Invited Paper

THz Signal processing concepts based on graphene

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Abstract: A number of THz signal-processing components are proposed. Firstly, a ballistic resonator is simulated for a graphene semiconductor structure. Graphene semiconductors have the advantage of exhibiting energy gaps depending on the width of the graphene sheet. Therefore loss free reflection of ballistic electrons as established by heterojunction epitaxy, can be realized by shaping the graphene widths. The design of corresponding THz oscillators is presented. Then quantum cascaded THz emitters are described. Finally, a number of basic components such as Schottky diodes on graphene transistors are discussed.

Keywords: THz wave, Ballistic electrons, Electron reflection, Semiconductor heterostructures, Quantum cascades in graphene, THz rectification by graphene FETs

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1. Introduction

The special properties of graphene make it very attractive for a manifold of applications. These properties include the potential for extremely high carrier mobility, its thickness of one atomic layer, compatibility to standard electron lithography processes, high transmission in the visible (97.7%), and carrier-density controllable transmission coefficient in the THz. This publication describes some simulations of these applications.

2. Semiconducting graphene

Graphene does not have a bandwidth and is a semimetal with charge carriers of zero mass. A bandgap can be formed by confining the graphene width in nanoribbon or nanoconstricition structures. For example, the induced bandgap by a 20 *nm* wide nanoribbon is about 50 *meV*, while for a nanoconstriction with a 20 *nm* constriction width; this can be about 130 *meV*. The charge carrier mass then increases, but is still very small. The energy gap of graphene stripes is similar to that of Carbon Nanotubes, whose value is Eg (*eV*) =0.8/d (*nm*) (d = CNT diameter).

3. Design of a ballistic graphene resonator

To obtain a ballistic graphene resonator, a pattern needs to be fabricated consisting of the following structure: narrow width - large width - narrow width (fig. 1). It is advantageous regarding higher signal powers not to use monolayer graphene.

The charge swing of ballistic electrons in III-V heterostructures was theoretically and experimentally reported by the author and his research colleagues by various publications [1-5]. For short distances the charge carriers (both electrons and holes) travel without being scattered, means as if they travel in vacuum. Such ballistic distances increase with the reduction of temperature. Ballistic distances at room temperature are a few hundred of nanometers. Ballistic transport is affected in the usual way by electric and magnetic fields, and the tunneling effect can occur. Also heterojunctions in common semiconductors cause a loss free reflection at the barrier, if this is higher than the electron energy and no tunneling can occur. Similarly, such THz components can be considered to be realizable in Graphene.

Multilayer Graphene would also be expected to enhance the resulting signal amplitude. The electron injection is by ohmic contacts (such as Cr/Au) due to a lower frequency bias (R_{fa} & R_{fb}), or by lower frequency optical pulsing.

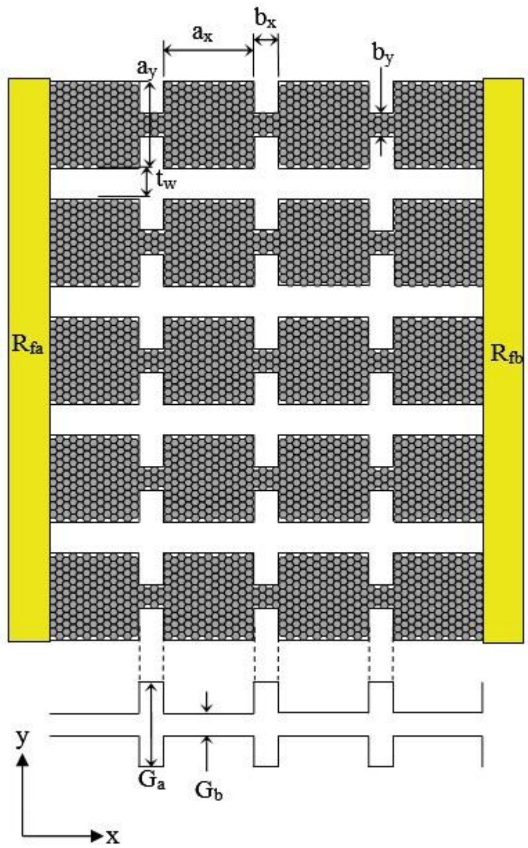

Fig. 1 Details of proposed structure

$$G_a = 500\ meV,\ \text{and}\ G_b = 100\ meV,$$
$$a_y = 200\ nm,\ \text{and}\ b_y = 40\ nm$$
$$a_x = V_0 / f\ ,\quad V_0 \approx V_F \approx 10^6\ m/s\ ,$$

V_0 the electron velocity, V_F the Fermi velocity in graphene [7, 8],

f , Terahertz frequency;

$$\text{for } f = 1\ THz:\ a_x = 1\ \mu m,$$
$$b_x = t_w \approx a_x / 3$$

The structure has to be fabricated by electron-beam lithography in the shape of a matrix of repetitions along x and y directions in order to increase the signal amplitude (fig. 1). In this way, a sheet of Graphene structures with THz ballistic resonances is possible with an overlaying antenna structure. Our design of such a matrix gives estimates the signal power to be achieved. The external THz resonator is either a cavity or a suitable over-laying dipole antenna structure, in order to couple the THz signal out with good efficiencies.

4. Quantum resonance structures

The design of a quantum electronic structure on semiconducting graphene is described here, where electrons (and holes) are heated appropriately by suitable stripe structures under the action of applied voltages. These electrons enter a resonance region with two states. By dropping from the higher energy state to the lower one, energy of a THz photon is lost and the corresponding photon can be emitted. Using an external resonator a laser can be realized, where the graphene nanostructures acts as active medium.

We illustrate in Fig. 2 a cascaded structure for THz emission where electrons are dominant. The structure is similar to a quantum cascade laser: At the end of one period, electrons drop into the next period, emitting photons and phonons. With a suitable external resonator, stimulated photon emission results in lasing.

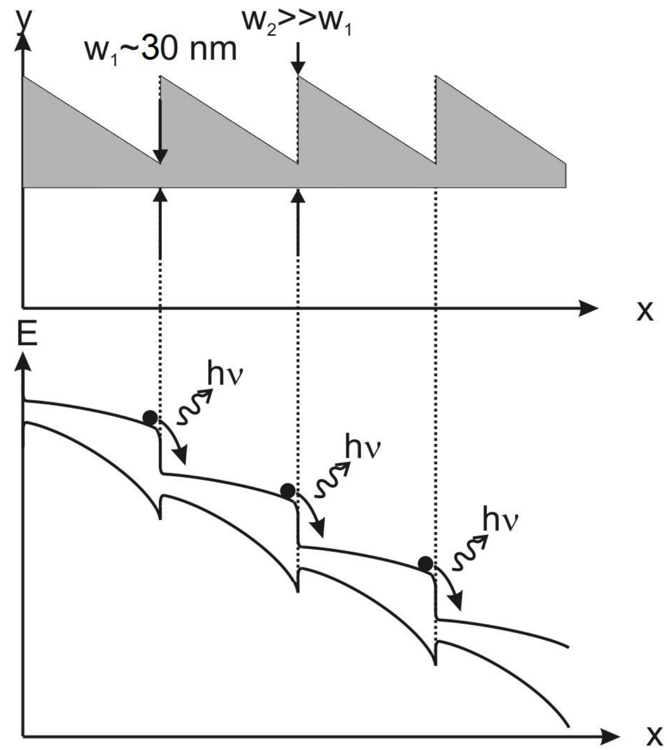

Fig 2. The concept of a ballistic resonator for the generation of THz signals is proposed and a designed.

Whether electrons or holes are the dominant carrier in charge transport depends on the doping of graphene which can be tuned by adsorbates. It appears that the ballistic electron reflection at a graphene barrier is not prevented. In fact, under suitable structural and operational conditions, total electron reflections occur [6]. It is likely that parallel Double Ballistics of electrons and holes occur then. The external THz resonator is either a cavity or a suitable over-laying dipole antenna structure, in order to couple the THz signal out with good efficiencies.

5. Further device concepts

Field effect transistors can rectify THz radiation, generating a DC bias that is proportional to the incident THz power. The rectification remains efficient even if the transistor is operated far above its respective maximum frequency for amplification. Such transistors require ohmic source-drain contacts and a gate Schottky-type contact to a two-dimensional electron gas (2DEG). Graphene with its excellent material parameters can be used as the 2DEG material in FETs, offering mobilities much higher than those of silicon devices and compatible with any kind of high resistivity substrate and CMOS processes. In terms of device processing, it is fairly simple to achieve ohmic source and drain contacts to graphene. However, obtaining high quality, low leakage Schottky-type gate contacts requires some engineering. The absence of a band gap prevents formation of natural Schottky contacts to graphene. An oxide or dielectric insulation layer is required. For efficient rectification, the thickness of this layer should be as small as possible in order to increase the control of the gate bias on the carrier density in graphene, which follows a simple plate capacitor model.

The gate dielectric must be of high quality to prevent charge trapping in the dielectric. These trapped charges lead to a drift in the effective gate bias and hysteresis. Thermally evaporated dielectrics show a large amount of chargeable traps and are a poor choice. Atomic layer-deposited materials such as Al_2O_3 have excellent materials properties and can be deposited in atomically thin layers. However, growth of a closed film on bare graphene is difficult: water is used as precursor for Al_2O_3 growth, but the hydrophobic nature of graphene prevents adhesion of water.

In the visible domain, the transmission loss through graphene is dominated by inter-band absorption. Due to the linear band diagram, it is fairly constant at a value of only 2.3%. Transmission in the THz domain, however, is dominated by intraband absorption of electrons (or holes) at the Fermi energy. The transmission through graphene can be controlled by the charge density in graphene: more carriers result in higher losses.

By adding structure to graphene, additional performance features can be generated. One of the simplest structures is a grating of graphene strips. The constriction gives rise to surface plasmon-polaritons which alter the THz transmission for the electric field along the grating.

A series of plasmonic structures for manipulating light has been proposed for the infrared range which may be extended to the THz. This includes waveguides and splitters. Further, the chemical potential of a graphene sheet can be periodically altered in order to generate additional functionality by plasmons. This includes spherical n-p junctions that act as lens.

Also, first THz metamaterials with an active graphene layer have been considered..

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