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Ultrahigh Sensitive Non-Resonant and Resonant Terahertz Detection by Asymmetric Dual-Grating Gate HEMTs

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Abstract

We have proposed terahertz (THz) detectors based on our original asymmetric dual-grating gate high electron mobility transistors (A-DGG HEMTs) designed and fabricated using InAlAs/InGaAs/InP material systems. We report on a record responsivity of 22.7 kV/W at 200 GHz and a superior low noise equivalent power (NEP) of 0.14 pW/Hz$^{0.5}$ at 292 GHz at room temperature. In addition, a resonant mode detection was observed at low temperature.

1. Introduction

In the modern terahertz (THz) science and technologies, various kinds of THz detectors, for example, Golay cells [1], pyroelectric detectors [2], bolometers [3] as well as Schottky barrier diodes (SBDs) [4] are used. These detectors except SBDs are thermoelectric types so that they exhibit slow response speed although having rather excellent detection sensitivity. The SBDs can serve fast response speed but suffer from poor sensitivity at higher frequencies due to their electron transit-type mechanism.

In such a situation hydrodynamic nonlinearities of two-dimensional (2D) plasmons in high electron mobility transistors (HEMTs) have attracted attention due to their potentiality of fast and sensitive rectification and detection of THz radiation [5]. Under the source-terminated and drain-opened asymmetric boundary conditions, the rectified dc photocurrent in the HEMT channel gives rise to a dc photovoltage at the drain terminal. Recently, InP- and GaN-based HEMTs as well as Si-MOSFETs have demonstrated improved responsivities. Excellent THz detection sensitivities have been reported including 5 kV/W at 290 GHz from Si-nMOSFETs [6] and 2.2 kV/W at 1 THz from InGaAs/InAlAs/InP HEMTs at room temperature by utilizing such a photovoltaic effect of 2D plasmons [7].

In this paper, we report on an ultrahigh sensitive THz detection and a superior low noise equivalent power (NEP) to sub-THz radiation ad 200 and 292 GHz at room temperature. Furthermore, we also demonstrate the detection with resonant-type behavior at 292 GHz at low temperature.

2. Device Design and Fabrication

The schematic view and SEM images of our original asymmetric dual-grating-gate (A-DGG) HEMT sample are shown in Fig. 1. There are two specific features contributing to an enormous increase in responsivity by orders of magnitude [8]. First, the dual-grating gates consisting of two sub-gratings: G_1 (with length L_{g1}) and G_2 (with length L_{g2}) working as broadband antenna for incident THz wave. Second, the ratio of the spacings between metal fingers of the two sub-grating gates (d_1 and d_2) is set to be 0.5. This A-DGG scheme breaks the mirror symmetry of the internal electric field distribution of the 2D plasmon cavities in the HEMT channel [7]. The designed parameters of the samples we used for the experiments are summarized in Table 1.

3. Experiments and Discussions

There are two types of detection mode, resonant and non-resonant, depending on the quality factor $Q = \omega\tau$, where ω is incoming THz angular frequency and τ is the electron momentum relaxation time. The non-resonant mode appears when $\omega\tau < 1$ due to a small value of τ at room temperature. On the other hand resonant mode appears when $\omega\tau > 1$ due to a large value of τ at low temperature.

200 and 292 GHz detection experiment at room temperature for non-resonant detection was carried out using a microwave signal generator and multipliers as a sub-THz CW light source. The THz radiation was focused onto an A-DGG area on the fabricated HEMT and photoresponse ΔU was observed by a lock-in technique. The responsivity R_v can be estimated using the equation $R_v = \Delta U \times S_t / (P_t \times S_d)$, where S_t is radiation beam spot size, P_t is the total source power of the incident beam and S_d is the active area of the transistor. Figure 2 shows the measured responsivity of sample #1-1 at 200 GHz and #2-3 at 292 GHz as a function of the gate bias V_{g2} for G_2 (V_{g1} for G_1 was fixed at 0 V). The maximum value of 22.7 kV/W was obtained at V_{g2} = -0.9 V, close to the threshold voltage at 200 GHz and 19.2 kV/W at 292 GHz near the threshold voltage. To the best of our knowledge, this is the highest responsivity ever reported for plasmonic THz detectors. Figure 3 shows the NEP of

sample #2-3 at 292 GHz calculated by the measured responsivity and source-drain resistance under almost zero drain bias condition. The resultant obtained value is 0.14 pW/Hz$^{0.5}$, excellent noise characteristic.

Figure 4 shows the measured photoresponse as a function of V_{g2} using 292 GHz source at low temperature. With decreasing the temperature, the photoresponse ΔU around V_{g2} = -0.75 V (corresponding to the voltage 1st plasmon mode appears) become sharper. Photovoltage $R\Delta I$ calculated from the photocurrent and the output impedance of the HEMT is also plotted in Fig. 4. There is a good coincidence on the peak positions between the measured photoresponse and the calculated photovoltage. It indicates that the resonant detection was observed successfully.

4. Conclusions

We observed the record-breaking responsivity 22.7 kV/W and excellent NEP for non-resonant detection using 200/292 GHz source. Furthermore, resonant-mode detection was clearly observed at 292 GHz at cryogenic temperatures. These experimental results prove that the advantage of the asymmetric dual-grating gate structure.

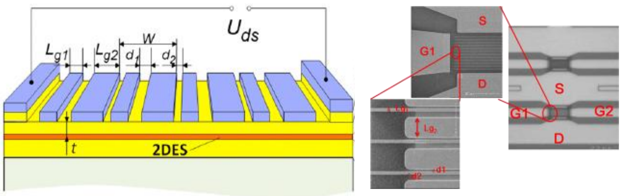

Fig. 1. Schematic (upper) and SEM images (lower) of the A-DGG HEMT.

Table 1. Designed parameters of the fabricated samples.

Sample #	1-1	2-3	2-4
L_{g1} (nm)	200	215~430	400~705
d_1/d_2 (nm)	200/400	400/800	400/800
L_{g2} (nm)	1600	1600	1600
# of fingers: G_1/G_2	8/9	8/9	6/7
Active area (μm^2)	20 × 20	20 × 20	20 × 20

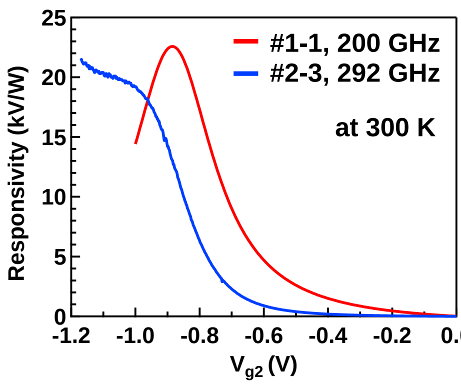

Fig. 2. Responsivity of sample #1-1 at 200 GHz and #2-3 at 292 GHz as a function of V_{g2} (V_{g1} = V_{ds} = 0 V).

Acknowledgements

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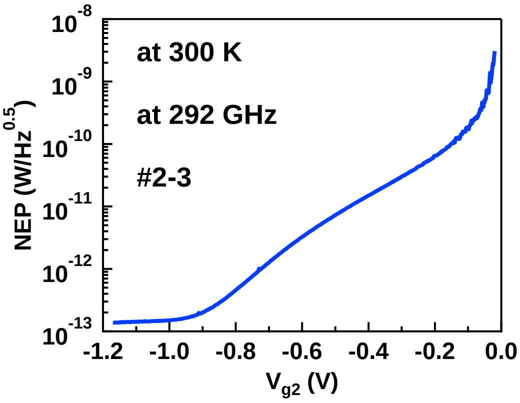

Fig. 3. Calculated noise equivalent power (NEP) of sample #2-3 at 292 GHz as a function of V_{g2} (V_{g1} = 0 V, V_{ds} = 1 mV).

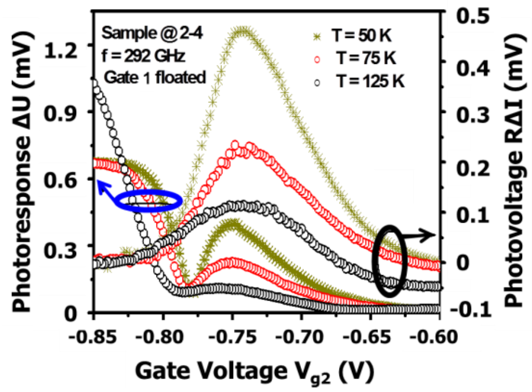

Fig. 4. Measured photoresponse (left) and the photovoltage (right) of sample #2-4 at 292 GHz as a function of V_{g2} (V_{g1} = V_{ds} = 0 V) at low temperature.