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Nanostructured materials for microwave receptors

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ABSTRACT

Microwave heating promises numerous benefits over conventional heating including rapid thermal ramps, energy transfer rather than heat transfer, material selectivity, and improved automation and safety. This set of advantages has led to growing application in industrial processes. Currently, use of microwave heating is restricted because many materials of interest have poor dielectric loss properties and therefore respond poorly to microwave radiation. For this reason, nanostructured materials with high dielectric loss constants that can absorb microwave energy and convert it to heat are desired. Combination of the nanoscale receptors with base materials offers the opportunity to create composites with a high dielectric loss factor. This review covers the development of nanostructured microwave receptors and their applications. The structure of microwave receptors and their compatibility with the base material have a significant effect on the final dielectric properties. Therefore, various nanostructured microwave receptors, their surface modification, and the effect of the interface between the nanostructured receptors and the base materials are reviewed. Fundamental aspects of dielectric materials and their role in dielectric performance are discussed. Finally, key challenges, directions for further studies, and some promising nanostructured microwave receptors are suggested.

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1. Introduction

Microwaves are a form of electromagnetic radiation with wavelengths ranging from 1 m to 1 mm. These wavelengths correspond to a frequency range of 300 MHz to 300 GHz. Most domestic and industrial heating processes are operated at either 915 MHz (higher power) or 2.45 GHz (cheaper source) [1]. Microwaves can be generated by high-power sources including magnetrons (used in microwave ovens and available at lower cost than other sources), klystrons, traveling wave tubes and gyrotrons [2]. Microwaves are widely used in telecommunications, limiting wavelength choices for home and industrial heating use, and in thermal applications such as sintering of ceramics, drying, and cooking. Athermal applications include microwave-assisted reactions [3–8].

Materials can be categorized as having the following interactions with microwaves: (1) insulators or low dielectric loss materials that transmit microwaves without loss (i.e. transparent); (2) conductors or materials that reflect microwaves; (3) absorbers or high dielectric loss materials that absorb microwave energy and convert it to heat based on the value of the dielectric loss factor [9]. Dielectric heating is associated with the ability of the material to absorb high-frequency electromagnetic radiation (radio and microwave frequency waves) via the interaction of dipoles in the material with the electric field component of electromagnetic radiation [10,11]. Although various mechanisms including atomic polarization, electronic polarization, dipole (orientation) polarization, ionic conduction, and interfacial or Maxwell-Wagner polarization can contribute to the overall dielectric response of materials [12], only Maxwell-Wagner and dipole polarization mechanisms result in the conversion of microwaves to heat [13]. In polar organic materials, the dipole polarization mechanism is dominant in the microwave heating process. The rotation of dipoles aligning with the alternating field (approximately 2.5 billion times per second) generates friction among the rotating molecules, which release the energy as heat [14]. Maxwell-Wagner polarization is the dominant mechanism for compound dielectrics or for the case of two electrodes connected to a dielectric material. This type of interfacial polarization operates via charges that move in a defined region of the material, for example π-electrons in graphitic carbons, and does not require the internal motion of atoms within the material [11,15]. In this case, the electrons cannot couple to the phase changes of the electric field and accumulate at material interfaces at which point the energy is dissipated as heat [10,11].

The imaginary parts of complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$), complex permeability ($\mu = \mu' - j\mu''$) and complex conductivity ($\sigma = \sigma' - j\sigma''$) are the material parameters commonly used to quantitatively characterize electromagnetic absorption properties. No material demonstrates high values for all of these parameters across a broad range of frequencies [16]. Dielectric constant (ε') represents the ability of the material to store energy and dielectric loss (ε'') signifies the efficiency of converting electromagnetic energy into heat. The dissipative behavior can also be characterized by the value of loss tangent ($\tan\delta = \varepsilon''/\varepsilon'$), which is useful for estimating the ability of the material to convert electromagnetic energy to heat. For effective microwave absorption a high loss tangent value is needed. Loss factor values become important when dielectric constant and loss tangent values are close to each other. Microwave receptors with high value of dielectric loss absorb electromagnetic radiation, which is dissipated by conversion to other forms of energy [17]. These dielectric receptors or magnetic materials are often incorporated into materials [18,19] to change dielectric loss, magnetic loss and impedance matching characteristics and tune the electromagnetic absorption property to a desired set of characteristics [20,21].

The application of microwaves for heating is established for consumer and industrial processes. However, the full potential of this technology has not yet been tapped and many industrial heating processes can be explored by incorporating nanostructured microwave receptor materials. Microwave heating of materials with nanostructured microwave receptors incorporated offers unique advantages, such as high heating rates, reduced processing time, and significant energy savings, which cannot be attained with conventional heating. There is much less attention to nanostructured materials with high dielectric loss as microwave receptors as compared to the extensive literature describing the high permittivity, low dielectric loss materials used in electronics [22]. This paper reviews the developments in the areas of nanostructured microwave receptors and suggests directions for future studies of promising new materials systems. Dielectric properties of various materials reported in the literature have also been tabulated. However, there is a challenge in the field to make comparison of the dielectric properties of these materials due to the differences in testing methods and conditions including temperature, frequency, density, humidity, etc. In some cases, the test conditions are not reported by the authors.