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Materials Today: Proceedings 3S (2016) S221 – S226

Proceedings of the International Conference on Diamond and Carbon Materials

Enhanced terahertz emission from monolayer graphene with metal mesh structure

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Abstract

The development of compact, low-cost sources and detectors operating at room temperature is needed to fully use terahertz (THz) electromagnetic waves in a variety of applications. Photo-excited graphene is expected to exhibit population inversion and enable the fabrication of a novel THz laser. We previously proposed a THz amplifier as a basic element in a THz laser by combining the population inversion in photo-excited graphene with the electric field enhancement due to the spoof surface plasmon polaritons induced on the surface of a metal mesh structure. For this work, we fabricated prototype THz amplifiers composed of chemical-vapor-deposition-grown graphene and a metal mesh structure and observed extremely amplified THz emission by using an electro-optic sampling method.

Selection and Peer-review under responsibility of the chairs of the International Conference on Diamond and Carbon Materials 2014.

Keywords: Graphene; Terahertz; Amplifier; Metal mesh structure; Surface plasmon; SPP; Field enhancement effect

1. Introduction

The terahertz (THz) electromagnetic (EM) wave region of 0.1–100 THz located between radio and light is expected to open up various applications including ultrahigh-speed wireless communications, material characterization, nondestructive evaluation, and imaging. However, the lack of commercially available microelectronic devices that

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Selection and Peer-review under responsibility of the chairs of the International Conference on Diamond and Carbon Materials 2014.
doi:10.1016/j.matpr.2016.02.037

can generate and detect THz waves at room temperature (RT) significantly hampers the development of the THz region. This situation is often called the “THz gap”. The reason for opening the THz gap is that the maximum operating frequency of electronic devices is limited by the electron velocity in semiconductors and that optical devices are affected by thermal noise at RT because the bandgap energy contributing to laser oscillation is small. Therefore, we expect that THz devices will be developed using a novel operating principle and/or materials.

Graphene, a two-dimensional honeycomb structure of carbon atoms, has attracted a large amount of attention due to its unique nature and potential applications [1, 2]. In particular, the linear energy-band structure of graphene leads to the development of THz device applications [3]. Excitation of surface plasmon polaritons in population-inverted graphene can dramatically enhance the THz gain [4], which has recently been experimentally observed [5]. Based on the EM properties of photo-excited graphene and metal mesh structures described in the next section, we came up with an idea for THz amplifiers with remarkably enhanced gain at a particular frequency by combining these structures [6]. The purpose of this study was to fabricate prototype THz amplifiers composed of chemical-vapor-deposition (CVD)-grown graphene and a metal mesh structure and to characterize them by using an electro-optic sampling (EOS) method.

2. Principle

Theoretical investigations predicted that the electron-hole pairs generated by the illumination of infrared light (ex. 1.55 μm) on to graphene would exhibit population inversion and negative dynamic conductivity (or gain) in a wide range, 1–10 THz, with a peak at around 3 THz despite strong carrier-carrier scattering [7–9]. Recently, Boubanga-Tombet *et al.* observed enhanced THz emissions from exfoliated graphene on a SiO_2/Si substrate by using EOS and revealed threshold behavior against pumping intensity, which suggested the occurrence of negative dynamic conductivity [10].

A structure having a periodic array of holes in a metal sheet, referred to as metal mesh structure, has been known to exhibit extraordinary optical transmission (EOT) at wavelengths slightly longer than the period of the array. Surface plasmon polaritons (SPPs) are induced when EM waves are illuminated on to the metal mesh structure. These SPPs are often called “spoof” SPPs to differentiate them from SPPs on a flat metal [11]. The EM energy stored as SPPs on both sides of the metal mesh is reemitted into free space on the output surface. The SPP-mediated resonant mode couples to the non-resonant radiation mode through evanescent waves in the hole, which produces Fano-resonance transmission spectra [12–14]. The EOT with metal mesh structure has been reported in a wide range of the EM wave regions including that of THz [15, 16].

3. Experimental

3.1. Basic structure of THz amplifier

Fig. 1(a) shows the previously proposed THz amplifier [6], and Fig. 1(b) shows a fabricated prototype THz amplifier. A semi-insulating GaAs substrate for supporting the graphene and metal mesh was used to generate THz waves by optical rectification and to avoid energy loss of both generated THz waves and induced SPPs. The CVD-grown monolayer graphene (Meijo Nano Carbon Co., Ltd.) was transferred onto the surface of the GaAs substrate with a thickness of 600 μm. A square metal mesh with a period of 60 μm and an edge length of holes of 30 μm was formed by depositing and lifting off 50-nm-thick Pt/Pd on the graphene. The period and edge length of holes were determined through finite-difference time-domain (FDTD) EM simulations so that the transmittance for the metal mesh peaked at 1.5 THz in consideration of the measurement system used in this work and THz gain spectrum shown by Ryzhii et al. [7]. We chose Pt/Pd because of better adhesion to graphene than other metals such as Au. This sample is referred to as GaAs + Metal + Graphene. For comparison, we fabricated two samples: monolayer graphene on a GaAs substrate (referred to as GaAs + Graphene) and a metal mesh with the same geometry on a GaAs substrate (referred to as GaAs + Metal).