Molecular Science and Molecular Engineering* (1959). The term molecular engineering was coined by him in the 1950s, and he suggested the feasibility of constructing nanomolecular devices. The Material Research Society's highest award, the von Hippel Award, is an international hallmark of excellence in the field of materials research. Von Hippel was the first recipient of this award in 1977, thereafter named for him.

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 US National Academy of Engineering 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

丛书序

五十年前，我坐在交通大学（上海）的一间教室里上一门叫“电介质物理”的课程，讲授者是已故的陈季丹教授，当时参加这门课程学习的同学有 30 位。这是电介质这门学科第一次被介绍到中国的大学里。此后，电介质研究成为中国科技界在发展电气和电子工程的过程中一个重点关注的领域。五十年过去了，中国数以千计的大学生、研究生、教授，科学家和工程师在从事电介质的研究和应用工作。在过去的五十多年里，西安交通大学、上海交通大学、电子科技大学、山东大学、中山大学、四川大学、南京大学、同济大学和中国科学院上海硅酸盐研究所、中国科学院物理研究所等许多单位在电介质研究方面投入了相当大的科研力量，为中国的电介质研究做出了各自不同的贡献。现在中国或许是在电介质研究中包括前苏联和英国在内的最重要的国家之一。已故的陈季丹教授是中国电介质研究的先驱者和奠基人。他的认真、踏实、严谨的学术态度，是中国电介质界最宝贵的财富。我愿借写这篇序言之机，向陈教授表示由衷的敬意。

然而，作为固态科学的一个分支，电介质科学的发展还不尽如人意。我们对实际电介质中电－物理过程的理解还很难超越经典电磁理论。例如，在实际电介质中，电荷的集合以什么方式对外加电场的激励作出反应，这些集合体之间以什么方式通讯和相互作用，都还不清楚；我们对实际电介质中的局域场、缺陷、非均匀性、空间电荷的了解还相当有限；至于电介质材料中的结构－性能关系，我们的认识也很粗浅；我们仍然在为如何计算碱金属卤化物晶体、水以及其他高介电常数材料的介电常数而苦苦努力。和固态科学的其他领域相比，如金属材料、半导体材料和磁性材料，电介质或许是固态材料中理解得最不够深入的一个领域。电介质科学的现状很不能令人满意。电介质科学工作者应该付出更多的努力以赶上 21 世纪现代科学技术的发展。

中国可能是世界上电介质研究群体最大的国家。在过去的几十年里，许多老一代科学家矢志不移地投身电介质研究，贡献了他们毕生的心血。新一代的电介质研究队伍已经越来越成熟和壮大。相比于老一代，他们受到了更好的学术训练，拥有更好的工作条件。中国的电介质学界应该为电介质科学的前进作出更大的贡献。然而，电介质科学直到现在还不是固态科学的主流学科。许多重要的英语著作发表在 20－60 年以前。其中最早的一本书是德拜的《极性分子》，出版于 1928 年。现在中国的年轻学者要读到这些

重要的经典著作非常困难。为了提升中国的电介质研究，西安交通大学电子材料研究所提出一个推介国外电介质科学重要著作的出版项目，在获得国外原出版社版权许可之后，在中国影印出版这些图书。我很高兴西安交通大学出版社欣然同意支持“经典电介质科学丛书”这一出版项目。我们将尽我们知识和判断力之所能仔细挑选，以保证“经典电介质科学丛书”能够囊括所有重要而有用且不失简明的著作。当然，囿于我们所掌握的知识和信息，或许有些重要著作被遗漏了。因此，我们对读者所提出的任何建议和提议，都深表谢意。

我想借此机会感谢本丛书的国内出版者——西安交通大学出版社，感谢他们对本项目的大力支持，也赞赏他们致力于提升学术水平的远见。同时，我也想感谢牛津大学出版社等原著的出版者，感谢他们慷慨授权这些著作在中国出版。我也要对这些著作的作者们表达崇高的敬意。我们不能一一向他们表达谢意，在此一并致谢并祝他们健康快乐！最后，我要感谢魏晓勇博士和徐卓博士，以及本丛书的责任编辑赵丽萍女士和贺峰涛先生，因着他们的热情和付出的辛勤工作，才使得“经典电介质科学丛书”这一项目得以实现。

姚熹
西安交通大学电子材料研究所
2006 年 4 月 20 日

To

NIELS BOHR and JAMES FRANCK

in friendship and gratitude

献　给

尼尔斯·玻尔和詹姆斯·弗兰克

以表友情和谢意

PREFACE TO THE SECOND EDITION

As a practicing engineer, I have used in my technical work the two-volume von Hippel set as an indispensable reference for dielectric properties of materials. When I realized that they were out of print, I sent copies of selected pages to Artech House for evaluation with the recommendation that both volumes be republished for the benefit of other interested engineers. Several months later, Artech House notified me that a decision had been made to republish, that the rights to republish had been secured from the retired author, and that, as implausible as it may seem, neither the previous publishers nor the author have any remaining copies of this set, as would be required for the republication process. Therefore, I supplied the original editions to Artech House for reproduction. I would like to thank the entire staff at Artech House for their professionalism in the handling of this republication.

Huntington Beach, California
August 1994

ALEXANDER S. LABOUNSKY
Principal engineer/scientist
McDonnell Douglas Aerospace

PREFACE TO THE FIRST EDITION

A treatise intended for physicists, chemists, and electrical engineers is likely to disappoint three groups of readers. If an author, in spite of this danger, embarks on such an adventure, intense compulsion must drive him. For a number of years my demon has urged me to oppose the trend of specialization by helping to develop a field of knowledge that belongs not only to physics and chemistry but is also of vital importance for modern electrical engineering. We may call this subject "dielectrics" by identifying with the name not a narrow class of so-called insulators, but any nonmetal, and even metals as a boundary case, if their interaction with electric, magnetic, or electromagnetic fields is under consideration. *Dielectrics and Waves* has been chosen as the title of this book because wave phenomena play a dominant part in our story, whether electromagnetic waves, probability waves of quantum mechanics, or the elastic waves of crystal lattices.

The phenomena "polarization," "magnetization," and "conduction" are the properties of matter at issue. For macroscopic physics and electrical engineering this is a familiar subject when viewed from the standpoint of Maxwell's theory. Matter appears here as a storage medium and wave guide of electric and magnetic energy and as a dissipator of such energy by conduction and other irreversible processes. These properties are considered as given quantities that may be tabulated by introducing some descriptive parameters, for example, the complex permittivity and permeability used in this book. At this point the subject "materials"

is dismissed by the present-day electrical engineer in favor of his private world of field vectors and equivalent circuits.

The physicist and chemist have pushed on to the task of unraveling the molecular phenomena behind these macroscopic parameters. The structure and behavior of isolated atoms and molecules and the behavior of electrons and ions in gases of low pressure are now relatively well understood; the dielectric properties of gases at high pressures and of liquids and solids are still known only in rough outlines. However, this task of "dielectric analysis" has progressed far enough to allow a successful beginning of "dielectric syntheses" in which the properties of materials are tailored to order by combining the proper atoms and molecules into specified arrangements.

This subject of dielectric synthesis is of vital importance to the electrical engineer, promising him a variety of new tools and a release from shackling limitations. Nobody, however, can leave his problems to others without losing control over his destiny. The electrical engineer has to remember that he is an applied scientist and join his colleagues of physics and chemistry in a co-operative venture of "molecular electrical engineering."

Seen from this point of view, I would want the book to be a trumpet of Jericho; alas it may only loosen some bricks that will fall on the author's head. This is a survey book which cannot go into many important details and has to leave unmentioned many significant contributions. Space does not permit to give the molecular aspects of conduction more than a cursory glance. I hope to make "Electric Conduction and Breakdown" the subject of a later volume.

To remedy some of these shortcomings a representative list of books covering special fields has been added. Much additional information may also be found in the companion book, *Dielectric Materials and Applications*, published simultaneously.

It is too much to hope that any reader will follow the unfolding of this biography of dielectrics with the puzzled attention normally reserved for a detective story. But it may be of some help in bringing physicists, chemists, and electrical engineers closer together and provide a better understanding between the mode of thinking of the theorist and the experimentalist on dielectric problems.

In dedicating this book to Niels Bohr and James Franck I am fulfilling a simple duty of gratitude to two masters of science who became my friends at decisive junctures of my life and who have set, with their scientific genius and humanity, an ideal for our generation.

Cambridge, Massachusetts
June 1954

A. VON HIPPEL

第二版前言

作为一名工程师，在涉及材料介电性能方面的技术工作中，我经常离不开冯·希佩尔的两本电介质专著。在得知印刷本脱销以后，我曾给 Artech House 出版社发去部分内容的复印件，请他们评估再版这两本著作，以方便其他感兴趣的工程师。几个月后，Artech House 通知我决定再版，并从已退休的作者那里获得了授权。然而难以置信的是，原出版商(MIT Press)和作者那里都没有再版所需要的著作样本。所以我提供了原版的样本给 Artech House 重新制版。感谢 Artech House 全体员工在再版过程中表现出的专业素养。

麦道公司首席工程师/首席科学家
亚历山大·S·拉邦斯基
1994 年 8 月
于加利福尼亚州汉庭顿海滩

第一版前言

内容涵盖物理、化学和电气工程三方面内容的论著易使读者感到困惑难解，有心尝试的读者必须有充分的认识和准备。多年来发自内心的冲动，使我想打破专业的壁垒，为物理学家和化学家，更重要地是为当代的电气工程师，总结撰写电介质方面的知识与著作，这里的电介质不仅指狭义的绝缘体，包括任何考虑与电、磁及电磁波相互作用的非金属材料及金属边界 。本书以《电介质与波》为题，是因为它主要论及波，包括电磁波、量子力学的几率波以及晶格中的弹性波。

“极化”、“磁化”和“电导”是物质的基本性能，从宏观物理学和电气工程的角度，以麦克斯韦理论处理的方法是我们熟知的。此时物质或作为能量存储的媒介，或是电磁能的波导，或通过电导和其他不可逆过程损耗能量。这些材料物性被认为是给定的参数，可以引入描述参数如复介电常数和复磁导率来列表计算。从这点而言，材料自身可以被今

天的电气工程师分解为他所熟悉的矢量和等效电路来理解和使用。

物理学家和化学家力求了解隐藏在这些宏观参数后的分子现象。孤立原子与分子的结构和行为以及稀薄气体中的电子和离子的行为已经可以较好地理解，而高压气体、液体和固体的介电行为人们仍了解得很少。不过“介电分析”已经进展颇多，可以开始“介电合成”的尝试，即通过原子和分子的特定排列来实现所需的性能。

介电合成对电气工程师而言十分重要，给他们提供了多种新工具来不受束缚。然而没有人可以把问题移交他人而不失去对目标的控制，电气工程师必须记住他是应用科学家，与他的物理学家和化学家同事应以“分子电气工程”为导向合作。

从这个观点来说，我希望本书成为一个杰里科号角(trumpet of Jericho)，或许它只是振松几块砖头落到作者头顶。本书是一本全局性的论述，不可能涉及许多重要的细节问题，可能会遗漏许多重要内容。篇幅不允许对分子层级的电导现象作过多论述，只能是略述，我希望以后能补上“电导与击穿”这部分内容。

作为弥补，我加上了有代表性的专业著作列表。许多进一步的内容也可以在同时出版的另一本书中找到，书名是《电介质材料及其应用》(*Dielectric Materials and Applications*)。

难以奢望任何读者会如读侦探故事那样来进一步探究本书的未尽之处，但本书仍会对物理学家、化学家和电气工程师加深彼此了解、为理论和实验工作者更好地理解电介质现象提供帮助。

谨以本书献给尼尔斯·玻尔(Niels Bohr)和詹姆斯·弗兰克(James Franck)，向这两位科学大师表示致敬。他们在我人生的关键时刻成为我的朋友，并用他们的科学天才和人性为我们这一代人设立了理想的标杆。

亚瑟·冯·希佩尔

1954 年 6 月

于马萨诸塞州坎布里奇

ACKNOWLEDGMENTS

In writing a book, one accumulates a great amount of indebtedness. I owe much to discussions with Professor J. C. Slater and with former and present co-workers of our laboratory, especially Dr. S. C. Abrahams, Professor H. B. Callen, M. E. Caspari, Professor D. J. Epstein, Dr. E. P. Gross, and W. B. Westphal. My co-workers Caspari and Epstein, together with our excellent draftsman, J. J. Maccarone, translated rough sketches into finished illustrations. Dr. L. G. Wesson gave invaluable help, assisted by Mrs. H. B. Armstrong, Miss E. J. Busby, and later by Miss A. Sils, in getting the book to the printer and seeing it through the press. Dr. E. P. Gross worked with me in the preparation of the problem section; Professor R. H. Cole read the major part of the manuscript in behalf of the publisher and made valuable comments. Dean F. G. Fasset, Jr., the director of the Technology Press, which publishes the companion volume *Dielectric Materials and Applications*, gave helpful counsel.

The scientific work of the Laboratory for Insulation Research is supported jointly by the ONR, the Army Signal Corps, and the Air Force under ONR Contracts N5ori-07801 and N5ori-07858. It is obvious that the book could not have been written without this background of sponsored free research; and it is a pleasant duty to acknowledge gratefully the unfailing support of our sponsors in keeping our research without restrictions and directed towards fundamental issues.

A number of figures have been adapted from publications of other authors as indicated in the references. I am grateful to these colleagues and their publishers for permission to use such material.

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