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Introductory Chapter: Electrical and Electronic Properties of Materials

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1. Introduction

Materials science is an interdisciplinary field having common interest to physicists, chemists, and engineers. Understanding the basic principles and properties of materials has been one of the most challenging attempts of mankind. Researches starting from apprehending a single atom to bulk materials such as metals, insulators, and semiconductors have led us to the point of current technological revolution. In this fascinating endeavor, electrical and electronic properties of matters have played a crucial role.

Properties from microscopic such as (but not limited to) band structure to macroscopic resistivity, conductivity, effective mass, permittivity, etc. are of immense interest to the materials scientists. Theoretical and experimental analyses of such characteristics are inevitable before employing different materials such as nanotube, polymer, ceramics, porous compacts, etc. in different fields of engineering.

2. Content Overview

There are many basic textbooks on the fundamental concepts of materials. This book is more specifically aimed to special materials that are of current interests. It is not possible to cover all the emerging materials and their properties in a small book. Still, the content of this concise yet complete enough book covers polyesters, varistor ceramics, powdered porous compacts, and some measurement and parameter extraction methods of dielectric properties. These classes of materials are of interest to materials scientists as well as to engineers, physicist, and chemist or other related fields. There are four contributed chapters in this book. Each class of materials as mentioned above is explained with reference to experimental works or real-world examples.

Researchers have been intrigued about the electrical conductivity of porous materials and been trying to cite its causes by studying it from various angles [1–6]. Model equations with empirical parameters to estimate the effective resistivity of metal powder systems are presented. It is shown that the effective electrical resistivity can be estimated from the material resistivity and the porosity degree of the sample and of the tap porosity of the starting powders. The validity of proposed equations has been experimentally justified with reasonably good agreement between experimental and fitted theoretical values. The equations would be useful to describe the early stages of electrical consolidation techniques. Electrical activation process has also been described based on the presented models, which may be useful to describe dielectric breakdown process of oxide layers.

During the last decade, polyesters, which include biodegradable and conventional polymers, have been under the limelight of interdisciplinary research [7, 8]. Their wide variety of applications in diverse arenas such as medical, ecological, and agricultural have attracted researchers from wider disciplines. Futuristic applications enabled by the chemical as well as physical metamorphosis of polyesters have also propelled their studies in different research fields. This has begged many questions regarding the behavior of polyesters under different electrical phenomena, which are yet to be answered. One such question, covered in this book, demands the analysis on behavior of polyester under a DC field [9].

In particular, the characteristics of aliphatic-aromatic polyesters such as poly(ethylene terephthalate) (PET), polycarbonate (PC), and aliphatic polyester such as poly(lactic acid) under an applied DC field are analyzed. The microstructure of polymers has important consequences for their electric properties as addressed in this book. For instance, electrets are materials which can retain a permanent electric charge, and the susceptibility of polymers to polarization enables their use as electret materials. As such, the electrical conductivity of poly(ethylene terephthalate) films in a DC field is discussed. Among other factors, the relative humidity of the medium is known to affect the properties of polymer films such as poly(ethylene terephthalate) [7, 10]. To address this notion, the electrical conductance of poly(ethylene terephthalate)-based products under different relative humidities in a DC field is studied.

In modern processing, the most common deposition techniques include physical vapor deposition (PVD) [11] and chemical vapor deposition (CVD) [12]. The potential of changing the innate electroinsulating properties of polyester fabrics via the use of these techniques as well as digital printing [13] to impart electroconductive and antistatic properties is also investigated in this book. In particular, studies on the contact electricity in the PET film and various metal systems are presented. A potential use of polyester fabrics in packaging is often hindered by its susceptibility to static electricity. The intent of this investigation is to reduce the risk in this potential use and also introduce new range of applications for polyester fabrics by extending its functionalization.

Another class of materials, varistor ceramics, has made their mark for applications in power system and protection circuits, which can be traced back to their excellent nonlinear current–voltage characteristics [14–16]. However, keeping in trend with the miniaturization of electronic devices, it has become imperative to improve the breakdown characteristics of existing varistors. It is known that the breakdown field is majorly affected by single grain boundary

characteristics, as determined by Schottky barriers and the amount of grain boundaries in the direction of the electric field [17, 18]. In this book, different doping techniques are introduced to improve the microstructure of varistors, in particular ZnO varistor ceramics and perovskite $\text{CaCu}_3\text{Ti}_4\text{O}_{12}$ (CCTO) ceramics, and to result in enhanced breakdown performance. Precisely, the electrical breakdown field is increased in $\text{Ca}_{1-x}\text{Sr}_x\text{Cu}_3\text{Ti}_4\text{O}_{12}$ ceramics via tailoring donor density and CCTO- $x\text{CuAl}_2\text{O}_4$ varistor ceramics synthesized in situ. Enhanced nonlinear electrical characteristics are obtained in CCTO-YCTO composite ceramics prepared with solid-state reaction method. The improvement in breakdown characteristics is attributed to the control of defect structure of Schottky barrier at grain boundaries and restricted grain size.

Besides their microstructure, the electrical performance of varistors has also been reported to vary within the bulk of the ceramic. Dimensional effect presents as the variation of the breakdown field in varistor ceramics with its thickness [19, 20]. It has been found that both the breakdown field and the nonlinearity in electrical characteristics decrease alarmingly as the thickness decreases beyond a critical limit. Investigating the origin of dimensional effect in varistor microstructures both theoretically and experimentally, the uniformity of grain sizes is found to have major consequences for the dimensional effect observed in ZnO ceramics as well as CCTO ceramics. To provide solid evidence for the idea, experimental efforts are made to eliminate dimensional effect in the aforementioned varistor ceramics by controlling grain sizes. Indeed, restrictions in grain sizes and their subsequent narrower distribution have allowed the observed dimensional effect to diminish.

The last chapter of this book focuses on the different measurement methods and extraction techniques that are employed to inherit the dielectric properties of dielectric materials. To facilitate increasingly novel applications in microwave, mm waves, and THz frequency range, accurate and precise knowledge of material properties is essential, which drives focus onto material characterization and appropriate measurement and extraction methods [21–23]. A particular dichotomy of the vast numbers of measurement methods can be into upconversion, such as a microwave or mm wave measurement method aimed at increasing frequency from 10^{10} to 10^{11} Hz, and downconversion to decrease the frequency from 10^{14} to 10^{12} or 10^{11} Hz. Important dielectric properties, such as complex permittivity and refractive index, are used for presenting the comparison and analysis in this study. A comparison is made between the expensive THz time-domain spectroscopy (THz-TDS) system and multimode laser diode (MLD) for TDS systems [24], where advantages of the latter are discussed theoretically and experimentally. The prospects of free space measurement method, traditionally labeled as a microwave measurement method, in measuring material properties in THz frequency range, are discussed.

Poor extraction of data from measurements made with high accuracy can also present as a hindrance to precise material characterization. In that regard, different calibrating and extraction techniques are applied to measured data in this chapter to establish a comparison between them. Extraction of the complex permittivity and permeability of the materials is enabled by scattering parameters using analytical, for instance, Nicolson-Ross-Weir (NRW), and numerical extraction techniques such as Newton-Raphson method [25]. Keeping with recent trends, the idea of using artificial intelligence (AI) methods to bolster numerical techniques in extracting the dielectric properties is also put forward [26].

3. Summary

Advanced knowledge in materials science is essential, particularly since, at the present time, scientific innovation in this area has excelled beyond expectations. This work serves that purpose very well. The content of this book is not only extremely appropriate for engineering students, material scientists, physicists, chemists, etc. but also equivalently beneficial to those who pursue this field in the industry.

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