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Optimization of the frequency response of a novel GaAs plasmonic terahertz detector

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Abstract
Previously there was reported a new type of high-speed plasmonic THz detector that can operate at room temperature. As an extension of that work, the sensitivity of the detector was investigated over a wide range of sub-THz frequencies. The measured frequency response is not purely monotonic but exhibits oscillatory behaviour with a number of maxima and minima. Our study reveals that such frequency dependence is caused by the interference of electromagnetic waves inside the detector substrate, as the frequencies of these extrema are found to be governed by the substrate thickness. We demonstrate that sensitivity of this type of detector can be optimized for the desired operating frequency within 0.06–0.7 THz spectrum by adjusting the substrate thickness. We also show that a monotonic frequency response with eliminated minima can be achieved by mounting the detector on a specially designed silicon lens.

Keywords Terahertz · Detection · Frequency response

1 Introduction

Over the years, terahertz electromagnetic radiation has been recognized for its great potential for numerous applications in security screening (Zhang and Xu 2010; Sheen et al. 2001), telecommunication (Kleine-Ostmann and Nagatsuma 2011) and spectroscopic analysis of various materials (Kawase et al. 2003; Shen et al. 2005). Presently, continuing and ever-growing interest in modern THz technologies stresses the urgent need for compact, robust, inexpensive detectors of high speed and sensitivity.

To this day, there have been proposed various types of advanced THz detectors (Dyakonov and Shur 1996; Knap et al. 2002; Shur and Ryzhii 2003; Shanera et al. 2005; Knap et al. 2009; Ojefors et al. 2010; Knap et al. 2016; Shaikhaidarov et al. 2016; Liu et al.

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2017; Mittleman 2018; Hillger et al. 2019). Although these solutions excel in some of the aforementioned technical aspects, they have, for the most part, some limitations in terms of the other critical characteristics. For example, thermal detectors such as pyroelectric sensors (Whatmore 1986; Ruan et al. 2009), microbolometers (Karasik et al. 2011) and Golay cells (Fernandes et al. 2011) offer enhanced sensitivity, whereas their operation speed remains rather modest. An alternative approach to detect THz waves involves first converting the incident radiation into an alternating potential of a relativistic plasma wave via a broadband antenna structure deposited onto the crystal surface. Physical properties of the correspondent plasma excitation in the hybrid two-dimensional electron system has been extensively studied recently (Muravev et al. 2015, 2019). Provided the asymmetry of the plasmonic waveguide, the oscillating potential of the plasma wave is rectified to yield the measurable photoresponse (Muravev and Kukushkin 2012). Such a plasmonic THz detector boasts an extremely short response time, on the order of 150 ps (Muravev et al. 2012). Importantly, besides the high operation speed, its technological advantages include low fabrication cost and high degree of scalability.

An exceptional operating speed makes this particular detector highly suitable for a number of advanced terahertz applications. For instance, considering new-generation wireless telecommunication links, it can be implemented in integrated THz receiver circuits as a single-pixel signal-sensing element. On the other hand, such detectors are capable of THz waves detection in a quasioptical setup and arbitrary number of them can be arranged in a linear or two-dimensional array to perform real-time sub-THz imaging for non-destructive testing, beam profiling and security screening (Andreev et al. 2018; Tsydynzhapov et al. 2018). Note that for a large amount of applications including sub THz spectroscopy studies and multi-frequency imaging a broadband photoresponse is desired, thus, in order not to limit the bandwith of the detector, it was fitted with a broadband on-chip antenna.

In continuation of our previous research (Muravev and Kukushkin 2012; Muravev et al. 2012), we investigated the sensitivity spectrum of a single plasmonic detector over an extensive range of sub-THz frequencies and explored the optimization capabilities of the detector frequency response. As a result, we discovered that by adjusting the substrate thickness, the detector resonant frequency can be controlled within a wide bandwidth from 60 to 700 GHz. Furthermore, we demonstrated that fitting the detector with a specially designed lens substantially modifies the frequency response of the detector as it greatly reduces its oscillatory component.

In this paper we report on the experimental study of the sensitivity spectrum of a single GaAs plasmonic detector. We describe the test scheme and discuss the measurement results and their practical implications.

2 Experimental setup

The frequency response of the detector samples was measured at room temperature in a quasi-optical setup depicted schematically in Fig. 1.

We employed a set of backward-wave oscillator (BWO) sources to generate a continuous-wave (CW) signal in 65–384 and 530–710 GHz frequency bands. The actual source frequencies were checked with a quasi-optical Fabry–Perot resonator (Clarke and Rosenberg 1982; Baker and Walker 1982) in a set of independent experiments. The power level of the radiation incident on the sample was monitored with a callibrated pyroelectric detector having uniform

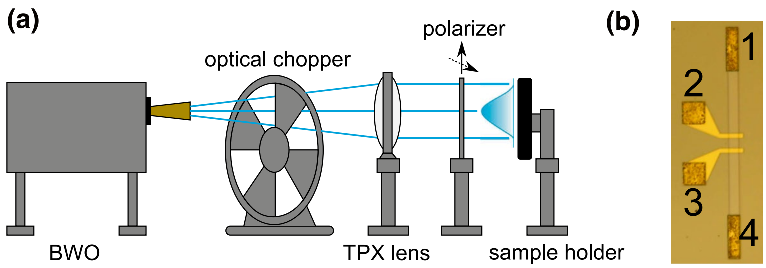

Fig. 1 **a** Experimental setup for measuring the frequency response of a single-pixel detector sample. A set of BWO sources is used to generate a CW test signal over the frequency ranges of 65–384 and 530–710 GHz. The sub-Thz radiation is first amplitude modulated by an optical chopper at the frequency of 23 Hz and then collimated to form a parallel beam. The source radiation is polarized with a quasi-optical polarizer. The photovoltage generated by the detector is measured with a lock-in amplifier synchronized with the optical chopper. **b** The microphotograph of the detector sensitive structure is presented. The microwave voltage is applied with the aid of external antenna between the pads 2 and 3, whereas the rectified signal is measured between the contacts 1 and 4

frequency response across the region of interest. For all our measurements, the incident-power level did not exceed 100 μW.

To effectively compensate for the divergence of the source beam, the radiation emitted from the output horn antenna of the BWO was collimated by means of a biconvex TPX lens with the diameter of 120 mm and the focal length of 60 mm to form a parallel beam with the area much larger than the detector size. The polarizer was introduced into the quasi-optical measurement scheme to ensure that the *E*-field component of the irradiance incident on the detector matched the detector preferred orientation. For practical purposes, the test sample was secured on a special holder in the center of the beam spot, as illustrated in Fig. 1.

The detector was fabricated from GaAs/AlGaAs heterostructure with embedded two-dimensional electron system (2DES) grown on a GaAs substrate. The density of the 2DES was $n_s = 8 \times 10^{12}\ \mathrm{cm}^{-2}$ and the resistance was $R_{\square} \sim 100\Omega$. To enable excitation of plasma waves, two metallic gates were lithographically formed on the top surface of the sample. The gates 2 and 3 restricted plasmonic resonator of 15 μm width and 20 μm length. The gates were connected to a broadband on-chip log-periodic antenna having external diameter of 1.5 mm. The microphotograph of the detector sensitive part is presented in Fig. 1b Incident terahertz radiation excited overdamped plasma waves in the detector channel (Shur and Ryzhii 2003; Dyakonov and Shur 1996; Knap et al. 2009). In other words, the incident radiation is compressed into highly-confined two-dimensional plasmons propagating in the 2DES channel and then rectifying the induced *ac* potential within the same device by asymmetric *dc* bias (~ 0.5 V) of the gates 2 and 3. In order to improve the signal-to-noise ratio, we utilized a standard lock-in detection technique to measure this voltage. The optical chopper amplitude modulated the source radiation at the frequency of 23 Hz, whereas the detector output voltage was measured with a lock-in amplifier in sync with the chopper.

3 Measurement results and discussion

The measured sensitivity spectra of six detector samples with GaAs substrate thickness (*d*) ranging from 195 to 620 μm are plotted in Fig. 2 with blue lines. For the purpose of clarity, all traces are offset with horizontal dashed lines denoting the zero reference for each data set. The value of d is indicated for each graph, respectively. The noise equivalent power of the detector amounts to 1 $\mathrm{nW}/\sqrt{Hz}$ at the sensitivity peak around 100 GHz.

For these measurements, the substrate thickness of each detector sample was adjusted by mechanical grinding and measured with a mechanical thickness gauge. In addition, every sample had a metallic reflector deposited on the bottom of the substrate with thermal evaporation. Note that the active detecting area is adjacent to the top surface of the detector.

As shown in Fig. 2, for each value of d the frequency response of the detector is oscillatory exhibiting a number of alternating peaks and nulls, where the sensitivity almost reaches zero. When the traces are compared, it becomes clear that the shift in positions of the maxima and the minima indicates their strong correlation with the substrate thickness.

Such oscillating behavior of the detector sensitivity may be caused by the interference of electromagnetic radiation inside the detector substrate. When electromagnetic wave reflected from the metallic bottom surface of the detector interferes constructively with the incident wave, the E-field on the surface of the substrate, *i.e.* at the exact location of the detector, is maximized, and the response of the detector reaches its peak value. Destructive interference, on the other hand, leads to minimal sensitivity. This

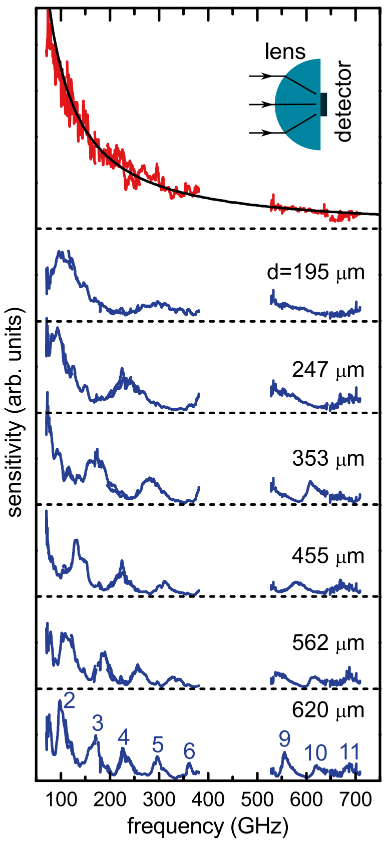

Fig. 2 Measured frequency response of six detector samples of different GaAs substrate thickness, d, plotted in blue lines. For the purpose of clarity, all traces are offset; the horizontal dashed lines represent a zero reference level. The corresponding value of d is indicated on the right side of each plot. The assumed number of the sensitivity peaks is indicated near each peak for the detector with a 620 μm substrate. On the top overlay graph, the red line designates the response of a detector mounted on a special silicon lens; the black line represents the overall monotonically-decreasing trend as a guide to the eye. (Color figure online)

implies that the GaAs substrate, in fact, acts as a resonator. Consequently, provided that the surface impedance of the detector itself can in effect be neglected, the constructive interference condition may be expressed as:

$$2nd = (N - 1/2)\lambda, \tag{1}$$

where n designates the refractive index of the volume, λ denotes the radiation wavelength and N is the order of interference, which can be used to enumerate the peaks in the sensitivity spectra.

To test the suggested hypothesis, in Fig. 3 we plotted the measured frequency of each peak against its expected number, N, for every substrate thickness under consideration. The number of the first observed peak for the samples with d equal to 620, 562, 455, and 353 μm was assumed to be $N = 2$ since for these cases the $N = 1$ peak was outside the given frequency range, yet it was observed for the smaller values of d. As illustrated in Fig. 3, for all the substrate thicknesses under investigation, the experimental data are perfectly fitted with straight lines intersecting the axis at $N = 1/2$, which is in full accordance with the proposed model. Thus, the position of the sensitivity peaks are governed solely by the interference of THz waves in the substrate.

In Fig. 4 we plotted the slopes of the fitted lines, $\Delta f/\Delta N$, as a function of parameter 1 / d. As can be seen from the figure, the distribution of obtained data points is well approximated with a straight line starting from the origin, which is fully consistent with the equation in 1. Therefore, the slopes of the lines are, in fact, found to be inversely proportional to the substrate thickness. Moreover, based on the fitted curve in Fig. 4, the refractive index, n, of the GaAs substrate was estimated to be $n = 3.8$, which is in good agreement with the value reported in literature (Afsar and Button 1983; Marple 1964). These experimental findings strongly support the above mentioned model and suggest a rather simple way to tune the detector sensitivity to any particular frequency of interest. Similar behavior due to the interference in the substrate has been previously reported for the emission spectra of quantum dot lasers (O'Reilly et al. 1998).

From the practical standpoint, some specific applications may require a more even frequency response without any minima. As a way of reducing the effect of THz light

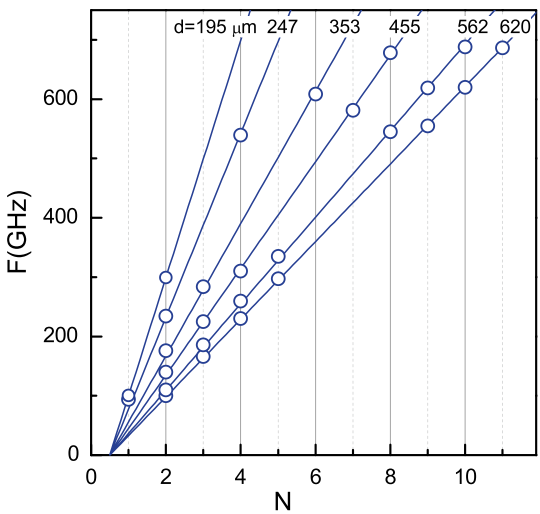

Fig. 3 Measured frequencies of the sensitivity peaks plotted versus the interference order, N. The lines represent a linear fit to the experimental data. The respective substrate thickness, d, is indicated at the top of each plot

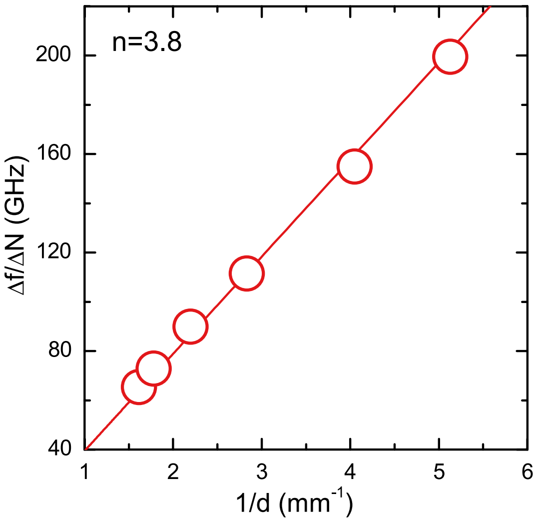

Fig. 4 The slopes of the lines from Fig. 3 plotted versus the inverse substrate thickness. The experimental data is then linearly fitted according to the Eq. 1 to yield the refractive index of GaAs $n = 3.8$

interference within the substrate, we fitted the 620 μ m detector with an extra hyperspherical silicon lens, as illustrated in the top inset of Fig. 2. The lens was made 10 mm in diameter and was specially designed to focus the incident radiation precisely on the detector spot. In a sense, the lens served as a semi-infinite substrate for the detector, which helped to suppress the inner interference and resulted in a more of a monotonic frequency response. In the top overlay graph of Fig. 2, the test data for the sensitivity of the detector mounted on a lens is displayed with a red line; the black line represents the overall monotonically-decreasing trend for a visual comparison. It is evident that the frequency response became far more steady without any substantial dips. In this case, a small residual fluctuation in sensitivity may be due to a slight mismatch between the refractive indexies of silicon and GaAs.

4 Conclusions

As a follow up on the previously reported research into development of a GaAs plasmonic THz detector, we have explored the sensitivity of such a single-pixel detector over a wide range of sub-THz frequencies as a function of its substrate thickness. Our experimental findings confirm that the frequency response of the detector is greatly affected by the interference of electromagnetic waves inside the substrate. We have demonstrated that by varying substrate thickness, detector sensitivity can be optimized for a specified operating frequency within 60–700 GHz range. Therefore, this type of a detector can be custom manufactured, either as a discrete element or as an array, to meet the desired frequency requirements in such application fields as THz telecommunications or real-time THz imaging in industrial NDT and security screening. Furthermore, we have shown that by mounting the detector on a hemispherical silicon lens there can be achieved considerable suppression of the interference within the substrate, and as a result, a more even frequency response with insignificant fluctuation.

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