Terahertz GaAs/AlGaAs- and InGaAs-based bow-tie diodes: spectral features and applications for imaging

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Abstract. Spectral features of broadband bow-tie diodes fabricated of InGaAs layers and modulation doped GaAs/AlGaAs structures are discussed. It is shown that sensitivity of both GaAs/AlGaAs- and InGaAs-based sensors at room temperature weakly depends on frequency in the range 0.01-1.0 THz; the sensitivity is found to be 0.3 V/W and 10 V/W, respectively. The InGaAs bow tie diodes coupled with silicon lenses are demonstrated in terahertz imaging application, their feasibility for real-time THz imaging is considered as well.

1. Introduction

Compact sensors operating at room temperature (RT) and suitable for material inspection, security and medical aims still remains an issue in applications of terahertz (THz) frequencies. A particular attention gains broadband and fast sensors having potential in spectroscopy and real-time imaging. To provide operation free from temperature limitations, principle behind device performance cannot be related to any intra-subband transitions. One of the possible ways is to employ plasma waves that can be excited in semiconductor field effect transistors with nanometric gate [1]. It is shown recently that spectrally broad photoresponse signal excited by the external radiation of 0.6 THz in commercial Fujitsu FH05X GaAs-based high electron mobility transistors with a gate length of 250 nm can successfully be used to record images at RT [2]. In order to achieve higher sensitivity and improve noise properties, and thus, imaging quality, silicon-based field effect transistors [3] seems to be the most suitable choice, in particular, as sensing elements in THz cameras [4].

In this communication, we consider another possible detection approach – asymmetric bow-tie diode application – in realization of compact RT THz imaging. We discuss spectral features of the bow-tie diode based on InGaAs layers and modulation doped GaAs/AlGaAs structures and show THz images recorded at room temperature. The diode uses concept of bow-tie antenna with structurally broken symmetry [5]: one of the two semiconductor leaves is metalized in order to couple incident radiation into the second one, where electrons are heated non-uniformly by the radiation. Consequently, the voltage signal across the leaves is induced without application of a bias voltage. A set of structures of different design has been grown by molecular beam epitaxy technique; for processing of diodes with apex ranging from 12 µm down to 800 nm we have used conventional optical and electron-beam lithography plus dry etching.
2. Samples and measurement techniques

The GaAs/AlGaAs structures consist of a 20-nm-thick GaAs cap layer, a Si-doped \((1 \times 10^{18} \text{ cm}^{-3})\) 80 nm \(\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}\) layer, an undoped \(\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}\) spacer of 45 nm, and 1 \(\mu\text{m}\) of undoped GaAs. Twenty surface-smoothing periods of undoped 3 nm-AlGaAs/1.5 nm-GaAs/0.5 \(\mu\text{m}-\text{GaAs}\) layers on top of the substrate are not depicted. The sheet electron density and the mobility at room temperature are \(5.5 \times 10^{11} \text{cm}^{-2}\) and 4700 \(\text{cm}^{2}/\text{V.s}\), respectively. More detailed description can be found in Ref. 5.

The core constituent of InGaAs-based device is \(\text{In}_{0.54}\text{Ga}_{0.46}\text{As}\) layer of 534 nm thickness grown on InP (001) substrate with one InAs monolayer in between. The electron concentration and mobility at room temperature are about \(2 \times 10^{15} \text{cm}^{-3}\) and 13 300 \(\text{cm}^{2}/\text{V.s}\), respectively. More detailed description can be found in Ref. 6.

A pulsed microwave electric field at 10 GHz and 35 GHz with pulse duration of 2-20 \(\mu\text{s}\) and a repetition rate of 40 Hz was delivered by magnetron generators. The THz radiation source (from 0.584 THz up to 2.52 THz) was an optically pumped molecular laser operating in a continuous wave regime.

3. Broadband sensing at room temperature

Frequency dependence of the voltage sensitivity of both structures is shown in Fig. 1. As one can see the sensitivity at RT of both GaAs/AlGaAs- and InGaAs-based sensors weakly depends on frequency from 10 GHz up to 1 THz. The experimental points are well fitted by phenomenological approach with small deviations which we assign to slightly varying radiation coupling conditions with frequency. It is seen that the sensitivity of the InGaAs-based diodes is more than order of magnitude higher (close to 10 V/W) in comparison to the one based on GaAs/AlGaAs (close to 0.3 V/W). Therefore the first type diodes are much better suited for THz imaging aims. Within the range of 1–2.52 THz, the sensitivity of both type diodes drops down faster that the phenomenological approach predicts. It can be explained by a weaker coupling of the incident radiation as it is illustrated by modeling using finite-difference time-domain method [5,6].

One can note that with the decrease of the apex size down to 2 \(\mu\text{m}\), for instance, in GaAs/AlGaAs structures, allows increase the sensitivity up to 2.5 V/W, which is nearly one order of magnitude higher compared to that of diodes with 12 \(\mu\text{m}\) apex size (0.32 V/W). It is worth noting, however, that further decrease of the apex size down to 1 \(\mu\text{m}\) or 800 nm gives no increase in the sensitivity. We attribute this effect with a weaker coupling of the incident radiation. In InGaAs-based devices the apex size decrease also increases the sensitivity, but the frequency dependence becomes distorted by bow-tie antenna-shape and geometry related resonances [7].

![Figure 1. Sensitivity as a function of frequency of InGaAs and GaAs/AlGaAs-based bow tie diodes with apex size 12 \(\mu\text{m}\). Points denote experimental data, lines – the phenomenological fit. Inset shows the shape of the diode attached to the silicon lens. Grey areas – parts covered by metal, white area – GaAs/AlGaAs or InGaAs layer.](image-url)
The dynamic range is illustrated in Fig. 2, where voltage-power characteristics of GaAs/AlGaAs and InGaAs bow-tie diodes with 12 μm apex placed in 10 GHz frequency radiation at RT and liquid nitrogen temperatures are given. As it is seen the dynamic range exceeds more than two orders of magnitude. The sensitivity of InGaAs-based diodes is around 6 V/W. One can note that at low temperatures GaAs/AlGaAs exhibits sensitivity of 40 V/W. The nonmonotonical behaviour observed above 10 mW can be attributed to the real-space transfer effects [8].

4. Application of the bow-tie diodes for terahertz imaging

To demonstrate THz imaging we have chosen InGaAs bow tie diodes coupled with silicon lenses. The object under test was a plastic capsule with pharmaceutical powder. The transmission spectra of the plastic capsule alone and filled with pharmaceutical powder are recorded using coherent time domain spectroscopy [9]. The results are shown in Fig. 3a. As it is seen, the medicine powder absorption is clearly distinguished in the frequency range of 0.25-1.5 THz. Thus, plenty of optically pumped molecular THz laser lines are suitable for THz-ray imaging of chosen pharmaceutical powder.

The THz recorded image in a transmission mode of the plastic capsule with pharmaceutical powder (its photo is presented as inset) enclosed in the paper envelope is presented in Fig. 3b. The image of the object mounted onto computer-driven X-Y stage was obtained pixel-by-pixel scanning it in a focal plane of the THz beam spot with radius of 0.95 mm (more parameters of the images are listed in the Fig. 3 caption). As one can see, the bow-tie diode clearly resolves concealed object in the THz light, it also reveals the powder level in the capsule. Shadowed pattern due to reflection between the envelope sheets is also clearly visible. Note that the intensity scale is logarithmic in order to resolve structure details of differently absorbing parts. The signal-to-noise ratio is more than 3000.

For real-time THz imaging it is of particular importance to know response time and noise equivalent power (NEP) of the device. The response time less than 7 ns, responsivity – 0.1 mA/W, and NEP – 5.8 nW/√Hz have been recently shown [10]. One deserves mentioning that for real-time imaging (for instance, at 50 frames/s capture rate) the InGaAs-based sensor demonstrates the dynamic range higher than 50 dB if a maximum not-saturating incident power of about 10 mW is applied.

As for comparison of bow-tie diodes with field effect nanotransistors one can note that the bow-tie diodes production is technologically less demanding, the diodes are not sensitive to the static electric charge and are more robust to overloads. More detailed comparison of parameters between bow-tie diodes and field effect transistors is given in Ref. 10.
Figure 3 (colour online) (a) Terahertz transmission spectra of plastic capsule (photo of the capsule on 5 mm squared background is given in the inset) half-filled with pharmaceutical powder and its image (b) at 0.693 THz (in the spectral plot it is denoted by the vertical blue line). The capsule is enclosed in the paper envelope. Horizontal and vertical scales are in pixels, intensity is normalized to the maximal value and plotted in logarithmic scale. Imaging parameters: 61×85 pixels, each of 325 μm size, lock-in integration time - 50 ms. Note that the signal-to-noise ratio is about 3500.

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