Minoru Taya

Electronic Composites

Modeling, Characterization Processing, and MEMS applications

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ELECTRONIC COMPOSITES

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Preface

The subject of "electronic composites" is both old and new. Electromagnetic properties (particularly dielectric constant and electric conductivity) of electronic composites have been studied extensively since the time of James Maxwell in the nineteenth century, while electronic composites are key materials for microelectronics that today include computer packages, actuators, sensors and micro-electromechanical systems (MEMS), nano-electromechanical systems (NEMS) and BioMEMS.

The aim of this book is to provide readers with an introductory knowledge of various models that can relate the parameters of nanostructure and/or microstructure of the constituent materials to the overall properties of the electronic composites. The readers that the author wishes to reach are graduate students and engineers who are interested in and/or involved in designing microelectronic packages, actuators, sensors, and MEMS/NEMS/BioMEMS. To determine the optimum micro- and nanostructure of electronic composites, a knowledge of the modeling of electronic composites necessarily precedes processing of the composites. This book provides a summary of such modeling. The contents of this book are introductory in early chapters (1–3) and more comprehensive in later chapters (4–8). To help readers who want in-depth knowledge, the book contains detailed appendices and a long list of references.

The author wrote a paper on "Micromechanics modeling of electronic composites" (Taya, 1995) and has been teaching "Electronic composites" as a graduate course at the University of Washington since 1998; the contents of the book originate from his lecture notes. There are no textbooks on electronic composites, presumably because electronic composites are strongly interdisciplinary, covering a wide variety of subjects. The author was motivated to edit his lecture notes into this book by including more recent subjects related to electronic composites.

Chapter 1 introduces a definition of electronic composites and their early study during the nineteenth and twentieth centuries. Chapter 2 discusses various types of electronic composites that are used in current applications: electronic packaging and MEMS, BioMEMS, sensors and actuators, and also the control of electromagnetic waves. In Chapter 3, the foundation is given of the basic equations that govern the physical behavior of electronic composites, ranging from thermomechanical to electromagnetic behavior. Chapter 4 is a key chapter of the book, discussing in detail modeling of electronic composites based on effective medium theory, which ranges from the rudimentary theory of the law of mixtures to the more rigorous Eshelby model of coupled behavior such as piezoelectricity. Chapters 5 and 6 discuss the resistor network model and the percolation model, respectively, which are effective for cases that cannot be modeled by the effective medium theory, providing a nanostructure–macro-behavior relation for electronic composites. Chapter 7 discusses the lamination model, which is simple but effective in estimating the overall behavior of electronic composites with laminated microstructure associated often with a number of modern microelectronic devices. This chapter includes design of (i) piezoelectric actuators for bending mode, (ii) thermal stress analysis in a thin film on a substrate, and (iii) electromagnetic wave propagation in laminated composites with two examples: switchable window and surface plasmon resonance. The final chapter (Chapter 8) opens with a discussion on selected engineering problems associated with the processing of electronic composites, to acquaint readers with current processing routes, ranging from lithography to deposition of organic films. This is followed by an account of standard measurements of key thermophysical properties and electromigration.

In all chapters, both index formulations with subscripts and symbolic notations are used. The former is sometimes needed for readers to grasp the exact relations in the governing equations while the latter provides readers with a simple expression, yet leading to matrix formulation, the most convenient form for numerical calculations.

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Contents

1
Introduction

1.1 What is an electronic composite?

"Composite" is a well-accepted word, generally referring to structural components with enhanced mechanical performance. There are a number of textbooks and review articles on these types of composites (e.g., Kelly, 1973; Tsai and Hahn, 1980; Hull, 1981; Chawla, 1987; Clyne and Withers, 1993; Daniel and Ishai, 1994; Gibson, 1994; Hull and Clyne, 1996).

Historically, composites with enhanced mechanical performance have been in existence from ancient-Egyptian time, *c.* 2000 BC, when bricks were made of mud, soil and straw (*Exodus*, Chapter 5, verse 7). Structural composites are designed primarily to enhance the mechanical properties of a matrix material by introducing reinforcement; the primary mechanical properties to be enhanced are strength, stiffness, and fracture resistance.

Normally, a composite consists of a matrix material and one kind of filler, but sometimes more than one kind of filler can be used, forming a "hybrid composite". Depending on the matrix material, one can group composites into three basic types: polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs). Among these, PMCs are the most popular type for electronic composites due to their low processing temperatures and associated cost-effectiveness.

An "electronic composite" is defined as a composite that is composed of at least two different materials and whose function is primarily to exhibit electromagnetic, thermal, and/or mechanical behavior while maintaining structural integrity. Thus, "electronic" should not be interpreted narrowly as referring only to electronic behavior, but instead be understood in much broader terms, including physical and coupling behavior. In this sense, electronic composites are distinguished from structural composites whose primary function is to enhance mechanical properties.

Among various applications, electronic composites have been extensively used as the major component materials in electronic packaging: printed circuit boards (PCBs), thermal interface materials (TIMs), encapsulants, etc., most of which are polymer-based composites providing ease of fabrication and cost-effectiveness. As an extension of electronic packaging, electronic composites are used now in micro-electromechanical systems (MEMS) and BioMEMS, where their functions are multi-fold: active, sensing and housing materials.

The properties of electronic composites can be tailored to meet specific applications. Thus, prediction of the composite properties at an early stage of designing electronic composites is a key task. Normally the composite property is expected to fall between those of the matrix and filler, following the law-of-mixtures type formula, and depends greatly highly on the microstructural parameters: volume fraction, filler shape and size distributions; the properties of the matrix and filler; and also the properties of the matrix–filler interface. Sometimes, the property of an electronic composite becomes quite different from those of the matrix material and filler, and is far from that based on the law-of-mixture type formula. Such a unique property of the composite can be designed purposely or found accidentally in the course of development of a functional composite; it is termed a "cross product" exhibiting "coupling behavior" (Newnham *et al.*, 1978). Since coupling behavior between various physical properties is included in the definition of electronic composites, composites with such coupling behavior are often referred to as "smart composites" or "multi-functional materials," which are the key materials systems for use in smart structures and devices ranging from bio-micro-electromechanical systems (BioMEMS) through sensors to actuators. Therefore, construction of accurate models for the macro-property–microstructure (or –nanostructure) relation is strongly desired. These models are multi-scale, i.e., covering nano-, micro-, meso-, and macro-levels. If these models at different scale levels are interconnected smoothly, one can establish a hierarchical model which will be useful for many scientists and engineers who want to design new smart (or intelligent) materials, MEMS and BioMEMS devices, and multi-functional structures. The main body of this book is devoted to presenting a number of such models. In the remainder of this chapter, we shall review earlier models of electronic composites.

1.2 Early modeling of electronic composites

Modeling of electronic composites in the nineteenth century and early part of the twentieth century focused on the prediction of the dielectric constant ε and electrical conductivity σ or resistivity ρ of a composite composed of spherical fillers with ε_f, σ_f (ρ_f) and matrix with ε_m and σ_m (ρ_m) where the subscripts f and m denote filler and matrix, respectively. Landauer (1978) made an extensive literature survey of early models for the electrical conductivity of composites that were proposed in the nineteenth century through to the mid twentieth century. We shall review some of the early models used to predict the electromagnetic properties of composites, i.e., (1) Lorentz sphere problem, (2) demagnetization in a ferromagnetic body, and (3) concepts of thermal, electric, and magnetic circuits. The first two provide the background for modeling based on the effective medium theory, the last for the resistor network model. Both models will be discussed in detail in later chapters.

1.2.1 Lorentz sphere problem

Consider a dielectric material with dielectric constant ε which is subjected to a uniform electric field **E**, Fig.1.1(a). At a macroscopic level, the dielectric material is considered to consist of a uniform electric dipole moment with polarization **P** (per unit volume). At the atomic level, one can find a free space with ε_0 dielectric constant between lattice points (atoms) or molecules that constitute the dielectric medium. If we consider a spherical domain of radius r_0 between the atoms or molecules, Fig. 1.1(b), a layer of electric charges (positive and negative) is distributed on the inner surface of the

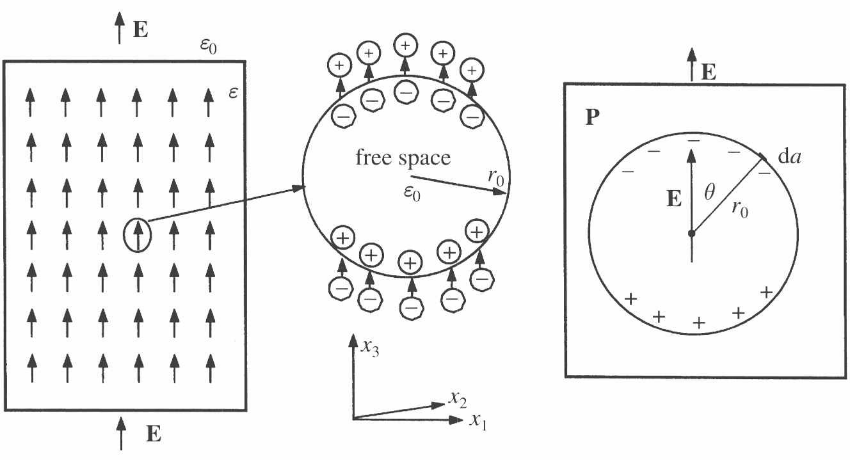

Fig. 1.1 Lorentz sphere problem: (a) macro-level model in a dielectric material subjected to uniform electric field resulting in uniform polarization **P**, (b) nano-level model where free space is polarized by pairs of positive and negative charges. (c) Lorentz sphere problem to idealize (b). (After Ishimaru, 1991, with permission from Pearson Education, Inc.)

sphere, which is called the "Lorentz sphere", Fig. 1.1(c). The net (or total) electric field $\mathbf{E}^{\mathrm{t}}$ in the sphere is expected to be larger than the applied field by an amount $\mathbf{E}_{\mathrm{p}}$, i.e.,

$$\mathbf{E}^{\mathrm{t}} = \mathbf{E} + \mathbf{E}_{\mathrm{p}}. \tag{1.1}$$

We shall compute the magnitude of $\mathbf{E}^{\mathrm{t}}$ using a model developed by four pioneers in the modeling of electric composites, Mossotti (1850), Clausius (1879), Lorenz (1880) and Lorentz (1909), which is summarized by Ishimaru (1991).

The magnitude of the charge P_r in the radial direction on the surface element da is given by

$$P_r = \mathbf{P} \cdot \mathrm{d}\mathbf{a} = P\cos\theta\ \mathrm{d}a, \tag{1.2a}$$

where

$$\mathrm{d}a = 2\pi r \sin\theta\ r\ \mathrm{d}\theta, \tag{1.2b}$$

and P is the magnitude of $\mathbf{P}$.

This charge P_r induces an electric field $\mathrm{d}E_{\mathrm{p}}$ in the radial direction given by the following formula

$$\mathrm{d}E_{\mathrm{p}} = \frac{P_r}{4\pi\, r_0^2 \varepsilon_0}. \tag{1.3}$$

Thus, the magnitude of the electric field, E_{p}, in the x_3-direction, contributed by the layer of distributed charge on the entire inner surface of the sphere, is obtained as

$$\begin{aligned} E_{\mathrm{p}} &= \int_s \frac{P_r \cos\theta}{4\pi\, r_0^2 \varepsilon_0} \mathrm{d}a \\ &= \int_0^{\pi} \frac{P\cos^2\theta}{4\pi\, r_0^2 \varepsilon_0} 2\pi r_0 \sin\theta\ r_0 \mathrm{d}\theta = \frac{P}{2\varepsilon_0} \int_0^{\pi} \cos^2\theta\ \sin\theta\ \mathrm{d}\theta \\ &= \frac{P}{3\varepsilon_0}. \end{aligned} \tag{1.4a}$$

Since the components of $\mathbf{E}_{\mathrm{p}}$ along the x_1- and x_2-directions are zero, the result of Eq. (1.4a) can be written in vector form as

$$\mathbf{E}_{\mathrm{p}} = \frac{\mathbf{P}}{3\varepsilon_0}. \tag{1.4b}$$

Macroscopically, the dielectric medium is governed by

$$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}, \tag{1.5}$$

where **D** is the electric flux density vector (coulombs [C]/m^2). The first term in Eq. (1.5) is the flux density in free space (i.e., if there were no atoms, or molecules) and the second term is the electric polarization vector resulting from electric dipole moments that exist in the dielectric medium. The electric flux density vector in a medium with dielectric constant ε is also proportional to the applied electric field, i.e.,

$$\mathbf{D} = \varepsilon\mathbf{E}. \tag{1.6}$$

For isotropic materials, **P** is proportional to the field **E** as

$$\mathbf{P} = \varepsilon_0\chi_e\mathbf{E}, \tag{1.7}$$

where χ_e is the electric susceptibility. From Eqs. (1.5)–(1.7)

$$\begin{aligned} \varepsilon &= \varepsilon_0(1+\chi_e) \\ \text{or} \quad \varepsilon_r &= \frac{\varepsilon}{\varepsilon_0} = 1 + \chi_e, \end{aligned} \tag{1.8}$$

where ε_r is the relative dielectric constant (non-dimensional) and ε_0 is the dielectric constant of free space, see Appendix B1.

At the microscopic level, the polarization vector **P** is composed of a number N of elemental dipole moments **p** which are in turn considered to be proportional to the net local field $\mathbf{E}^t$ in the sphere, i.e.,

$$\mathbf{P} = N\mathbf{p} = N\alpha\mathbf{E}^t, \tag{1.9}$$

where α is the polarizability. From Eqs. (1.1), (1.4), and (1.9), we have

$$\begin{aligned} \mathbf{E}^t &= \mathbf{E} + \frac{\mathbf{P}}{3\varepsilon_0} \\ &= \mathbf{E} + \frac{N\alpha\mathbf{E}^t}{3\varepsilon_0}. \end{aligned} \tag{1.10}$$

Equation (1.10) provides the relation between $\mathbf{E}^t$ and **E**,

$$\mathbf{E}^t = \frac{\mathbf{E}}{\left(1 - \dfrac{N\alpha}{3\varepsilon_0}\right)}, \tag{1.11}$$

which can be rewritten in terms of ε_r by using Eqs. (1.7), (1.8) and (1.10):

$$\mathbf{E}^{\mathrm{t}} = \frac{(\varepsilon_{\mathrm{r}} + 2)}{3}\mathbf{E}. \tag{1.12}$$

Equating the right-hand side of Eq. (1.11) to that of Eq. (1.12) and using Eq. (1.8), we obtain

$$\chi_{\mathrm{e}} = \frac{\dfrac{N\alpha}{\varepsilon_0}}{1 - \left(\dfrac{N\alpha}{3\varepsilon_0}\right)} \tag{1.13a}$$

and

$$\varepsilon_{\mathrm{r}} = \frac{1 + 2\left(\dfrac{N\alpha}{3\varepsilon_0}\right)}{1 - \left(\dfrac{N\alpha}{3\varepsilon_0}\right)}. \tag{1.13b}$$

Equations (1.13) provide the relation between polarizability α and relative dielectric constant ε_{r}:

$$\alpha = \frac{3\varepsilon_0}{N}\frac{(\varepsilon_{\mathrm{r}} - 1)}{(\varepsilon_{\mathrm{r}} + 2)}. \tag{1.14}$$

The above formulation, established by the four pioneering physicists named above, is known as the "Clausius–Mossotti" formula or "Lorentz–Lorenz" formula. Among these physicists, Lorentz summarized the formulae of his predecessors, and the model of Fig. 1.1 is called the "Lorentz sphere."

1.2.2 Other models for dielectric constants

Let us extend the case of Fig.1.1 to that of a filler material with dielectric constant ε_2 embedded as spheres in a matrix material with constant ε_1, Fig. 1.2. The effective dielectric constant ε_{c} of the composite is given by modifying Eq. (1.13b):

$$\frac{\varepsilon_{\mathrm{c}}}{\varepsilon_1} = \frac{1 + \dfrac{2N\alpha}{3\varepsilon_1}}{1 - \dfrac{N\alpha}{3\varepsilon_1}}, \tag{1.15}$$

where the polarizability α is now replaced by

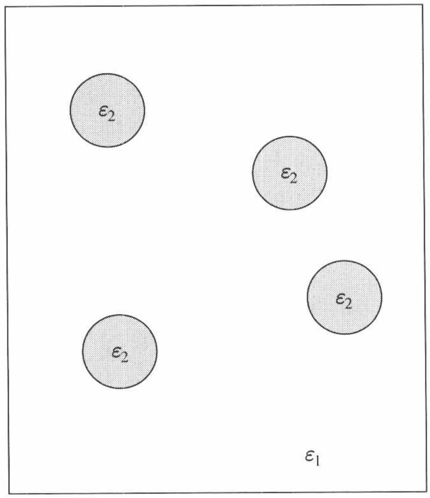

Fig. 1.2 Filler with dielectric constant ε_2 embedded in a matrix with constant ε_1.

$$\alpha = \frac{3\varepsilon_1(\varepsilon_2 - \varepsilon_1)}{(\varepsilon_2 + 2\varepsilon_1)} V \tag{1.16}$$

and V is the total volume of filler material in a sphere. If the spheres occupy a volume fraction f and N is interpreted as the number of the spheres per unit volume,

$$f = NV. \tag{1.17}$$

Note that $NV = 1$ in Eq. (1.14) where, effectively, the spheres occupied the entire space.

After substituting Eqs. (1.16) and (1.17) into Eq. (1.15), the composite dielectric constant ε_c is obtained as

$$\varepsilon_c = \varepsilon_1 \frac{1 + 2f\dfrac{(\varepsilon_2 - \varepsilon_1)}{(\varepsilon_2 + 2\varepsilon_1)}}{1 - f\dfrac{(\varepsilon_2 - \varepsilon_1)}{(\varepsilon_2 + 2\varepsilon_1)}} \tag{1.18}$$

which can be rewritten as

$$\frac{(\varepsilon_c - \varepsilon_1)}{(\varepsilon_c + 2\varepsilon_1)} = f\frac{(\varepsilon_2 - \varepsilon_1)}{(\varepsilon_2 + 2\varepsilon_1)}. \tag{1.19}$$

The formula Eq. (1.18) was first derived by Maxwell (1904), who considered the case of concentric spheres where an inner sphere with electric conductivity