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Carbon nanotubes as a basis for terahertz emitters and detectors

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ABSTRACT

We propose and justify two schemes utilizing the unique electronic properties of carbon nanotubes for novel THz applications including tunable THz generation by hot electrons in quasi-metallic nanotubes and THz radiation detection by armchair nanotubes in strong magnetic fields.

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1. Introduction

Creating compact reliable sources and detectors of terahertz (THz) radiation is one of the most formidable tasks of the contemporary applied physics [1]. One of the latest trends in THz technology [2] is to use carbon nanotubes—cylindrical molecules with nanometer diameter and micrometer length [3]—as building blocks of novel high-frequency devices. Below we discuss several novel schemes to utilize physical properties of single-wall carbon nanotubes (SWNTs) for generation and detection of THz radiation.

2. THz emitters

The first proposed scheme of THz generation is based on the electric-field induced heating of electron gas resulting in the inversion of population of optically active states, with the energy difference within the THz spectrum range. The electron energy spectrum of metallic SWNTs, $\varepsilon(k)$, linearly depends on the electron wave vector k close to the Fermi energy [3]. In Fig. 1 the zero of energy is defined as the Fermi energy position in the absence of an external field.

When the voltage is applied along the SWNT axis, the electron distribution is shifted in the way shown by the heavy lines in Fig. 1a corresponding to the filled electron states in the presence of the applied voltage. It results in the inversion of population and, correspondingly, in optical transitions between filled states in the conduction band and empty states in the valence band (Fig. 1b). It is well known that the major scattering mechanism in SWNTs is due to electron–phonon interaction [3]. Since the scattering processes erode the inversion of electron population, an optimal condition for observing the discussed optical transitions takes place when the length of the SWNT $L<l_{ac}$, where $l_{ac}\approx 2.4\,\mu\text{m}$ is the electron mean-free path for acoustic phonon scattering. Below we consider such short SWNTs only. If the electron heating energy $\Delta\varepsilon$ is less than the value $\hbar\Omega\approx 0.16\,\text{eV}$, at which the fast emission of high-energy optical/zone-edge phonons begins, the electronic transport is ballistic and $\Delta\varepsilon = eV$, where V is the potential

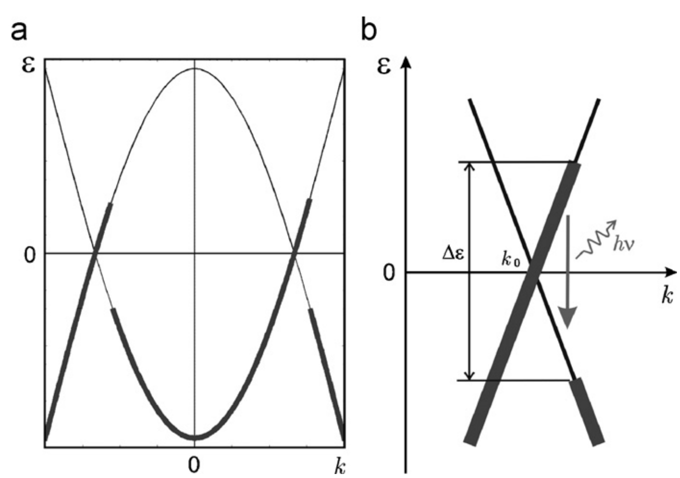

Fig. 1. (a) The filling of electron states (heavy lines) in the first Brillouin zone of SWNT in the presence of the bias voltage; (b) the scheme of electron radiation transitions resulting in terahertz emission from SWNT.

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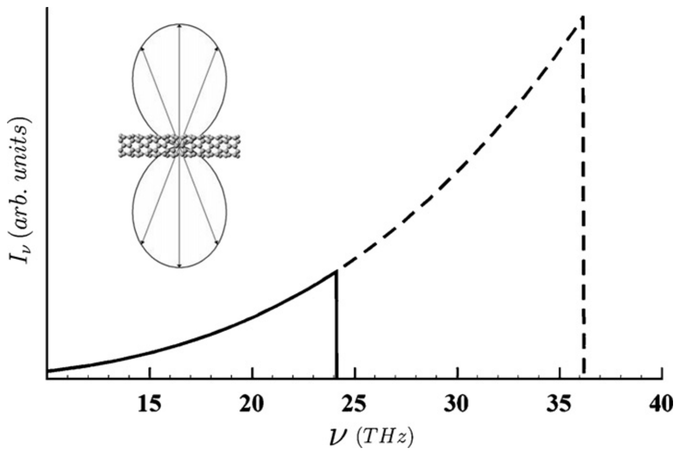

Fig. 2. The spectral density of spontaneous emission as a function of frequency for two values of applied voltage: solid line for $V = 0.1$ V; dashed line for $V = 0.15$ V. The inset shows the directional radiation pattern of the THz emission with respect to the nanotube axis.

difference between the SWNT's ends. At higher applied voltages, $V \geqslant \hbar\Omega/e$, the heating energy is $\Delta\varepsilon \approx \hbar\Omega$. The heating results in the spontaneous photon emission with the peak frequency $\nu \approx \Delta\varepsilon/h$ controlled by applied voltage and restricted by the SWNT optical/zone-edge phonon energy corresponding to the frequency of about 40 THz. Let us select a SWNT with the crystal structure most suitable for observation of the discussed effect. Firstly, the required nanotube should have metallic conductivity and, secondly, the optical transitions between the lowest conduction subband and the top valence subband should be allowed. It is well known that he crystal structure of SWNTs is described by two integers (n, m), which completely define their physical properties [3]. The SWNTs with true metallic energy band structure, for which the energy gap is absent for any SWNT radius, are the armchair (n, n) SWNTs only [4]. However, for armchair SWNTs the optical transitions between the lowest conduction and top valence subbands are forbidden[5]. So we propose to use for the observation of THz generation the so-called quasi-metallic (n, m) SWNTs with $n - m = 3p$, where p is an integer. These nanotubes, which are gapless within the frame of a simple zone folding model

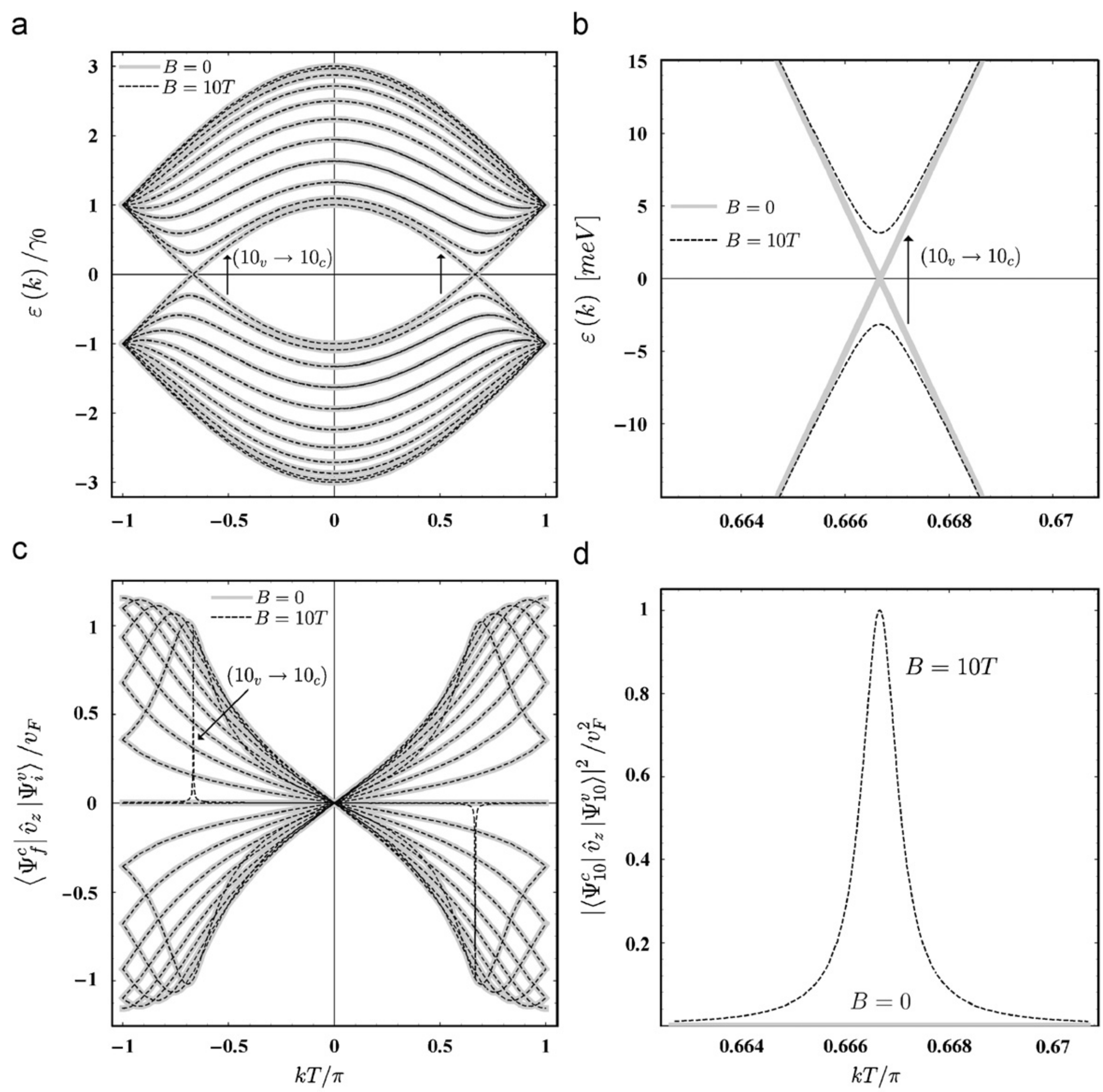

Fig. 3. (a) Band structure of a (10, 10) SWNT, with and without an external magnetic field along the nanotube axis; (b) detailed view of the gap, which is opened between the top valence subband and the lowest conduction subband in an external field $B = 10$ T; (c) the change in the dipole optical transitions matrix elements, for the light polarized along the SWNT axis, due to the introduction of the external magnetic field. The only appreciable change is in the appearance of a high narrow peak associated with the transition ($10\nu \to 10c$), which is not allowed in the absence of the magnetic field; (d) dependence of the squared dipole matrix element for the transition ($10\nu \to 10c$) on the 1D wave vector k, with and without an external magnetic field.

of the π-electron graphene spectrum [3], are in fact narrow gap semiconductors due to curvature effects. However, their band gap is decreasing rapidly with increasing the nanotube radius [4]. Therefore for large values of R this gap can be neglected even in the case of moderate applied voltages due to the Zener tunneling of electrons across the gap [6]. For example, for a zigzag $(30,0)$ SWNT the gap is $\varepsilon_g \approx 6\,\text{meV}$ and the Zener breakdown takes place for the electric field $E{\sim}10^{-1}\,\text{V}/\mu\text{m}$. Since almost the whole voltage drop in the ballistic regime occurs within the few-nanometer regions near the contacts, a typical bias voltage of 0.1 V corresponds to an electric field, which is more than sufficient to achieve a complete breakdown. In Fig. 2 the spectral density of emission from the quasi-metallic SWNTs is shown for two values of the bias voltage. It is clearly seen that the maximum of the spectral density of emission has strong voltage dependence and lies in the THz frequency range for experimentally attainable voltages. The directional radiation pattern, shown in the inset of Fig. 2, reflects the fact that the emission of light polarized normally to the nanotube axis is forbidden by the selection rules for the optical transitions between the lowest conduction subband and the top valence subband. The discussed effect can be used for creating a THz source with the frequency controlled by the applied voltage.

3. THz detectors

The problem of detecting THz radiation is known to be at least as challenging as creating reliable THz sources. Our proposal of a novel detector is based on several features of the truly gapless (armchair) SWNTs shown in Fig. 3. The main property to be utilized is the opening of the gap in these SWNTs in a magnetic field along the nanotube axis [3]. For a $(10,10)$ SWNT this gap is approximately 1 THz in the field of 6 T. The gap grows linearly with increasing both magnetic field and the nanotube radius. It can be shown [6] that the same magnetic field also allows dipole optical transitions between the top valence subband and the lowest conduction subband, which are strictly forbidden in armchair SWNTs without the field [5]. The electronic (hole) energy spectrum near the bottom (top) of the gap produced by magnetic field is parabolic as a function of a carrier momentum along the nanotube axis. This dispersion results in the van-Hove singularity in the reduced density of states, which in turn leads to a very sharp absorption maximum near the band edge and, correspondingly, to a very high sensitivity of the photocurrent to the photon frequency. Notably, the same effect can be used for the generation of a very narrow emission line having the peak frequency tunable by the applied magnetic field. A population inversion can be achieved, for example, by optical pumping with the light polarized normally to the nanotube axis.

4. Conclusion

We have demonstrated that a quasi-metallic carbon nanotube can emit the THz radiation when the potential difference is applied to its ends. The typical required voltages and nanotube parameters are similar to those available in the state-of-the-art transport experiments. The maximum of the spectral density of emission is shown to have the strong voltage dependence, which is universal for all quasi-metallic carbon nanotubes in the ballistic regime. Therefore, the discussed effect can be used for creating a THz source with the frequency controlled by the applied voltage. Appropriately arranged arrays of the nanotubes should be considered as promising candidates for active elements of amplifiers and generators of the coherent THz radiation. Finally, we have discussed the feasibility of using the effect of the magnetic field, which opens the energy gaps and allows optical transitions in armchair nanotubes, for tunable THz detectors and emitters.

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