Terahertz imaging with bow-tie InGaAs-based diode with broken symmetry

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A silicon-lens coupled bow-tie InGaAs-based diode with broken symmetry is demonstrated for terahertz imaging applications below 1 THz at room temperature. Transient features and the dynamic range of the bow-tie InGaAs-based sensor are explored experimentally, proving the possibility to use the device in real-time imaging systems. Response time is found to be less than 7 ns, responsivity of 0.1 mA/W, and noise equivalent power of 5.8 nW/$\sqrt{\text{Hz}}$.

Introduction: A large variety of possible applications of terahertz (THz) radiation in material inspection, for security and medical aims requires convenient and compact room temperature (RT) operating systems. Very recently, an innovative approach was demonstrated using a dual-wavelength mid-infrared quantum cascade scheme for intracavity frequency-difference mixing via giant second-order nonlinear susceptibility [1]. The invention has opened a new route in scaling down dimensions of room-temperature THz sources. As for sensors, recent experiments on THz imaging at RT employing plasma waves in GaAs high-mobility field effect nanotransistors have illuminated a novel channel in the development of compact THz cameras [2].

In this Letter, we demonstrate that a silicon lens-coupled InGaAs bow-tie diode with broken symmetry [3] relying on non-uniform two-dimensional electron gas heating [4] can successfully be applied for THz imaging in a passive scheme at RT. Investigation of transient and dynamic range features of the InGaAs-based detector shows that the detector can be adapted for real-time imaging systems. The measured rise time is shorter than 7 ns, and the dynamic range is about 20 dB at the bandwidth of 100 MHz. Data analysis revealed that the dynamic range is limited by the detector response saturation at the incident power of around 10 mW and the Johnson thermal noise.

Diode design and experimental setup: An active part of the device is made of a $In_{0.54}Ga_{0.46}As$ layer grown on InP substrate with one InAs monolayer in between. The bow-tie diode with broken symmetry is shaped by etching as an asymmetric bow-tie antenna with one of the two semiconductor leaves being metallised [3]. The THz radiation induces an inhomogeneous electric field concentrated in the vicinity of the neck of the diode. Therefore, electrons are heated non-uniformly in the semiconductor leaf and, as a result, the detector signal originates without application of bias voltage [4].

An optically-pumped molecular THz laser operating at 0.693 THz frequency and emitting power of about 2 mW was used as a source of THz radiation in the imaging experiments. The laser frequency is chosen in the range where the InGaAs bow-tie sensor sensitivity is high and nearly independent of frequency [3]. To study the transient properties of the device, we employed a 94 GHz frequency pulse generator (pulse duration is 300 ns, peak power a 200 W, repetition rate 100 Hz). The horn antenna was used to target the radiation to the detector placed at a distance of 10 to 30 cm from the source. The Schottky diode, calibrated attenuators, and power meter (Agilent W8486A) were installed in the waveguide for accurate pulse shape and radiation power control. All the signal connections are matched to 50 Ω impedance. The THz detector was connected to the low-noise current preamplifier which was designed for easier signal readout. The impedance of signal conversion, the bandwidth, and the output voltage noise root mean square (rms) value of the preamplifier are of about 10^5 V/A, 100 MHz and 5 mV, respectively. The preamplifier consumes 25 mA current at 3 V voltage supply, therefore regular batteries were used to decouple signals from the radiation source and to avoid any extra noise introduction. The data was measured with the 500 MHz bandwidth oscilloscope.

Results and discussion: The THz images in transmission mode of a metallic jewel and a plastic capsule with pharmaceutical powder (photos for comparison are presented as insets) enclosed in a paper envelope were recorded at 0.693 THz frequency. The results and imaging setup details are shown in Fig. 1. The studied objects were mounted onto a computer-driven X-Y stage and pixel-by-pixel scanned in the lens focal plane where the THz beam radius was 0.95 mm (more parameters of the images are listed in the Figure captions). As one can see, the bow-tie diode clearly resolves concealed objects in the THz light; it also reveals shadowed pattern due to reflection between the envelope sheets.

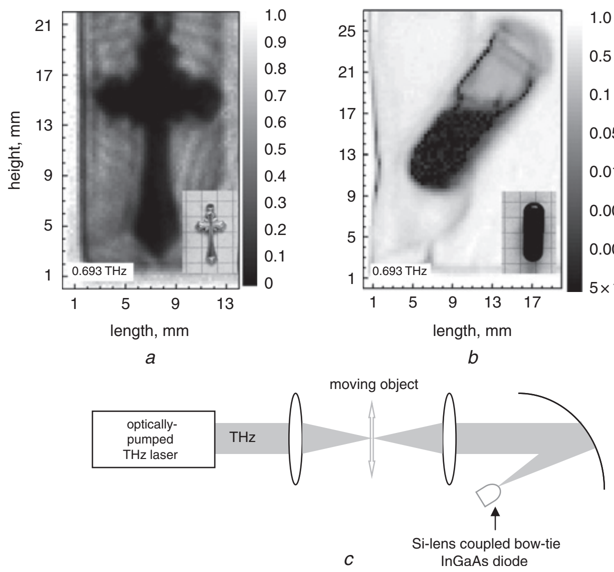

Fig. 1 *THz images of metallic jewel and plastic capsule with pharmaceutical powder both inside paper envelope*

Pictures captured at 0.693 THz frequency at RT with signal-to-noise ratio more than 1000. Chopper frequency, 320 Hz; incident power about 0.1 mW
a THz image of metallic jewel
Intensity normalised to maximal value; scale is linear. Image consists of 60 × 88 square pixels each 250 μm size. Lock-in integration time, 20 ms
Inset: Photo of object placed on 5 mm squared background
b THz image of plastic capsule with pharmaceutical powder
All scales same as previous image but intensity scale logarithmic. Imaging parameters: 61 × 85 square pixels each 325 μm size; lock-in integration time, 50 ms
Inset: Object photo for comparison
c Experimental setup
THz radiation is collimated by high pressure polyethylene lenses with 6 cm focus. Detector signal amplified with low-noise current preamplifier (conversion impedance 10^8 V/A; bandwidth, 10 kHz) and is measured by lock-in amplifier

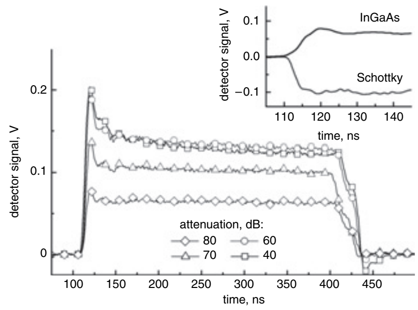

Fig. 2 *Twenty times averaged waveform of THz detector with 100 MHz bandwidth preamplifier at different 94 GHz frequency pulse power*

Inset: Expanded waveform of THz detector and Schottky diode at 80 dB

For practical application in real-time imaging one needs to know the transient properties and dynamical range of the sensor. Typical waveforms recorded at different 94 GHz source powers are shown in Fig. 2. These data are recorded using a low-noise 100 MHz bandwidth current preamplifier. As one can see, within the first 50 ns, the distortion, increasing with the illumination power, is visible. After 150 ns, the response sets to a steady value. The inset of Fig. 2 shows comparison of the waveforms recorded by the THz detector and a Schottky diode. Both detectors demonstrate comparable waveforms. The THz detector response time estimated from an oscilloscope trace is found to be less than 7 ns.

The dynamical range of the device is estimated measuring the current induced by the external radiation at 94 GHz. The signal dependence on the incident power is shown in Fig. 3. It is seen that the detector signal increases with power up to 10 mW, and above this value saturation begins. We note that the incident power is the power which hits the THz detector surface; it was estimated by finding the ratio between

emitted source power and the power impinging on the bow-tie diode area. The detector signal adequacy to radiation power was investigated by varying the distance between the detector and the antenna. The result is shown in the inset of Fig. 3. As one can see, the response signal of the diode is proportional to an inverse-square of the distance, i.e. the THz detector signal is directly proportional to the irradiation.

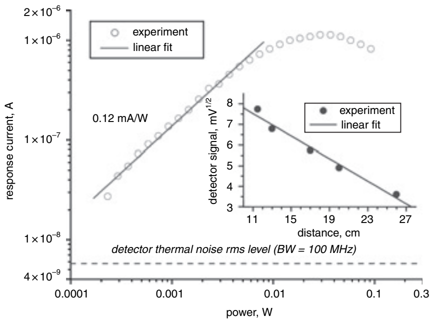

Fig. 3 *Response current of THz detector against incident power*

Dashed line indicates rms value of Johnson thermal-noise of detector with internal resistance of 50 kΩ. Signal bandwidth, 100 MHz
Inset: Square root of detector signal against distance from W-band horn antenna at incident power of about 3 mW

The measured noise is found to be equal to the Johnson thermal noise of the detector. The noise current rms value at RT of the THz detector with a typical internal resistance of 50 kΩ is shown as a dashed line in Fig. 3. The detector dynamic range is 20 dB at the investigated 100 MHz bandwidth and the noise equivalent power (NEP) is 5.8 nW/$\sqrt{}$Hz. One can see that the maximum response is limited at the signal current of about 1 μA, therefore the dynamic range can be gained only at the expense of bandwidth. For example, the dynamic range can be 20 dB enhanced by a bandwidth cut from 100 MHz to 10 kHz. It is worth mentioning that the bandwidth needed for a real-time imaging is even lower. For instance, at a typical 50 frames/s capture rate, the THz detector will demonstrate dynamic range higher than 52 dB if a maximum not-saturating incident power of about 10 mW is used.

Comparison with field effect transistors: For THz imaging applications, it is reasonable to compare the parameters of the bow-tie diode with FET-nanotransistors used in [2, 5, 6]. The response time of bow-tie diodes is below 7 ns (the bandwidth >50 MHz), while in GaAs HEMTs, fast plasmon response demonstrated experimentally [6] is below 0.2 ns (the bandwidth >2 GHz). The responsivity and the NEP of the bow-tie diode are 5 V/W and 5.8 nW/$\sqrt{}$Hz respectively, while the relevant parameters for the GaAs nanotransistor are 0.32 V/W and 37.3 nW/$\sqrt{}$Hz [2]. It is noted that in respect of these parameters a more promising option seems to be silicon MOSFETs. It was demonstrated that the NEP value up to 0.1 nW/$\sqrt{}$Hz and responsivity as high as 200 V/W can be reached with proper antenna coupling [5]. It is noted that the bow-tie diodes are technologically less demanding than nanotransistors and operate in a passive scheme. Also, we observe no negative outcome on incident power up to 0.1 W in pulse mode, nor any damage caused by static electric charge, which is an issue in FET applications.

Conclusion: A silicon lens-coupled bow-tie InGaAs-based diode with broken symmetry is demonstrated for different terahertz imaging applications at 0.693 THz at room temperature. Study of transient and noise performances has shown that the device exhibits a rise time less than 7 ns, responsivity of about 0.1 mA/W and NEP of about 6 nW/$\sqrt{}$Hz.

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