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Review article

Mechanisms and applications of carbon nanotubes in terahertz devices: A review

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ABSTRACT

Terahertz (THz) technology has been widely utilized in fields of multiple disciplines because of its unique properties such as broadband and directivity. With existing and emerging technologies increasing demand for compact, fast and broadband terahertz devices, high-performance THz devices are becoming indispensable. Carbon nanotubes (CNTs) with superior optical and electronic performance have prompted intense research and significant advances, paving the way for realistic applications. In this review, we introduce the mechanisms of utilizing carbon nanotubes to generate, modulate, polarize, and detect terahertz radiation. We also discuss recent carbon nanotube terahertz devices based on these mechanisms, including THz antennae, emitters, amplifiers, transistors, polarizers, and1 detectors. Furthermore, the main performance achievement for such devices is summarized briefly, and an outlook on the performance improvement for existing deficiencies is presented.

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1. Introduction

Terahertz (THz) radiation generally refers to the electromagnetic waves at the frequency of 0.1–10 THz, which lies between the microwave and infrared regions of the spectrum [1]. THz technology has been widely utilized and has found significant applications in multiple disciplines and areas (Fig. 1), including optics [2], physics [3], materials science [4,5], agriculture [6], biology [7], pharmaceutical quality control [8], and medical inspection [9], because of its unique properties such as directivity and broadband [10]. With the birth of the first terahertz quantum cascade laser (QCL) in 2002 [11], great growth in the development of THz QCLs has covered the “THz gap”. Although THz QCLs have been applied commercially, they still face the need for cryogenic operating temperatures [12–15]. Furthermore, there remains unexplored territory for THz technology mainly because of a lack of affordable and efficient THz devices [16]. As a result, searching for high-performance, stable, and compact THz devices is extremely necessary [17]. The carbon nanotubes (CNTs), which have potential applications because of their interesting and diverse optical and electronic properties, have achieved such a goal [18].

Carbon nanotubes discovered in 1991 triggered one of the most widely studied subjects in the field of physics [20]. Currently, CNTs are becoming a central subject in many applied areas of physics, as well as electronic and photonic engineering [21]. They are seamless cylinders of at least one layer of graphene [22]. On the basis of the number of tube layers, CNTs can be divided into three categories that are single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs) and multi-walled carbon nanotube (MWCNTs) [23]. No previous material has possessed the combination of superlative photoelectric and thermodynamics properties attributed to the strength of the carbon-carbon bonds [24]. CNTs are the strongest materials ever discovered by human beings [23,25,26]. Additionally, CNTs have excellent high thermal conductivity, as well as chemical and environmental stability [24]. Especially notable is the extraordinary electronic properties of CNTs [27]. They can carry a current density as high as 10^9 A/cm^2 because of the interplay of high mechanical strength, high thermal conductivity, and extremely low electrical resistivity. It is worth mentioning that they are capable of superconductivity at low temperatures [28,29]. The unique electrical properties of CNTs are largely attributed to their one-dimensional (1D) characteristics and the peculiar electronic structure of graphite. Furthermore, the manner in which the SWCNT is rolled from a graphene sheet strongly dictates its electronic properties [30]. A SWCNT may behave electrically as either a metal or semiconductor depending on its helicity index (chiral angle) [31]. The chiral vector $C_h = na_1 + ma_2$ is described by a pair of integers (n, m) connecting two crystallographically equivalent sites on a two-dimensional (2D) graphene sheet that can determine the structure [32]. Generally, (n, m) tubes with $n = m$ are metals, (n, m) tubes with $n - m = 3j$ $(j \neq 0)$ are small gap semiconductors, and others are all medium-gap semiconductors [33]. It should be emphasized that metallic armchair $(n = m)$ nanotubes are gapless, while non-armchair $(\mathrm{n} \neq m)$ tubes are actually narrow-gap semiconductors with small curvature-induced bandgaps [32]. Semiconducting nanotubes have bandgaps ranging from approximately 1.8 eV–0.18 eV inversely with diameter; therefore, semiconducting CNTs behave more like silicon, while metallic CNTs have conductivities higher than copper [34]. The characteristics of carbon nanotubes are listed in Table 1.

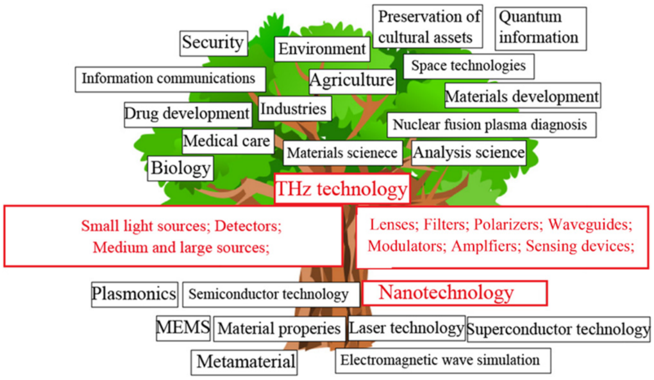

Fig. 1. Illustration of the relationship between the nanomaterials and terahertz devices [19]. Figures adapted with permission from The Japan Society of Applied Physics, Copyright (2015). (A colour version of this figure can be viewed online.)

CNTs are appealing materials for photonics and optoelectronics because they offer several advantages such as radiative decay and nonlinear optical phenomena, as well as transport, photoconductivity, and photovoltage properties comparable with silicon-based materials [37]. CNTs are already being used in several areas of technology including flat panel displays [38], scanning probe microscopes [39], sensing devices and fuel cells [35]. These facts imply that CNTs have important application value for high-frequency THz devices. More precisely, there are two reasons for using CNTs as high-frequency THz devices. First, fabricating ballistic high-frequency room-temperature devices based on CNTs is mainly attributed to their large mean free paths [36]. Second, the cutoff frequency of CNT ballistic devices is exactly in the THz range [36]. It is widely accepted that SWCNTs are rolled from graphene. Therefore, to better understand the properties of CNT THz electronics, it is necessary to clarify the electronic band structure of graphene. In graphene, the sp^2 hybridization setup is that each atom is connected evenly to three carbons in the $x - y$ plane, which forms the typical hexagonal (honeycomb) lattice of a graphite sheet. The honeycomb structure of graphene carbon atoms can be considered as the superposition of two triangular lattices. The distance between two neighboring carbon atoms is 0.14 nm, and the unit lattice is spanned by the vectors a_1 and a_2[40]. The hexagon displayed