Semiconductors and nanostructures-based sources of terahertz radiation

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Abstract. A review of several approaches to obtaining the emission of terahertz spectral range based on the use of semiconductor micro- and nanostructures is presented. Physical principles of terahertz sources based on impurity related carrier transitions including transitions involving resonant impurity states and on carrier heating in strong electric field are discussed. Emitter of millimeter radiation based on transit time resonance in n-InP is described and the way to rise the frequency up to several THz is suggested

1. Introduction

Considerable recent attention has been focused on practical application of the radiation in terahertz (or far-infrared) spectral range. This spectral range (λ ≈ 30 – 300 µm) lies between optical and radio frequencies. Special features of the interaction of terahertz radiation with matter determine the wide range of possible application of terahertz-based devices in non-destructive testing, environmental monitoring, biology, medicine, space communication, spectroscopy etc.

The main problem facing researchers in this field is the lack of low-cost effective and convenient in use sources and detectors of radiation for terahertz spectral range. It is difficult to take full advantage of both optical and radio frequency methods. At the same time, terahertz radiation sources with the specified properties can be realized using semiconductors or semiconductor nanostructures. Semiconductor quantum cascade laser [1] is the most promising solid state emitter of terahertz radiation but a wide application of this perfect device is restricted with very complicated technology of its production.

The present paper is devoted to the brief review of several methods of obtaining the terahertz radiation based on the use of semiconductor micro- and nanostructures. We consider mainly the sources of spontaneous terahertz radiation.

2. Terahertz sources based on impurity related carrier transitions

The energies of intracenter carrier transitions in doped semiconductors and semiconductor nanostructures correspond to terahertz spectral ranges, so the use of impurity related carrier transitions is one of the ways to make THz emitter. The common feature of such emitters is the need to use low temperatures.

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The methods of obtaining the radiation differ in the way to depopulate final states for carrier transition. Usually, impurity ionization in electric field or optical excitation are used.

2.1. Stressed GaAsN/GaAs microstructures
The first THz laser based on carrier transitions between impurity states was realized on stressed p-Ge [2]. External mechanical strain in bulk p-Ge splits not only light hole and heavy hole subbands of valence band but also acceptor states. At a certain value of strain, the acceptor states related to the heavy hole subband become resonant with the continuum of light hole subband. At low temperature, applied electric field ionizes impurity; free light holes are heated in electric field and can be captured with resonant impurity states. As a result, the population inversion can appear between some resonant states and localized ones resulting in THz emission. A significant drawback of this approach is the use of external stress.

In frame of the approach described in [2], we suggested to use internal strain appearing in layered structure with different lattice constants of the layers [3]. Diagram of localized and resonant impurity states and possible hole transitions is shown in figure 1 (a). Terahertz luminescence spectra under strong electric fields were studied in strained GaAsN layers grown on GaAs substrate and doped with Be. Results are shown in figure 1. Position of the emission spectrum correlates well with the calculations.

![Figure 1](image)

**Figure 1.** Diagram of optical hole transitions in GaAs$_{0.982}$N$_{0.018}$/GaAs structure in strong electric field (a); emission spectrum at $T = 10$ K and $E = 1600$ V/cm, arrows show calculated energies of marked hole transitions (b).

2.2. Nanostructures with GaAs/AlGaAs quantum wells
Resonant impurity states can appear not only owing to mechanical strain but also due to size quantization. In doped quantum wells, the formation of subbands of size quantization is accompanied also by quantization of impurity levels and formation of series of impurity levels below each subband (it is correct if the impurity bound energy is less than energy distance between subbands). Some of these states may be resonant with the states of underlying subband. At low temperature, longitudinal electric field applied in the plane of the structure ionized the impurity. Free electrons are heated with electric field and can be captured with upper resonant states. Electron accumulation on the resonant state makes possible radiative electron transitions from the resonant states to localized ones.

Terahertz radiation of this type was observed in 30 nm thick GaAs/Al$_{0.3}$Ga$_{0.7}$As quantum wells [4]. Diagram of the possible electron transitions and emission spectra are shown in figure 2. Impurity-related nature of the observed radiation is confirmed by good agreement of the experimental spectra with calculated energies of impurity-related electron transitions.
2.3. THz emission under interband optical excitation

Low-temperature interband photoluminescence in doped semiconductor nanostructures can be used for the depopulation of the ground impurity states. Under interband optical excitation, the recombination of nonequilibrium holes and electrons initially localized at non ionized donors can exist along with exciton or electron-hole recombination. After interband optical excitation the electrons on ground donor state can radiatively recombine with nonequilibrium holes, so ground donor states are depopulated. Nonequilibrium electrons in the first subband of size quantization can be captured on the ground states of positively charged donors with emission of terahertz photons. Diagram explaining these processes in GaAs/AlGaAs quantum well is shown in figure 3 (a).

Terahertz emission under interband optical excitation in bulk n-GaAs and p-Ge was reported in [5]. We present the results obtained in n-GaAs/AlGaAs quantum wells. Quantum well structures are of considerable interest because the energy distances between impurity levels can be easily changed with changing the structure parameters.

Figure 3. Schematic diagram of optical electron transitions in doped GaAs/AlGaAs quantum well in terahertz (THz) and near-infrared (NIR) spectral ranges (a); emission spectra at $T = 4.4$ K (solid line) and $T = 10$ K (dashed line) measured in 30 nm thick GaAs/Al$_{0.3}$Ga$_{0.7}$As quantum well under interband optical excitation. Arrows show calculated energies of allowed electron transitions (b).

Emission spectra measured in GaAs/AlGaAs quantum well structure are shown in figure 3 (b). In this case terahertz emission was associated not only with $e_1 \rightarrow 1s$ electron transitions from the first subband $e_1$ but also with $2p_{x,y} \rightarrow 1s$ transitions between excited and ground impurity states (energy
level diagram is similar to one shown in figure 2(a)). This conclusion is confirmed by calculations of the energies of the corresponding transitions.

3. Terahertz sources on hot carriers
Free carriers in semiconductor and semiconductor nanostructures can be heated with strong electric field. Under conditions of heating, the electron temperature rises and exceeds the temperature of lattice. Black-body like spectrum of radiation emitted by electron gas contains the part belonging to terahertz spectral range. Because electrons can be heated to high temperatures without significant heating of lattice, such approach is perspective for simple obtaining terahertz emission with relatively high intensity.

High electron temperatures in electric field can be achieved in structures with high electron mobility such as modulation-doped GaN/AlGaN heterojunctions [6]. Heterostructure under investigations represented a standard HEMT (high electron mobility transistor) structure consisting of a set of GaN/Al$_{0.3}$Ga$_{0.7}$N layers. At high electric field and lattice temperature $T = 4.2$ K, the donors are ionized and temperature of free electrons can reach the values of 400 K (see figure 4). The experimental and calculated dependences of terahertz emission intensity on electric field in this structure are also shown in figure 4. Calculations used blackbody model for the emission from hot 2D electrons. The experimental results are in a good qualitative agreement with the considered theory. The noticeable quantitative discrepancy rising at high electric fields can be attributed to the optical phonon accumulation.

![Figure 4](image-url)

**Figure 4.** Field dependence of the integral terahertz emission (dashed line – experiment, circles – calculation) and electron temperature (solid line, calculation) in GaN/AlGaN heterostructure. Lattice temperature $T = 4.2$ K.

4. Electron transit time resonance
Last part is devoted to optical phonon transit time resonance. This phenomenon can be observed in semiconductors with sharp onset of optical phonon scattering. For the first time, this mechanism was considered in [7]. It relies on the quasi-periodic dynamics of carriers in strong electric fields inside the optical phonon sphere in the momentum space. Such an electron transport gives rise to the electrical instability and as a result to amplification and generation in the frequency range corresponding to the period of the electron motion in the momentum space. For the first time short millimeter wave generation caused by this effect has been observed experimentally in bulk n-InP (spectra of stimulated emission are shown in figure 5) [8].

Spectral range of the radiation observed in [8] (0.06-0.2 THz) is not very convenient and interesting for practical use. The theory tells us that the stronger is the carrier-phonon interaction the higher will be the upper generation frequency. On this basis, wide band gap semiconductors (nitrides) are very promising materials to realize a terahertz maser due to a high value of the optical phonon energy and the strong interaction of electrons with polar optical phonons which are expected to increase the frequency of the resonance up to a few THz. It was also theoretically shown that for 2D electrons confined in a quantum well the transit time resonance is more pronounced due to abrupt turn on of the optical phonon scattering. From this point of view, the use of GaN/AlGaN HEMT (high electron mobility transistor) heterostructures is the most perspective way to realize emitter of
stimulated terahertz radiation due to high electron mobility in these structures and increasing the quality of GaN-based structures.

5. Summary
In this paper, several methods to produce terahertz radiation are presented. To date, spontaneous terahertz emission only with the use of these methods was obtained. Nevertheless, the experimental results are in a good qualitative agreement with the theory and may be considered as a first steps to the realization of terahertz emitter having a practical application.

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