Novel 3D rectification effect for high-speed, high-sensitivity plasmonic THz detector

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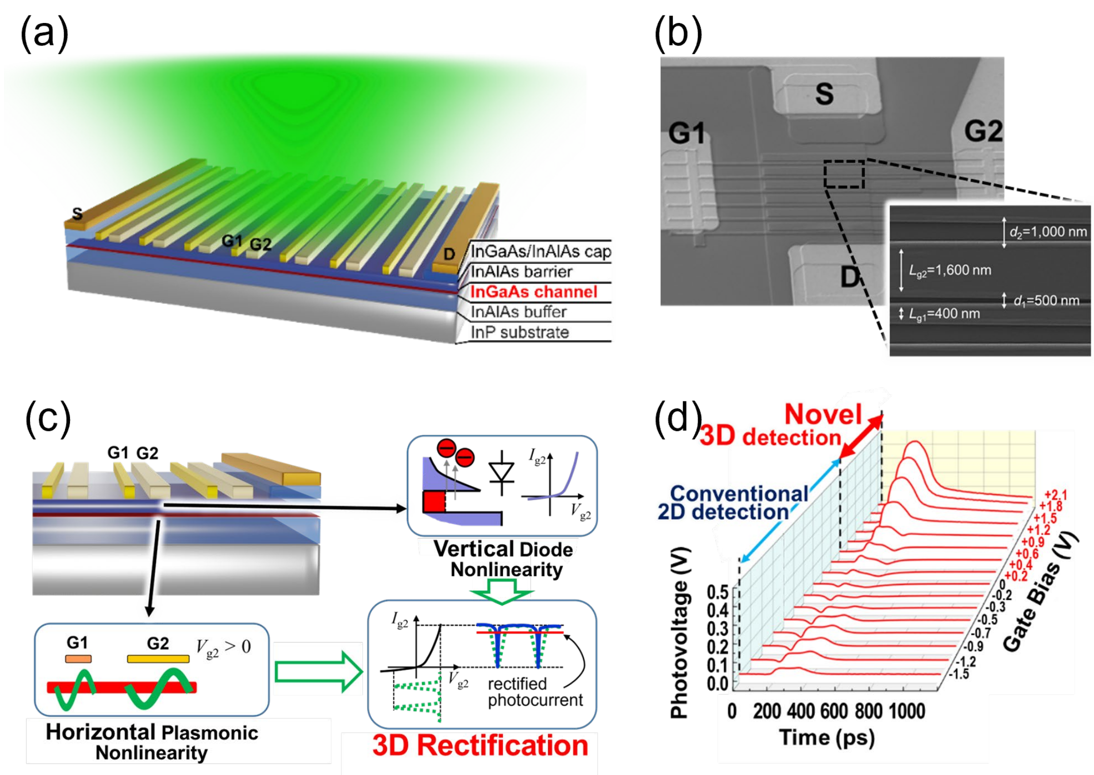

Figure 1: A 3D rectification effect in an asymmetric dual-grating-gate plasmonic THz (THz) detector.

1. Pre-reading

Two-dimensional (2D) plasmons, collective charge density quanta of 2D electrons excited in the electron channel of a semiconductor field-effect transistor, have attracted attention as an operation principle to realize a room-temperature-operating, high-speed, high-sensitivity terahertz (THz) detector (plasmonic detector). Due to their strong nonlinear rectification effect associated with the fluid nature and their fast response not limited by the electron transit time, a high detection performance exceeding conventional electronic and optical devices is expected.

A research group led by Associate Professor Akira Satou at Research Institute of Electrical Communication, Tohoku University in collaboration with Professor Tetsuya Suemitsu at New Industry Creation Hatchery Center, Tohoku University, and a research team led by Dr. Hiroaki Minamide, Team Leader, at RIKEN Center for Advanced Photonics have fabricated a plasmonic THz detector based on an indium phosphorus compound-semiconductor high-electron-mobility transistor (HEMT) and evaluated THz detection characteristics at room temperature. As a result, by applying an abnormal strong positive bias to the gate terminal of the transistor and reading out the detection signal from the gate terminal, instead of the conventional drain terminal with a normal gate bias level, a novel detection principle, "plasmonic three-dimensional (3D) rectification effect", was discovered that superimposes a gate-to-channel diode current nonlinearity onto the plasmonic hydrodynamic nonlinear rectification effect (Fig. 1).

By employing this novel THz detection scheme, we have succeeded in a significant enhancement of the THz detection responsivity outperforming the conventional detectors by more than one order of magnitude, and we have also succeeded in the development of a device modeling manifesting the operation principle with quantitative agreement with experimental data obtained. Furthermore, it has been demonstrated that, by following this operation principle, the output impedance of the device can be matched to the standard high-speed transmission line impedance of 50 Ω, and that the problem of waveform distortion due to multiple reflections in conventional drain-readout configurations can be dramatically eliminated in the detection of high-speed modulated signals.

These are groundbreaking achievements that pave the way to the realization of next-generation 6G & 7G ultrahigh-speed wireless communications.

2. Background

Terahertz waves are electromagnetic waves with a frequency lying between that of radio waves and light waves, and have unique characteristics not found in other electromagnetic waves, such as the fact that they overlap with the vibrational frequency of molecules of substances, and thus almost all matter exhibits inherent absorption characteristics of their own finger prints in this THz range. For this reason, the development of technologies utilizing THz waves is progressing rapidly in various scientific and industrial fields, such as spectroscopy and imaging for safety and security to see the “invisible," and ultra high-speed wireless communications. In particular, the development of 6G and 7G technologies, the next generations of ultrahigh-speed wireless communications using THz waves, is essential for the dramatic improvement of information and communication services that are indispensable for the realization of a near-future super-smart society. However, the development of electronic devices such as transistors and optical devices such as lasers has been extremely difficult due to the substantial physical limitations of operation in the THz band. In particular, further performance improvement is required to realize THz wave detectors that operate at room temperature, can be miniaturized and integrated, and have high speed and high sensitivity, which are essential as a means of receiving 6G and 7G wireless signals in a real time manner.

Against this background, 2D plasmons, collective charge-density quanta of 2D electrons excited in the electron channel of a semiconductor field-effect transistor, have attracted attention as an operation principle to realize a room-temperature-operating, high-speed, high-sensitivity THz detector (plasmonic detector), which is difficult with conventional electronic and optical devices, due to their strong nonlinear rectification effect associated with the fluid nature and their fast response not limited by the electron transit time. In particular, a detector that introduces a unique transistor electrode structure called an asymmetric dual-grating-gate structure can efficiently couple plasmons with THz waves (Fig. 1(a)). The conventional operation principle that reads out the photovoltage signal from the drain terminal has the advantage that the detection signal can be enhanced by making the internal resistance very high (typically around 100 kΩ), but the output impedance cannot be matched to the standard high-speed transmission line impedance of 50 Ω. This causes waveform distortion due to multiple reflections of the detection signal between the signal wiring with the next stage, severely degrading the receiver performance. In other words, there is a trade-off between the detection sensitivity and speed performances, which has been a major barrier to the practical application of ultrahigh-speed wireless communications.

3. Innovative research

Assoc. Prof. Satou's research group fabricated a plasmonic detector with an asymmetric dual-grating-gate structure based on an indium phosphorus compound-semiconductor HEMT (Fig. 1(b)) and evaluated its detection performance by a THz pulse detection measurement at 0.8 THz at room temperature with a new method to read out a detection signal from the gate terminal of the device under the application of an abnormal strong positive bias to the gate terminal. Under this original detection scheme, we discovered a novel detection principle called "plasmonic 3D rectification effect" (Fig. 1(c)), resulting in a significant enhancement of the current detection responsivity by more than one order of magnitude over the conventional performance (Fig. 1(d)). This novel operation principle can be explained as follows. At a high positive gate bias voltage, a heterobarrier between the InGaAs channel and the InAlAs barrier layer provides the exponentially increasing diode-like current nonlinearity associated with electron tunneling. Then, the 2D plasmonic photocurrent oscillating at the incoming THz radiation frequency as well as all the higher harmonic frequencies are generated and introduced into the channel to induce the in-plane plasmonic rectification. This results in multiplication of the diode nonlinearity (vertical direction to the channel) and the plasmonic nonlinearity (in-plane direction to the channel), leading to the giant "3D rectification effect". This significant enhancement in measured photovoltage was successfully verified by a device modeling with a simplified formulation of this physical picture.

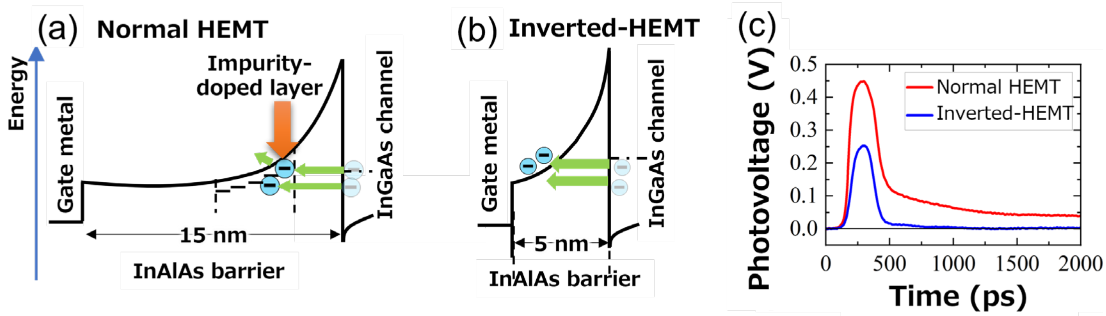

Figure 2: Drastic enhancement of detector photoresponse by introduction of the inverted HEMT structure.

On the other hand, an undesired very long tail photoresponse waveform was observed after the output pulse waveform corresponding to an incident THz pulse wave. Such a slow response limits the data rate of error-free operation in wireless communications and must be eliminated. The cause of this tail waveform was found to be the electron trapping by the donor levels at the InAlAs carrier-supply layer existing in the electron tunneling path between the gate and the channel in the normal HEMT structure (Fig. 2(a)). By introducing the so-called inverted-HEMT structure (Fig. 2(b)), where the carrier supply layer is situated under the channel layer out of the tunneling path, The tail waveform was completely eliminated (Fig. 2(c)). This demonstrated the superiority of the inverted-HEMT structure for wireless communication applications.

The maximum measured current detection responsivity obtained for the device with a normal HEMT structure (Fig. 3) was 0.49 A/W and is more than one order of magnitude higher than that in the conventional drain-readout. It is also higher than the responsivity of existing electronics-based THz detectors such as Schottky barrier diodes (0.3~0.4 A/W at 0.8 THz). The output resistance of the gate-readout HEMT structure was approximately 100 Ω at a gate bias of +2.1 V, assuring that the impedance matching with a 50-Ω transmission system can be achieved easily by the HEMT design optimization which was difficult in the conventional drain-readout scheme because of its inherently very high output resistance on the order of 100 kΩ.

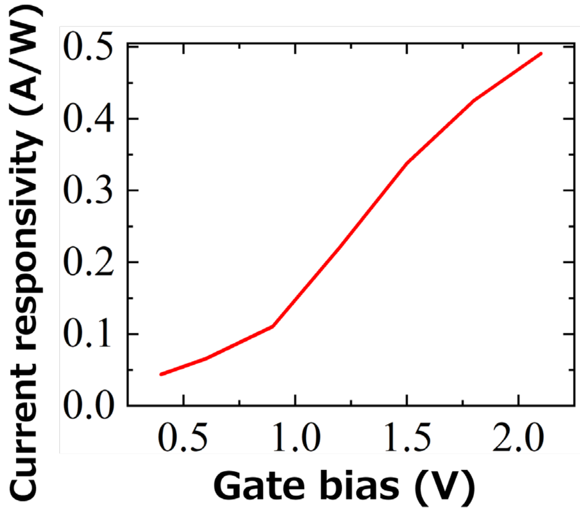

Figure 3: Current detection responsivity of the device.

4. Applications and perspectives

The obtained THz detection responsivity characteristics can be well qualified to be sufficiently high to realize a room-temperature-operating THz detector for transmission of about 100 m, which is required for receivers of next-generation 6G- & 7G-class ultrahigh-speed THz wireless systems. On the other hand, as mentioned above, there is a room for further performance enhancement in plasmonic detectors utilizing the 3D rectification effect, for example, an improvement on the band engineering of the electron tunneling-path heteroepitaxial layers between the cannel and the gate electrode to maximize the diode-like nonlinearity. Then therefore, in the very near future, it is fully expected that the transmission distance of next-generation ultrahigh-speed wireless communications 6G & 7G can be extended to the kilometer level.

These research results are published online with the title "Gate-readout and a 3D rectification effect for giant responsivity enhancement of asymmetric dual-grating-gate plasmonic THz detectors" in Nanophotonics, a high-impact factor journal.

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Akira Satou: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.
Takumi Negoro: Data curation, Investigation, Methodology, Validation, Visualization.
Kenichi Narita: Data curation, Investigation, Methodology, Validation, Visualization.
Tomotaka Hosotani: Data curation, Investigation, Methodology, Validation.
Koichi Tamura: Formal analysis, Investigation, Methodology, Validation, Visualization.
Chao Tang: Investigation, Methodology, Validation, Visualization, Writing – original draft.
Tsung-Tse Lin: Investigation, Methodology, Resources, Validation, Writing – original draft; Paul-Etienne Retaux: Software, Investigation, Methodology, Validation, Formal analysis.
Yuma Takida: Investigation, Methodology, Validation, Resources.
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Taiichi Otsuji: Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.
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[Original publication]
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