Prospects for the Application of Two-Dimensional Materials to Terahertz-Band Communications

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ABSTRACT

In this paper, we review some of the key properties of emergent two-dimensional (2D) materials that make them potentially attractive for application in the hardware components needed to enable future communications in the terahertz (THz) band. Graphene is a material that has attracted enormous interest in recent years, due to its high electrical and thermal conductivities, and its capacity to exhibit pronounced and controlled plasmonic effects. Here we describe several schemes that seek to exploit these characteristics for the sourcing, manipulating, and detection of THz signals. Another class of 2D materials that are also promising for use in this area are the transition metal dichalcogenides (TMDs). These include materials such as MoS_2 and WS_2, which, like graphene, exhibit a multi-valley conduction band structure. In contrast to graphene, however, the valleys of TMDs are highly asymmetric, a characteristic that may allow the realization of novel high-frequency sources capable of THz operation.

CCS CONCEPTS

• **Hardware → Wireless devices**; **Plasmonics**; *Analysis and design of emerging devices and systems*;

KEYWORDS

Terahertz-band communications, two-dimensional materials, graphene, transition metal dichalcogenides

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1 INTRODUCTION

Recent decades have witnessed massive growth in the use of wireless devices, a trend that is placing increasing burdens on the spectral bands used for communication. As wireless networks evolve from RF to the mm-wave bands, it is clear that the continued expansion of this technology will ultimately require the ability to tap into uncharted regions of the electromagnetic spectrum. Most notably, the terahertz (THz) region (1 THz = 10^{12} Hz) lies at the boundary between between the capabilities of electronic and optical technologies, and is ripe for development of high-speed communications [1].

Harnessing the full capacity of the THz band (1–10 THz) requires the development of new hardware able to source, manipulate, and detect signals in this frequency range. This turns out to be a significant challenge. While there have been decades of effort devoted to this problem, in numerous laboratories across the world, the recent emergence of atomically thin semiconductors presents a new opportunity to push this technology forward. It is this issue that we focus on in this short paper, in which we briefly highlight some of the features of 2D materials that make them of interest for THz applications.

2 GRAPHENE: A MEDIUM FOR TERAHERTZ PLASMONICS

Graphene is a two-dimensional carbon material that has excellent electrical conductivity, making it very well suited for propagating extremely-high-frequency electrical signals [2]. Moreover, graphene supports the propagation of THz surface plasmon polariton (SPP) waves. This is a very unique property, as SPP waves only propagate in conventional plasmonic materials in the infra-red and above. In addition, the SPP wave propagation properties can be dynamically tuned by changing the graphene conductivity, which ultimately leads to reconfigurable devices.

Motivated by these properties, graphene-based plasmonic devices for THz-band communications have been proposed. In [4], we proposed the use of graphene to create plasmonic nano-antennas that can efficiently operate in the THz band. The proposed nano-antennas, which leverage the propagation properties of SPP waves on graphene, are just a few micrometers long and hundreds of nanometers wide, i.e., two orders of magnitude smaller than THz metallic antennas. In [5], we proposed and analyzed the performance of a THz plasmonic signal source and detector based on a hybrid graphene III–V semiconductor HEMT. Compared to existing plasmonic sources and detectors, the generated plasma wave is not directly radiated, but utilized to launch an SPP wave on the graphene layer that extends towards the nano-antenna. More recently, we proposed a THz plasmonic phase modulator built with a tunable graphene-based waveguide [6]. This requires integrating into the fabrication process high-quality graphene, which we are synthesizing by chemical vapor deposition and working to optimize the transfer process.

3 TWO-DIMENSIONAL TRANSITION METAL DICHALCOGENIDES

Transition metal dichalcogenides (TMDs) are materials with the general chemical formula MX_2, in which M is a transition-metal atom (such as Mo, W, etc.) and X is a chalcogen atom (such as S, Se, or Te) [7]. Similar to graphene, these materials may be isolated in "monolayer" form by various techniques, with the monolayer actually consisting of a single layer of metal atoms that is sandwiched between two layers of chalcogen atoms. In this form, these materials are direct semiconductors, with bandgaps slightly larger than those of Si or GaAs (MoS_2: 1.8 eV; WS_2: 1.9 eV; WSe_2: 1.7 eV). Another important feature of these materials is their multi-valley conduction band structure, which, in pronounced contrast to that of graphene, is highly asymmetric. This point is illustrated for the representative case of WS_2 in Fig. 1, where we plot the variations of the energy bands along the principal directions of symmetry within the hexagonal crystal.

This reveals the presence of a direct gap ($E_g = 1.8\,\text{eV}$) at the high-symmetry K point, and of a satellite valley that is located at T between the Γ and K points. The energy separation (Δ) of these two valleys is around 80 meV, and the electron mass in the satellite valley ($m_T^* = 0.75m_o$, where m_o is the free-electron mass) is heavier than that near the K point ($m_K^* = 0.32m_o$). From this description, it is clear that the TMD bandstructure has many features in common with gallium arsenide, which has long been realized as a material for microwave generation via the Gunn effect. In this effect, electrons in the conduction band of GaAs are driven up its central "gamma" valley under the action of an electric field, eventually gaining sufficient energy that they are able to scatter into the higher energy "L" valleys. Carriers in these valleys exhibit a lower mobility than those within the Γ valley, resulting in the appearance of negative differential conductance (NDC) in the current-voltage characteristic of the material. The NDC in turn allows the material to function as a high-frequency source of electromagnetic radiation, which radiates in the microwave bands as carriers are driven back and forth between the Γ and L valleys.

The similarity of the bandstructure of the monolayer TMDs to that of GaAs means that the former materials may also be expected to exhibit NDC and radiation emission. There are reasons to be encouraged, however, that this emission may occur in the THz, rather than the microwave range. The key property here is the maximal (or saturated) drift velocity that electrons are able to attain under the application of large electric fields. There is growing experimental evidence that, in TMDs, this velocity may significantly exceed that of conventional semiconductors ($10^6\,\text{m s}^{-1}$ *vs.* $10^5\,\text{m s}^{-1}$), allowing correspondingly higher frequency of emission as high-field domains

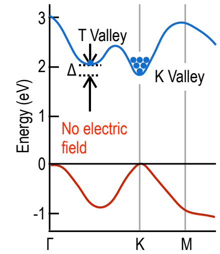

Figure 1: Bandstructure of monolayer WS_2. The T valley is located between the Γ and K points, and is separated from the K valley by an amount Δ. The relative thermal population of the valleys is indicated schematically at zero bias.

are able to propagate through the TMD channel at faster speeds. A key condition for observation of NDC is that the T valley should not be overpopulated at thermal equilibrium, a requirement that is sensitive to the precise value of the inter-valley separation (Δ in Fig. 1). According to recent unpublished results, [3] this separation is sensitive to mechanical strain, a feature that allows for external control of NDC, and for the coupling of mechanical properties to the THz characteristics.

4 CONCLUSIONS

We have discussed the potential applications of 2D materials to emerging THz technology. These materials, which come in many different forms, offer promise as compact elements that can be used to source, manipulate, and detect THz radiation. It seems clear that these materials will be of key importance to the development of future THz technology.

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