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Electrical Detection of THz Frequencies by Asymmetrically Shaped n-n$^+$-GaAs Diodes

Algirdas Suziedelis, Jonas Gradauskas, Steponas Asmontas, Gintaras Valusis,
Hartmut G. Roskos

Abstract **– We propose a planar diode based on a thin asymmetrically-shaped n-n$^+$-GaAs junction prepared on an elastic polyimide film as THz detector. The device can be used to detect electromagnetic radiation in the range from 0.129 THz up to 2.5 THz at room temperature. The principle of operation of the device is based on non-uniform carrier heating effects caused by both the asymmetrical shape of the structure and the presence of the n-n$^+$-junction. An estimate of the sensitivity of the device based on a phenomenological approach for the description of the physical processes gives good agreement with the experimental data within the studied range of frequencies.**

I. INTRODUCTION

Detection of terahertz radiation usually relies on optical techniques employing mainly either photoconducting dipole antennas [1] or free-space electro-optic sampling [2]. Despite of a very high sensitivity and attractive frequency band features (with electro-optic THz detection it is possible to measure coherent transients spanning frequencies from 100 GHz to over 30 THz [3] if the sensor crystals is selected properly), the detection system requires coherence between the optical and the THz radiation and thus is suited only for detection of THz signals generated by optical means.

As an alternative, electrical methods for THz detection can be utilized. For instance, it was determined that THz radiation produces a strong modulation of the photocurrent due to intrasubband THz absorption in coupled quantum well diodes [4]. Very recently, voltage -tunable THz detectors for 2-5 THz have been demonstrated [5]. Here, the principle of operation is based on the convolution of the THz absorption coefficient and the effect of carrier heating on the photocurrent.

This communication presents a n-n$^+$-junction GaAs diode which can be used for electrical detection of electromagnetic radiation from frequencies from 100 GHz up to 2.5 THz at room temperature. The device operation relies on non-uniform free-carrier heating effects in asymmetrically necked n-n$^+$-junctions under external THz illumination, causing a voltage drop over the ends of the sample. Hence, a bias voltage is not required for device operation. The planar geometry enables us to avoid undesirable design-induced effects such as parasitic capacitances and layer contact resistances due to the small size of the Ohmic contacts which are inherent for whisker-contacted diodes.

II. DEVICE FABRICATION TECHNOLOGY

Fig. 1 shows the asymmetrically shaped diode fabricated photolithographically on the basis of a n-n$^+$-GaAs epitaxial structure. For metal contacts to the diodes Ge-Ni-Au thermal evaporation was used. The metallisation patterns were formed using direct lift-off technique. The metal contacts were then annealed in inert gas atmosphere. Further, the semiconductor structures were covered with poliymide material by spin-on technique and cured at 250^0 C for one hour in order to obtain an elastic poliymide film with a thickness of 10 μm serving as mechanical support layer for the finished device. After thinning the semiconductor substrate to a desirable thickness, the semiconductor wafer was completely removed by wet etching at the metal contacts. As a result of the technological procedures, an array of diodes each with a length of 500 μm, thickness of 3 μm and width at the neck of about 10 μm was obtained.

Fig. 1 shows the layout of the device. It should be noted that the doping in the n-region is close to 10^{15}cm^{-3}, while it is about $2 \cdot 10^{18}$cm^{-3} in the n$^+$-region. The high doping of the narrower part of the semiconductor structure is desirable in order to improve the impedance matching of the diode.

III. MEASUREMENT TECHNIQUES

The device frequency characteristics was examined over a wide range of THz frequencies at room temperature.

In the range of 0.129÷0.143 THz we employed clystrons generating pulsed signals with a duration of several microseconds and a repetition rate of 40 Hz. In this kind of experiments the detector diodes were placed in rectangular waveguides.

In the range of frequencies from 0.693 THz up to 2.52 THz we used a CO$_2$ -pumped CW THz laser. Here, a teflon lens served to concentrate the incident field on the freely-mounted sample. The signal was measured by lock-in amplifier at a chopper frequency of 40 Hz.

In all experiments, the electric field was oriented along the sample.

IV. THEORETICAL ANALYSIS

The operation of the device and its voltage sensitivity were analyzed in the warm-electron range using a phenomenological approach including equations for the

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A. Suziedelis, J. Gradauskas and S. Asmontas are with the Semiconductor Physics Institute, A.Gostauto 11, LT-2600 Vilnius

G. Valusis and H. G. Roskos are with Physikalisches Institut der Universität, Robert-Mayer Str. 2-4, D-60054 Frankfurt

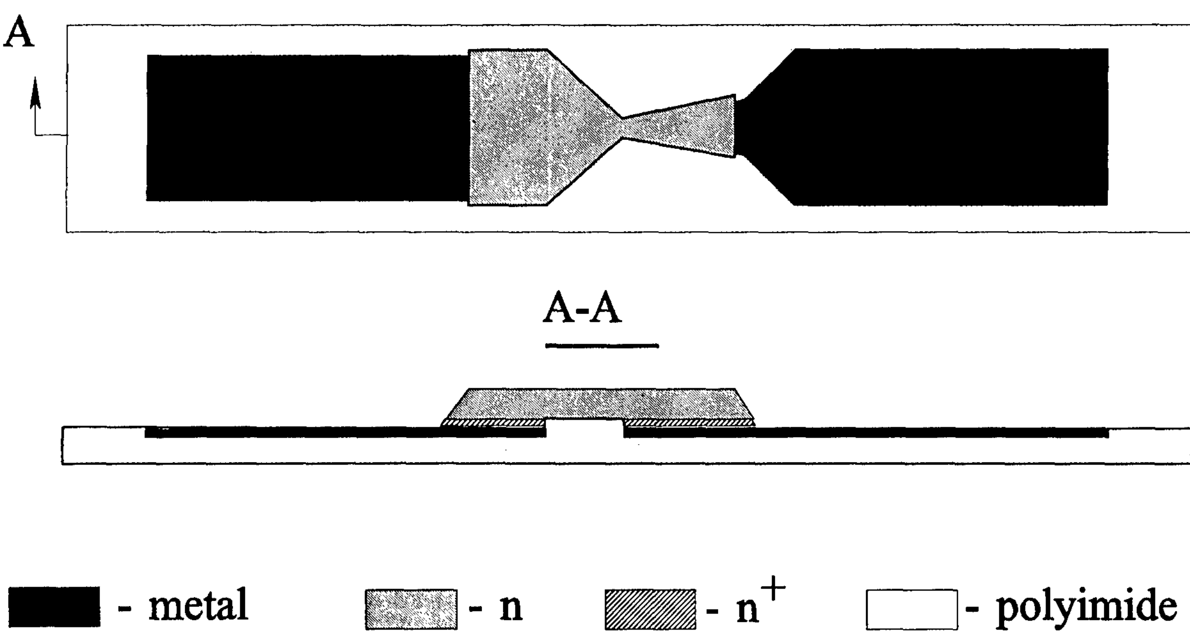

Fig. 1: Schematic view of the asymmetrical n-n$^+$- GaAs diode

current density, heat balance, heat flow density and the electric field. Further details can be found in [6].

V. EXPERIMENTAL RESULTS AND DISCUSSION

The principle of the diode operation is based on thermo-electromotive forces of hot carriers under the influence of the external THz radiation. First, due to the asymmetrical shape of the diode, the gradients of the electric field at different sides of the diode are different, consequently, non-uniform carrier heating occurs. As a result, this so-called bi-gradient effect of hot carriers [7] induces a voltage signal along the sample. Second, since the structure contains a n-n$^+$-junction, a conventional thermoelectromotive force of hot carriers also arises in the diode in addition to the bi-gradient one. Therefore, the increased doping of the some of the necked part of the diode not only allows to get better matching of the sample resistance with the impedance of the waveguide, which is especially important for application of these diodes in microwaves [8], but also enhances the voltage sensitivity of the device.

Fig. 2 presents the theoretical prediction (solid line) and the measured data (circles) of the voltage sensitivity of the device as a function of frequency in the THz range. It is seen that this dependence is nearly independent on frequency up to 0.3 THz. The observed decrease at higher frequencies is due to electron momentum relaxation.

As is evident from Fig.2, the experimental values of the voltage sensitivity are in a good agreement with the theoretical calculations within the studied range of frequencies. It should be pointed out here, how the experimental values of the voltage sensitivity have been determined. We have proceeded in the following way: The voltage response as a function of the THz power absorbed in the active region of the device can be deduced from the static I-V-curve. What remains unknown, however, is the power absorbed in a specific measurement geometry. The absorbance in the active region has to be estimated in a careful way as described in detail in ref. [8]. For our free-space detection geometry covering the range from 0.693 THz to 2.52 THz, it is estimated that only a fraction of 10^{-4} of the incident power contributes to carrier heating in the active area and thus to the voltage signal.

The detected signal was found to be linearly proportional to the incident power in all studied frequencies (power-voltage characteristics are not given in this communication). This illustrates the suitability of the proposed device for the electrical detection and power measurement of THz frequencies over a broad frequency range.

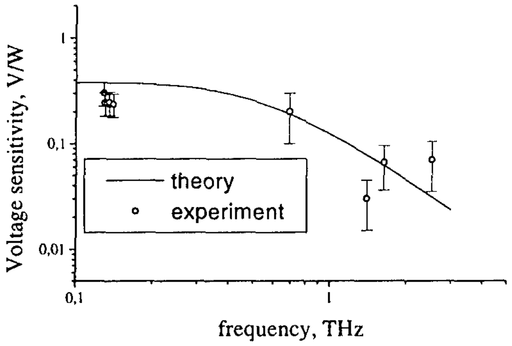

Fig. 2: Voltage sensitivity at THz frequencies

Despite a number of advantages, such as the wide frequency band of operation, the fact that no bias voltage is needed, and the room-temperature operation, it is evident that the device suffers from rather low voltage sensitivity, which around 0.1 THz it is close to 0.3 V/W while at 2.5 THz it amounts to 0.06 V/W. Clearly, for direct applications higher values are desirable. Theory [8] shows two ways to solve his problem: Firstly, since the sensitivity is proportional to the mobility of the carriers, semiconductor material with high mobility values should be found to be more suitable for the production of the device; secondly, since the sensitivity is inversely proportional to the square of the size of the necked part of the diode [8], it should be possible to achieve a voltage sensitivity reaching 100 V/W at the range of frequencies below 0.5 THz by narrowing the neck down to 300 nm size.

VI. CONCLUSION

We proposed a wide-band THz detector based on asymmetrically necked GaAs structures containing a n-n$^+$-junction. The origin of the voltage signal arising over the sample is the result of nonuniform heating of free electrons caused by external illumination. The experiments indicate that the bigradient and the thermoelectric effects of hot carriers can be successfully employed for THz-frequency detection and encourage to look for better designs of the device in order to increase its voltage sensitivity.

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