ISSN – 2277-7911
Impact Factor – 5.519

YOUNG RESEARCHER
A Multidisciplinary Peer-Reviewed Refereed Research Journal

Jan-Feb-Mar 2024
Vol. 13 No. 1

Recent Advances In Low-Dimensional Nanostructures For Superior Microwave Attenuation: A Review

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DOI - 10.5281/zenodo.17121016

Abstract:

Electromagnetic interference and leakage have risen to the fourth-largest pollution source due to the vigorous progression of fifth-generation wireless communication and military multiband radars. The deployment of enhanced microwave absorption materials is an implementable strategy for addressing the problem of electromagnetic interference. Traditional bulk-phase materials feature single microwave attenuation model, unmatched impedance matching, and weak electromagnetic response, which renders them inappropriate for the design of enhanced microwave absorption materials. Low-dimensional nanostructures with programmable crystal and electronic structures, controllable micro-nanoscopic morphologies, and quantum and dielectric confinement effects have become highly sought-after research hot. The exploitation of low-dimensional nanostructure provides an attractive pathway for the development of state-of-the-art microwave absorption materials. Low-dimensional nanostructures, including zero-, one-, two- and mixed-dimensional nanomaterials, are extensively explored for applications in microwave absorption fields. In this review, the basic microwave attenuation mechanisms of low-dimensional nanostructure are firstly introduced thoroughly. Then, the recent advancements of low-dimensional nanostructure microwave absorption materials are systemically combed and summarized. Finally, the challenge and perspective for the future orientation of next-generation microwave absorption materials enriched by low-dimensional nanostructures are provided. Predictably, low-dimensional nanostructures represent the future of cutting-edge microwave absorption materials.

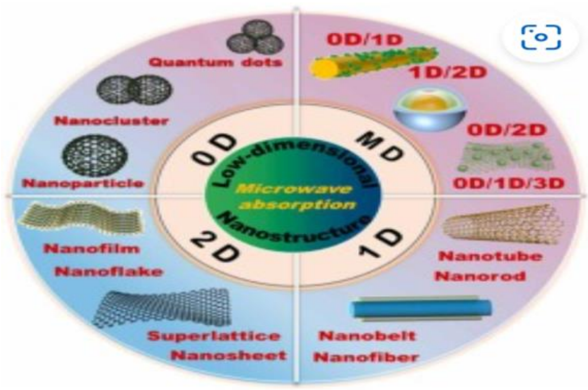
***Keywords:* Electromagnetic interference, programmable crystal and electronic structures, quantum dots (QDs), one-dimensional (1D) nanowires, nanotubes, or nanoribbons, and two-dimensional (2D) nanosheets**

Introduction:

With the rapid advancement of information science and technology, sophisticated electronic devices have become indispensable in national defense and daily life [1]. Excessive electromagnetic radiations in the space environment can generate serious electromagnetic interference and pollution [2], [3]. The pervasive microwaves interfere with precise equipment, bringing about signal disruptions and instrument failures [4], [5], [6]. Even more importantly, the excessive microwave exposures would adversely affect human physical and mental health, including disruption of tissues, organs, and endocrine systems [7], [8]. Furthermore, numerous highly complex weapons, such as fighter jets and missiles, may become the major targets of enemy assault due to unexpected electromagnetic leakages [9], [9]. Hence, the applications of advanced electromagnetic stealth technologies are critical to avoiding detection and attack of weaponry [1]. To alleviate the severe impacts of excessive microwave radiation and interference, electromagnetic functional materials with strong electromagnetic response and attenuation capability have been elaborately explored [2]. Correspondingly, the employment of microwave absorption materials has undoubtedly been developed as the foundation of advanced electromagnetic stealth or protection technologies [3]. In the past half century, there has been a surge in microwave absorption materials, principally including magnetic metals or ferrites, ceramics, carbon black or graphite, and conductive polymers [4]. However, the abovementioned microwave absorption materials are severely constrained in practical applications because of their high-density, difficult processing, poor stability, and insufficient researches in low or ultrahigh frequencies [16], [7]. The limitations of conventional materials present genuine challenges for the development of enhanced microwave absorption materials, leading to the thick thickness, narrow effective absorption bandwidth (EAB), weak reflection loss (RL) intensity as well as poor service stabilities [8], [9]. After comprehensive consideration, there are urgent requirements to explore high-performance microwave absorption materials with low-density, ultra-thin thickness, broad EAB, and strong RL intensity in virtue of the exploitation of state-of-the-art nanostructure and unique design strategies [2]. Fortunately, with the rapid advancements of quantum physics and nanotechnologies, low-dimensional nanostructures such as zero-dimensional (0D) quantum dots (QDs), one-dimensional (1D) nanowires, nanotubes, or nanoribbons, and two-dimensional (2D) nanosheets or nanoflakes have been thrived at a hitherto unseen rate, as Fig. 1 shown [2], [2]. Furthermore, 2D nanostructure can be successively composited with 0D or 1D nanostructures to achieve mixed-dimensional (MD) nanostructures.

Descriptions:

Microwave Attenuation Mechanisms of Low-Dimensional Nanostructure:



When microwaves strike the surface of microwave absorption substance, three steps normally take place, as illustrated in Fig. above]. Electromagnetic energy, which consists of microwaves, is dissipated by interacting with the molecular or electronic structures and turned into heating [2]. Surface reflections and internal multiple reflections are both types of microwave reflections. Surface reflections degrade the attenuation capabilities of microwave absorption materials and reduce

Zero-dimensional Microwave Absorption Materials:

Many well-established techniques have been utilized to produce size-tuneable 0D materials. The 0D nanostructures, such as quantum dots, nanoclusters, and nanoparticles, have been widely studied [7]. Generally, 0D nanostructures possess significant size-limited features [7]. Therefore, the travel of electrons in 0D nanostructures is constrained, and the interior electrons are not free to migrate [7]. The existence of unsaturated active centres and abundance of surface atoms for 0D.

Challenges and Perspectives of Low-Dimensional Nanostructure Microwave Absorption Materials:

The design and development of low-dimensional microwave absorption materials have made great progress at the current stage, and their corresponding theoretical preparation methods and precise control strategies are becoming more and more mature.[9] However, the industrialization and engineering of low-dimensional nanostructure microwave absorption materials still have many difficult challenges,

Methods Outcomes:

Generally, low-dimensional nanostructures are emerging materials with ultra-high aspect ratios, in which the electron mobilities at nanoscale are constrained to a single dimension [2]. Low dimensionality has an enormous influence on its physical and chemical characteristics for nanostructures [6]. Thus, decreasing the dimensionalities of nanostructures often leads to changes in carrier concentrations, electric and magnetic fields, and dielectric constant and so on [7], [8]. Specifically, the response of low-dimensional nanostructures to alternating electromagnetic fields is extremely sensitive [9]. In this case, a larger multi-parameters space is often utilized for the directed and exact modulation of structure and physical characteristics to optimize the unique quantum states and features [30]. For example, the small-scale characteristics of low-dimensional nanostructures often result in unique confinement and quantum-size effects. Therefore, low-dimensional nanostructures possess unmatched electromagnetic response merits in alternating electromagnetic fields that cannot be compared to its macroscopic bulk-phase materials [3]. Exploring advanced low-dimensional nanostructure microwave absorption materials and applying them to the electromagnetic protection of national defense weapons and intelligent electronic equipment have become the main development direction of electromagnetic stealth technology [6], Low-dimensional nanostructures have a domain-limiting impact because of their nanoscale, while the bulk-phase material cannot be realized [3]. The change of dimension, for instance in low-dimensional carbon nanostructures nanomaterials, can effectively modulate energy gaps and conductivities [3]. Generally, the conductivity of carbon nanostructures increases while the energy gap decreases from 0D fullerene to 2D graphene. Therefore, lowering the thickness of nanostructure is advantageous for increasing carrier mobility, conductivity, and specific surface area [3]. Correspondingly, dimensionality modification can significantly boost electromagnetic shielding and microwave attenuation capabilities for low-dimensional nanostructures [3], Bracingly, the widely studied low-dimensional nanostructures have sparked extensive research on their physical and chemical properties [3]. The perfect electromagnetic responses, surface effects, quantum size and tunnelling effects of low-dimensional nanostructure microwave absorption materials provide brand new insights into the mechanisms of microwave attenuation [3], this review begins with an introduction to the basic design and theories of microwave absorption materials, followed by the microwave attenuation mechanisms of low-dimensional nanostructure materials. Afterwards, the recent advancements of low-dimensional nanostructure microwave absorption materials including zero-, one-, two-, and mixed-dimensional nanostructures, are systemically combed and summarized. Finally, the challenge and perspective for the future orientation of next-generation microwave absorption materials enriched by low-dimensional nanostructures are provided. Overall, this review provides valuable and enlightening guidance for the utilization of low-dimensional nanostructures to achieve microwave absorption materials, leading to electromagnetic protection and eventually promoting electromagnetic safety in practical applications.

Conclusion:

With the development of high-precision military equipment and the full advent of the 5G-6G digital eras, the demand and standard of high-performance microwave absorption materials will be higher. Low-dimensional nanostructures have been developed into the most promising microwave absorption materials due to their unique physicochemical properties and electromagnetic responses. In this review, the basic microwave attenuation mechanisms of low-dimensional nanostructure are firstly.

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