21世纪高等学校
规划教材

“十三五”江苏省高等学校重点教材

材料物理

双语教程

◎密保秀 高志强 编著

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内 容 提 要

本书深入浅出地讲解了与材料性质相关的物理机制，以及材料性质的应用。主要内容包括：（1）材料的组织结构的基本知识及电子理论基础；（2）材料的各种物理性质。本书语言以英文为主，每一章都有对重点、难点句子的中文翻译。

本书在结合教学大纲和教学实践的基础上，融合了国内外同类教材的特点，并根据现代科学技术的发展增加了新内容。本书不同于传统的材料物理教科书，主要介绍金属及非金属中的无机材料，并加入了有机材料的物理性质，同时将侧重点由传统的力学及热学性质转向了现代的光电磁性质。

本书可以作为材料专业本科生的材料物理教材或者低年级硕士生的参考教材，也可以作为材料科学与工程领域相关科技工作者的参考书。

◆ 编　　著　密保秀　高志强
　责任编辑　李　召
　责任印制　彭志环

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前 言

Foreword

“材料物理”是高等院校中材料科学与工程专业及其相关专业的基础课程，是学生掌握材料性质的基础。将其设为双语教学，有助于学生在掌握专业知识的同时，拥有国际视野，并与国际高等教育逐步接轨。如果要实施双语教学，双语教材是必不可少的。然而，目前国内还没有出版材料物理的双语教材。

“材料物理”课程在南京邮电大学开设以来，编者经历了从母语到双语教学的全过程。本书是通过教学实践以及与学生的充分沟通后逐步完善而定稿的。此外，编者均毕业于物理与材料科学专业（博士），一直从事与材料相关的科研工作，紧跟该领域的前沿发展，并对材料性质有着深刻的理解，这些为本书的成稿奠定了雄厚的基础。

本书采取双语编排，每个章节包括：（1）正文（英语，局部中文翻译）；（2）本章小结（中文），（3）专业词汇（双语）；（4）思考题（英文）。全书文字深入浅出，非常适合作为学生教材。本书在满足国内教学大纲要求的同时，也为学生今后从事材料相关的科研奠定了基础。同时，书中的英文大部分来自原汁原味的英文原版书籍，并通过作者的整理加工编辑而成，有利于学生专业英语水平的提高。此外，书中含有英文重点、难点句子的中文翻译，可帮助英文相对薄弱的学生更好地理解专业知识，同时提高英文水平。

本课程的教学时数为 32～48。各章的参考教学课时见以下的课时分配表。

章	课程内容	学时
Chapter 1	Introduction	1～2
Chapter 2	Basic Structure and Organization of Atoms in a Material	2～4
Chapter 3	Fundamentals of Electron Theory	3～4
Chapter 4	Solid State Phase Transformation	4～6
Chapter 5	Mechanical Properties	4～6
Chapter 6	Electrical Properties	6～8
Chapter 7	Magnetic Properties	4～6
Chapter 8	Optical Properties	4～6
Chapter 9	Thermal Properties	4～6
课时总计		32～48

本书的编写参考了大量的中文教材和英文原版书籍，在此对这些参考书的作者表示感谢。同时，感谢南京邮电大学提供的江苏省首批赴美双语教学研修的机会，感谢材料院领导的关心与支持。感谢以下基金的支持：江苏省教改项目（2013JSJG225、2015JSJG028）、南京邮电大学教改项目（JG03013JX05）、南京邮电大学卓越教师培育计划（ZYJH201402）、南京邮电大学名师培育项目（2015 年）、江苏先进生物与化学制造协同创新中心、江苏省有机电子与信息显示协同创新中心、江苏高校优势学科建设工程（YX03001）。同时，南京邮电大学材料学院 GM 组的研究生刘杰、赵璐、王东平、陈洁、王超对本书的格式校对及图形绘

制做了大量工作。材料学院的钱洁、张晶晶、程佩珊、朱琦、张慧、徐若尘、邓尚平、姜茜、徐雪琪、王东琳、李锐、张伟、李进翔、宋雨鑫、王子恺对本书的出版也提供了帮助，在此一并表示感谢。

由于作者能力所限，加之双语特点，疏漏和不妥之处在所难免。恳请广大读者在使用过程中给予批评指正，以利于再版之际的修改和完善。与本书相关的讨论与交流，也十分欢迎。联系方式：iambxmi@njupt.edu.cn；iamzqgao@njupt.edu.cn.

密保秀，高志强

2017 年 8 月

目 录

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Chapter 1 Introduction

This chapter talks about the course scopes of material physics. After giving the definition and classification of materials, the history of material development has been briefly introduced. The relationships among material science and engineering, material physics, material chemistry, quantum dynamics, solid-state physics are discussed. Meanwhile, the content-emphasis of material physics is pointed out. Finally, the importance for material science is stated.

1.1 Definition of Material

Material is a broad term for the (chemical) substance, or a mixture of substances that constitute a thing. Based on their properties they can be used in structures, machines, devices, commercial products, and systems. There is a myriad of materials around us—they can be found in anything from buildings to spacecraft. In short, materials are the useful matter of the universe, the usefulness of materials is governed by the property of material itself.

The term property describes the behavior of materials when subjected to some external impacts such as force, heating, cooling and electric field etc.[1] For examples, the tensile strength of a metal is a measure of the material's resistance to a pulling force and the electrical conductivity of a material refers to the ability of conducting charge under an electric field.

1 性质一词用来描述材料对某种外界作用下的反应行为，这些作用包括力、加热、冷却以及电场等。

A property may be a constant or may be a function of one or more independent variables, such as temperature, electronic filed etc. Materials properties often vary to some degree according to the direction in the material in which they are measured, a condition referred to as anisotropy. The behavior of material properties that relate to different physical phenomena often can be modeled by the differential constitutive equations. In most case, these behaviors can model as linear in a given operating range and significantly simplify the differential constitutive equations that the property describes.

Some materials properties are used in relevant equations to predict the attributes of a system a priori. For example, if a material of a known specific heat gains or loses a known amount of heat, the temperature change of that material can be determined. Materials properties are most reliably measured by standardized test methods. Many such test methods have been documented by their respective user communities and published through ASTM International.

In general, material properties include but not limit to acoustical properties, atomic properties, chemical properties, electrical properties, environmental properties, magnetic properties, manufacturing properties, mechanical properties, optical properties, radiological properties, thermal properties etc. Our course will deal with the properties related to the physical phenomena such as mechanical and electrical behavior of materials.

1.2 Family of Materials

Metals and nonmetals should be the first of material classification by atomic bonding nature. Then along with civilization and material development, organic materials are isolated from nonmetals' family. Therefore, the nonmetal materials are divided into inorganic materials and organic materials; the latter usually refers to carbon-based materials generally made of covalently bonded carbon, hydrogen, oxygen, and nitrogen, etc, with minor species also containing elements of halogen, sulphur and phosphor.[2] Nevertheless, some carbon-containing compounds are traditionally considered as inorganic, such as carbon monoxide, carbon dioxide, carbonates, cyanides, cyanates, carbides, since their components and properties are very similar to other inorganic materials.

2 因此，非金属材料被分为无机材料和有机材料。有机材料通常是指碳基材料，一般含有通过共价键结合的碳、氢、氧和氮等，偶尔也含有卤素、硫及磷元素。

Sometimes, we also typically identify materials either as structural materials or functional materials, with mechanical or opto-electro-magneto/thermal properties to be considered, respectively. And according to the nature of chemical bonding or components, these functional materials can be further divided into four main families: Metals (e.g., steel), Polymers (e.g., plastics), Ceramics (e.g., porcelain), and Composites (e.g., glass-reinforced plastics). Additionally, considering atom stacking mode, there are crystalline, polycrystalline and amorphous materials; by conductivity, there are insulator, semiconductor, conductor and superconductor; according to space scale, there are bulky, nanomaterials and thin films; in terms of availability, there are natural and artificial materials; etc.

1.3 Brief History of Material Development

Materials played the key role in the history of world civilization and the progress of humankind development. The most important aspect of materials is that they are enabling; materials make things happen.[3] For example, in the history of civilization, natural materials used, such as stone, iron, and bronze, shown an important milestone in mankind's development, even coined the names of historical periods, such as Stone Age, Chalcolithic

3 材料是人类文明进步的关键，材料最重要的是有能力促使事件发生。

Age, Bronze Age and Iron Age. In today's fast-paced world, the discovery of making high quality silicon single crystals and the understanding of their electricity properties open the door of the information age.

In many cases different cultures leave their materials as the only records which anthropologists can use to define the existence of such cultures. The progressive use of more sophisticated materials allows archeologists to characterize and distinguish between peoples. This is partially due to the major material of use in a culture and to its associated benefits and drawbacks. For example, the innovation of smelting and casting metals in the Bronze Age started to change the way that cultures developed and interacted with each other. Starting around 5500 BCE, early smiths began to re-shape native metals of copper and gold - without the use of fire - for tools and weapons. The heating of copper and its shaping with hammers began around 5000 BCE. Melting and casting started around 4000 BCE. Metallurgy had its dawn with the reduction of copper from its ore around 3500 BCE. The first alloy, bronze came into use around 3000 BCE. Iron-working came into prominence from about 1200 BCE.

Prehistorically, before the consummation of material science, human beings had learned to use materials by empirical knowledge, the materials include: (1) organic materials: wood, ivory, bone, fiber, and rubber; (2) inorganic materials: minerals and ceramics including stone, flint, mica, quartz, clay, and diamond; (3) metals and alloys: iron, copper, silver and gold.

Just as shown in Figure 1.1, the accumulation of empirical knowledge pushed human civilization forward, which renders the creation of scientific knowledge that further promote the civilization and give insight to empirical knowledge. Thus, the science and technology on materials were gradually developed, which can further promote the development of new materials and explore their unique applications.[4]

4 （通过对材料的使用），人类积累了大量经验知识，这促进了人类文明的进步，也产生了科学知识。科学知识又进一步促进了人类文明的进步，并揭示了经验知识的本质。由此，材料科学与技术也就逐渐形成，并成为新材料发展以及开发其独特应用的基础。

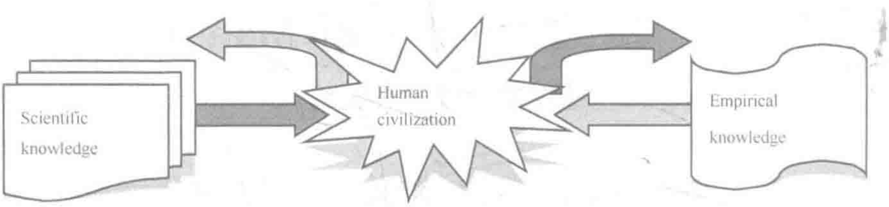

Figure 1.1 Both the empirical and scientific knowledge promote the progress of human civilization

Historically, in the development of material science, the discovery of modern atomic and molecular theory is the fundamental basis of all materials science and a key to understanding material structure and processes, which includes the following milestones:[5]

In 1869, Dmitri Mendeleev published the periodic table of the elements, correlating all atoms in materials.

In 1900, Planck's hypothesis well explained the blackbody radiation by introducing the concept of quantum for radiation.

In 1901, X-ray was found by the German physicist W. K. Roentgen. Since then, the X-ray analysis technology has been used in material science to investigate the construction and structure of materials.

In 1905, Einstein used photon theory explained the photoelectric effect, evidencing the particle nature of light.

In 1911, super conductivity was found by Kamerlingh Onnes in mercury at temperature of 4.2 K, adding a new special member in conducting materials.

In same year 1911, Rutherford introduced his 'classical' atomic model consisting of small nucleus surrounded by electrons, firstly disclosing the core-shell structure of atoms.

In 1924, de Broglie suggested wave particle duality, initializing an approach of quantum dynamic explanation between material macro-properties and microstructure.

In 1928, Bloch's theorem explained the conductivity of metal, which was further developed by Wilson in 1931 to insulator.

In 1960, the practical development of field effect transistor leads to the development of integrated circuit (IC).

In 1960, the first laser (ruby laser) was invented.

It can be said that the science of material began with metals, which was termed as metallurgy. Metals possess excellent mechanical properties such as formability and strength, thus serve as prime materials for structural applications.[6] Additionally, their excellent electrical and thermal conductivity has rendered them indispensable for electrical engineering. Despite its very long tradition, metallurgy is not a classical scientific discipline itself. Up to medieval ages, the knowledge of the extraction and fabrication of metals had been considered as a national secret asset and had been only traded orally from generation to generation.[7] As a matter of fact, metallurgy was a discipline of alchemies in medieval times and comprised a colorful mixture of empirical recipes and superstition. With increasing scientific character of more recent centuries metallurgy became a discipline of chemistry, where it remained even up to now at many universities. The rapid development of the technology to understand the material properties, in particular due to the

5 纵观历史，现代原子及分子物理的发现是材料科学发展的基础，也是理解材料结构及工艺的关键。其中的里程碑包括：

6 可以说材料科学始于金属，即冶金学。金属拥有出色的机械性能，其可成型性及强度都很好，可以用作基础建筑材料。

7 虽然冶金学历史较长，但它本身不是一门经典的学科。直到中世纪，金属冶炼及铸造知识都被认为是国家机密仅仅通过口述方式代代相传。

discovery of radiative beam, such as X-rays, electron beam and ion beam, and their application to material composition and structure, revealed that the properties of metals were not determined by the gross chemical composition, in contrast to common belief at that time. This made metallurgy become a discipline of physical chemistry.[8]

The development of the atomistic foundations of our understanding of mechanical and electronic properties of metallic materials in the frame work of dislocation theory and electron theory of metals finally shifted the focus of metallurgy to physics at the beginning of the 20th century. Eventually it engendered the discipline of metal physics, which has dominantly influenced the science of metals in the past 50 years.[9] In fact, our current understanding of metallic and non-metallic materials on the basis of atomistic models has essentially been developed only in the past 80 years of research in metal physics. The objective of this research has been to describe the properties of a material on the basis of atomistic physical models, which can be formulated in terms of equations of state. This allows for a prediction of materials behavior on a theoretical basis and changes the material research from try and error to the theoretical guiding. This will significantly reduce the cost and time on the experimental investigations and testing of materials behavior.

In the sixties and seventies of the 20th century it became obvious that the urgent demand for high performance materials and competitive mass products had to include the development of non-metallic materials, for instance ceramics for high temperature components and plastics for a weight savings in automobiles and airplanes.[10] Materials research revealed soon, however, that the foundations of physical metallurgy within limits can be readily applied to other materials, in particular to crystalline solids. Crystallography, constitution, diffusion, phase transformations, physical properties, and so on, are the foundations of the understanding of all kinds of engineering materials. Of course, there are also specific differences. For instance, dislocation theory, which is indispensable for an understanding of plastic deformation of metals, is of less importance for brittle ceramics, but it teaches the reasons for the brittleness and, therefore, offers respective for counter actions. For polymers which are usually non-crystalline, an appropriate dislocation concept of their mechanical properties is still too complicated to be useful, and the deformation behavior of plastics is, therefore, currently restricted to phenomenological tribological models.

Material development generated the strong belief that it is possible to

8 由于对材料性能理解技术的迅速发展，尤其是X-射线、电子及离子束的发现及其在材料成分和结构上的应用，人们逐渐意识到金属的性质并不像通常认为的那样，是由其总的化学组成决定的。这使得冶金学转变为物理化学的一个学科。

9 在20世纪初，在位错理论及电子理论框架下的金属材料的力学及电学性质，进一步向原子水平发展，并将冶金学的焦点转移到物理。最终形成了金属物理学科，并在过去的50年里，主导着金属科学的发展。

10 20世纪六七十年代，基于人们对高性能材料及有竞争力的大规模生产的渴望，非金属材料得以发展。例如，陶瓷可用于高温组件，塑料可用于机动车及飞机来减轻重量。

derive a comprehensive description comprising the different classes of materials and that the future world be multi-material.[11] This worldwide trend in the seventies of the past century caused the classical independent disciplines of metallurgy, ceramics, and plastics to merge to a new discipline "material science and engineering", encompassing both the science and engineering aspects of materials, and which has become our modern powerhouse of materials research and development.

11 材料的发展使人们坚信，有可能得到一个包括不同类型材料的综合性描述模型，而且未来世界应该是多种材料的。

1.4 Material Physics and Other Related Science

As shown in Figure 1.2, the development of novel materials and processes requires a deep knowledge of the physical and chemical foundations of materials, especially the knowledge of the relation between microscopic structure and macroscopic properties of materials, which facilitates the systematic tailoring of materials properties. These form the multidisciplinary including material science.[12]

12 新型材料及其工艺的开发需要对材料物理及化学基础、尤其是材料宏观性质与微观结构之间关系的深入理解，以利于对材料性能的系统裁剪。由此形成了包括材料科学在内的多个学科。

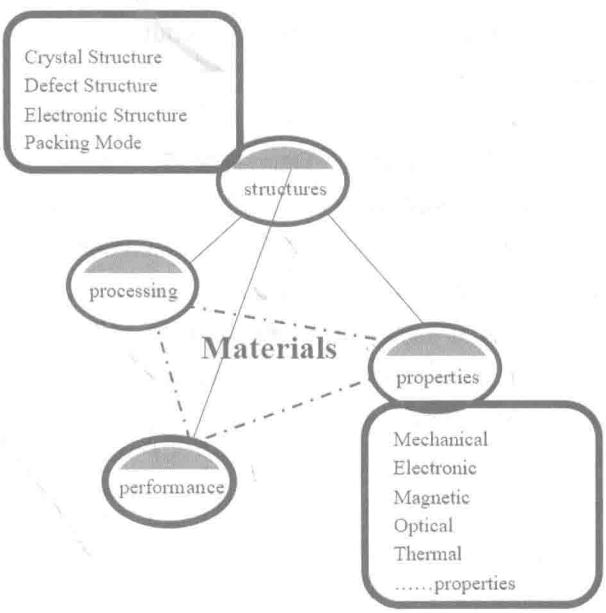

Figure 1.2 Different aspects of materials

- **Material science and engineering**

Materials science and engineering can be thought of as a combination of the sciences of chemistry and physics within a backdrop of engineering. Chemistry helps to define the synthetic pathways, and provides the chemical makeup of a material, as well as its molecular structure. Physics provides an understanding of the ordering (or lack thereof) of atoms and/molecules and electronic structure, and physics also provides the basic principles that enable a description of materials properties. The combined information provided by physics and chemistry about a material leads to the determination and correlation of materials properties with the process used to prepare the material, and with the materials structure and morphology.

The material physics and material chemistry are the roots of material science. The term material science is relatively young and not very precisely defined. Sometimes it is understood as an extension of metallurgy to non-metallic materials. Material engineering in some degree, means, material processing.[13]

13 材料物理及材料化学构成了材料科学的基础。材料科学的概念相对比较新，目前没有精准的定义。有时材料科学被理解为冶金学到非金属材料的延续。材料工程在某种程度上代表材料工艺。

Generally speaking, the "science" focuses on discovering the nature of materials, which in turn leads to theories or descriptions that explain how structure relates to composition, properties, and behaviours. The "engineering," on the other hand, deals with use of the science in order to develop, prepare, modify, and apply materials to meet specific needs. The field is often considered an engineering science because of its applied nature. Materials science and engineering is interdisciplinary or multidisciplinary, embracing areas such as metallurgy, ceramics, solid-state physics, and polymer chemistry.[14]

14 材料科学与工程是交叉学科，或者说是多学科；它包含冶金学、陶瓷、固体物理及聚合物化学等领域。

- **Material physics**

Material physics is a part of material science; it is also the largest branch of condensed matter physics. The purpose of material physics is to study the physics phenomenon, the effect of microstructure on material properties, as well as the physical mechanisms in materials. Alternatively, it can be said that material physics uses the physics to describe materials in the aspects of force, heat, conductivity, magnetism and light, and they are the key elements of this textbook.

- **Solid-state physics**

Solid-state physics deal with the condensed matter, or solids, through methods such as quantum mechanics, crystallography, electromagnetism, and metallurgy. Solid-state physics studies how the large-scale properties of solid materials result from their atomic-scale structure. Thus, solid-state physics forms the theoretical basis of materials science. It also has direct applications, for example in the technology of transistors and semiconductors.

- **Quantum mechanics**

Quantum mechanics (QM – also known as quantum physics, or