The response rate of a room temperature terahertz InGaAs-based bow-tie detector with broken symmetry

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***Abstract* — Transients of an InGaAs-based bow-tie diode with broken symmetry are experimentally investigated. The 100 MHz bandwidth low-noise preamplifier is designed and successfully adapted. The main peculiarities of the terahertz detector are detection in passive scheme, flat frequency response up to 1 THz, the voltage sensitivity of about 5 V/W, and the rise time less than 40 ns.**

***Index Terms* — infrared, submillimeter wave, microwave, and radiowave detectors; terahertz detectors; hot carriers; semiconductor asymmetrically shaped diodes.**

I. Introduction

Rapid evolution of terahertz (THz) electronics and its implementation in many areas require new concepts in developing compact broad-band THz sensors operating at room temperature [1]. In addition, rapid response of the detectors would be an advantage indicating their versatility in recording circuits.

In this work, we report an experimental study of transient properties of the InGaAs-based bow-tie diode with broken symmetry. The principle of operation is based on a non-uniform carrier heating in a high-mobility electron gas layer [2-3]. Electromagnetic waves detection on mobile carriers heating promises much faster detector transients in comparison to bulk detectors of thermal action, for example thermopile, bolometers etc. Here we show the potential of the InGaAs-based bow-tie detector connected in a passive detection scheme and in common with the fast low-noise current preamplifier.

II. Detector

The detector design is shown in Fig. 1. Its active part is an $In_{0.54}Ga_{0.46}As$ layer grown by molecular beam epitaxy on a semi-insulating substrate of InP (001). The thickness of the InGaAs layer is of about 534 nm. The concentration of free electrons is of about 2×10^{15} cm^{-3} and the low-field mobility is of about 13300 cm^2/Vs at room temperature. The Ohmic contacts are made of Ti/Au/Pt compound evaporated and annealed on top of the InGaAs layer. One of the structure's leafs is also metallised in order to concentrate an incident radiation into the neck. The mesas of the height of a few micrometers are created by wet etching. After cleaving of the wafer, the sample is wired and attached to a hemispherical silicon lens of 6 mm diameter from the substrate side. All elements are then mounted in the cylindrical metal case with 29 mm diameter and 32 mm length.

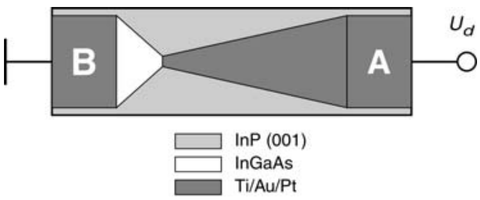

Fig. 1 Top view of the detector made of bow-tied InGaAs with broken symmetry formed on the InP substrate. The size of the detector: total length is 500 µm, width – 100 µm, apex size – 12 µm, lengths of the InGaAs leaf – 50 µm, and metallized 'right' leaf – 250 µm. The contacts are labelled as A and B to clarify the polarity of applied voltage. The electric field of incident THz radiation is oriented along the diode.

The principal of operation relays on non-uniform carrier heating in high-mobility electron gas. The metallized leaf acts as a coupler of the incident THz radiation, while the second leaf is active where electrons are heated non-uniformly. Consequently, the voltage signal with a polarity corresponding to the hot-carrier effect is induced over the leaves without any application of the dc-bias.

An internal electric field distribution along the neck for different polarity of the external dc-voltage is shown in Fig. 2. The forward bias connection is for electron flow from 'A' contact towards 'B' contact (see Fig. 1). In-plane geometrical asymmetry induces a different gradient of the internal electric field depending on the polarity of the voltage applied. It is seen that this difference is appreciable only within several microns from the neck for this particular design which parameters is indicated in the caption of Fig. 1. The electric field distribution dependence on the polarity of an external voltage causes the different spatial accumulation of hot-carriers in the vicinity of the neck resulting in asymmetry of the current.

The measured I/V characteristic of the asymmetrically shaped diode is shown in the inset of Fig. 2. At low electric field the current magnitude does not depend on the polarity of the applied voltage. But, when the sample is turned to a strong field regime, the temperature of electrons increases and they accumulate differently in the vicinity of the detector neck. This affects on the symmetry of the I/V characteristic and can be successfully used for the detection of the THz radiation

The asymmetrically shaped diode is sensitive to the polarization of the incident electromagnetic wave. The strongest signal is obtained when diode is oriented along the direction of the electric field. The difference found experimentally is up to 10 times between the signals for perpendicular and parallel detector orientations.

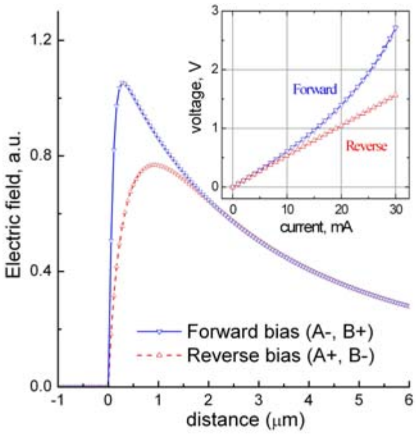

Fig. 2 Calculated internal electric field distribution along bow-tie diode neck. The X-axis denotes the distance from the apex of the sample. The InGaAs leaf is placed from position 0 to the direction of positive numbers. The insert shows I/V curve of the diode. The reverse bias curve corresponds to polarity: contact A is positive, contact B is negative.

III. Detector with preamplifier

Additionally, a low-noise preamplifier is designed to make easier signals readout. The InGaAs asymmetrically shaped diode is connected to the preamplifier in the photovoltaic mode as it is depicted in the inset to Fig. 3. Advantages of such connection are absence of dark current flow through the diode, low noise and signal linearity. We managed to design the preamplifier with performances: the impedance of signal conversion is of 100 000 V/A, the bandwidth is up to 100 MHz, the output noise voltage is below 250 nV/Hz$^{1/2}$. Calculated and measured preamplifier parameters are shown in Fig. 3. The signal at the output can swing up to ± 1.5 V corresponding to maximum input currents of 150 μA. The preamplifier low power consumption (voltage and current is ± 3 V and 25 mA, respectively) allows simple batteries to source an electrical scheme avoiding an additional noise introduction.

The view of the THz detector with internal low noise preamplifier is shown in Fig. 4. The InGaAs asymmetrically shaped diode and preamplifier are shielded from external noise pick-up inside the metal cylinder. The silicon lens is mounted in the centre of the cap. The dimensions of the THz detector with preamplifier are 46 mm diameter and 40 mm length.

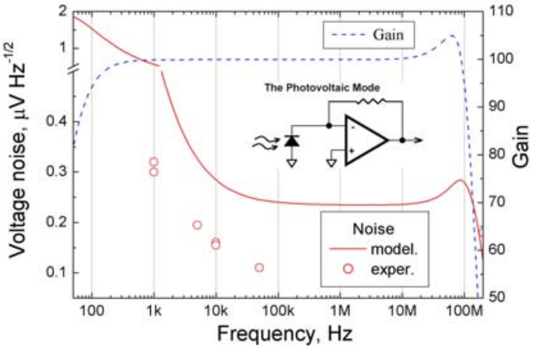

Fig. 3 Preamplifier gain-frequency (dashed line – modelling) and voltage noise-frequency (solid line – modelling, dots – experiment) characteristics.

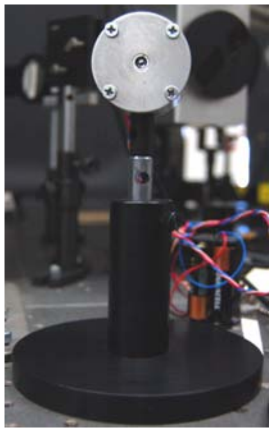

Fig. 4 Picture of the THz detector composed of the silicon lens, InGaAs asymmetrically shaped diode, and low-noise preamplifier. The detector is suited for free space experiment. The preamplifier is sourced from four AA-size alkaline batteries.

IV. Results in THz range

The THz radiation source is an optically-pumped molecular laser generating 0.1 ms duration and 30 Hz repetition rate pulses. The gas of HCOOH is pumped and the laser is set to operate at the wavelength of 433 μm (0.69 THz frequency). The 25 cm focal length lens is used to focus THz laser beam to the spot size of roughly 2 mm a full width at half maximum. No other optical elements are used between the laser and the THz detector placed at the focal distance.

The detector response to the THz excitation at room temperature is shown in Fig. 5. The results were recorded turning the length of the laser resonator. In this manner different longitudinal modes in the THz resonator are selected for the lasing. It is seen that the parameters of the THz pulse (rise time, duration, and shape) can be recorded. To estimate transient characteristics, the microwave radiation source with a fast rise time was involved.

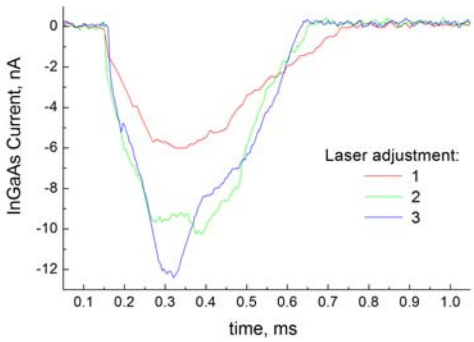

Fig. 5 The pulse shape of the THz laser for different mode structure of the output beam.

V. Results in GHz range

The signal synthesizer (model HP 8673C) and the TWT amplifier was used as another source delivering the pulse power up to 100 W. This source was set to generate 10 GHz frequency with 10 Hz repetition rate, 40 ns rise time, and up to a few milliseconds duration pulses. The parameters of the pulse were controlled with the Schottky diode and the resistive sensor specially designed for X-band [4].

The time response of the asymmetrically shaped diode excited with a rectangular pulse is shown in Fig. 6. It is seen that the pulse shape is well preserved. Note that the differentiating RC circuit is used to separate an offset voltage.

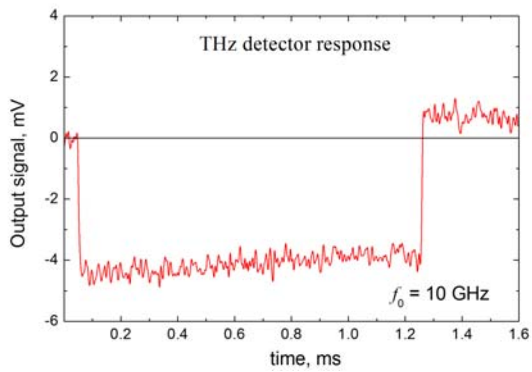

Fig. 6 An oscilloscope trace of the THz detector with preamplifier. The pulse duration is about 1.1 ms, the frequency – 10 GHz.

An expanded oscilloscope trace of the THz detector with and without preamplifier is shown in Fig. 7. One can see that the rise time of the detector response is equal to 40 ns at both experimental setups. The last and the pulse shape confirm that the applied low-noise preamplifier does not slow down the response of detector or distort the signals. Attentive investigations of the synthesizer pulses revealed that InGaAs-based bow-tie detector exactly replicates the excitation pulse. Therefore, one can conclude that the response time of the THz detector is not worse than 40 ns, as the rise time of the microwave source.

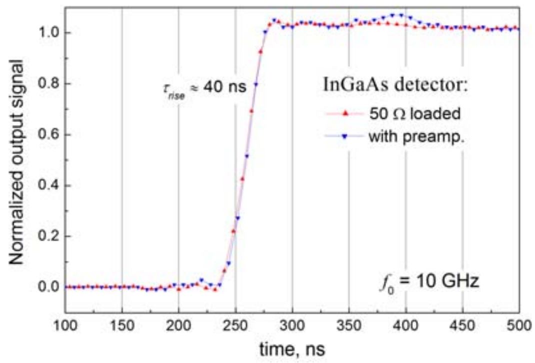

Fig. 7 An oscilloscope trace of the THz detector loaded with 50 Ohm resistor or connected to the fast current-preamplifier.

Conclusions

The response rate of a room temperature terahertz InGaAs-based bow-tie detector with broken symmetry has been experimentally investigated. The 100 MHz low-noise preamplifier connecting THz detector in the photovoltaic scheme has been developed and tested. The response time of the THz detector has been found to less than 40 ns. The real value is hidden by limited possibilities of the pulse source used. It has been demonstrated that the room temperature THz detector is fast enough to record longitudinal modes beating in the optically-pumped molecular laser cavity.

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