



Broadband Terahertz Detection in Dual-Side Gated Graphene

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Abstract

In this work, we fabricated graphene terahertz detectors with dual-side metallic gate. Detectors using only one set of gates showed a monotonic change in responsivity as gate voltage changed, with a peak value of ~ 12 V/W within 0.1 THz, and no distinguishable response above 0.1 THz. The dominating mechanism was found to be the photo-thermoelectric (PTE) effect. Detectors using multiple sets of gates showed monotonic and non-monotonic change in responsivity as gate voltage changed, with peak responsivity of 462 V/W at 0.082 THz and 198 V/W at 2.52 THz. In the frequency ranges where the responsivity changed monotonically, the dominating mechanism was found to be the PTE effect for frequencies. In the frequency ranges where responsivity changed non-monotonically, the dominating mechanism was found to alternate between the plasmon rectification effect and the PTE effect at different gate voltage. The excitation of graphene plasmons promised non-degrading responsivity below 0.105 THz and at 2.52 THz.

Keywords Graphene · Plasmons · Terahertz · Detection

Introduction

Nowadays, electromagnetic waves-related technologies have been widely used in our daily life. One of the fundamental devices is a detector. Detectors operating at high frequencies, such as infrared and visible frequencies, usually utilize photonic methods to generate a response. Detectors operating at low frequencies, such as radio frequencies, usually utilize electronic methods to generate a response. In between lies the terahertz (THz) waves, spanning from 0.1 to 10 THz, with potential applications in sensing [1], biomedicine [2, 3],

security [4, 5], and communication [6, 7]. However, neither photonic methods nor electronic methods show high performance in THz frequencies. New detection mechanisms and their optimization are desired for realizing THz detectors with high responsivity, low noise-equivalent power, short response time, high dynamic range, and broad bandwidth at room temperature.

The discovery of low-dimensional materials shed a light on THz detection. Graphene-based bolometers were reported since 2010 [8–11], but most bolometers only show high performance under cryogenic temperatures. The excitation of resonant graphene plasmons can help to generate high response under room temperature by the plasmon drag effect

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[12] and plasmon ratchet effect [12–16] for under-damped plasmons. Under cryogenic temperatures, detectors based on the plasmon ratchet effect can yield strong THz response [14, 16]. However, at room temperature, the (post-fabrication) carrier scattering time of the state-of-the-art CVD-grown graphene can hardly reach 0.2 ps, and then graphene plasmons will quickly be overdamped. In the overdamped regime, the plasmon rectification effect [17–24] will yield broadband response, but the response frequency is usually limited to below 1 THz.

Except plasmons, other mechanisms can also yield high THz response. Photo-thermoelectric (PTE) THz detector operating at room temperature was demonstrated by Castilla et al. with low NEP of $80 \text{ pW/Hz}^{1/2}$, high peak responsivity of 105 V/W , broad bandwidth from 1.8 THz to 4.25 THz, and short response time $< 30 \text{ ns}$ [25]. The high mobility of graphene ($\sim 20000 \text{ cm}^2/\text{Vs}$) was essential to the good performances. High responsivity depended on the special design on structural asymmetry, as graphene shows no asymmetry. Detectors with higher peak responsivity of 700 V/W and shorter response time $< 0.12 \text{ ns}$ were demonstrated by Cai et al., which used different metals to contact with graphene and thus producing asymmetry in Seebeck coefficient [26]. Later, many works focused on utilizing the photo-galvanic effect in type-II Dirac materials, which possess asymmetry in band structure and thus naturally show response to THz illumination [27–30]. Guo et al. demonstrated responsivity up to 10 A/W , response time of $1 \text{ }\mu\text{s}$, and NEP of $2 \text{ pW/Hz}^{0.5}$ at room temperature [27]. More recently, many researchers reported detectors that showed response from low THz band to infrared, visible, and ultraviolet frequencies [31, 32].

Despite the success these low-dimensional-materials-based THz detectors achieved in yielding high peak responsivity at certain frequencies, high responsivity over a broad THz bandwidth, e.g., from < 0.2 to > 2 THz, is still challenging because of the lack of a broadband coupler. In order to achieve broadband high responsivity, we proposed using metallic metamaterials to enhance the excitation of graphene plasmons in our previous work, which will degrade into hot carriers and generate THz response by the PTE effect [33]. Although non-degraded response was demonstrated from 0.02 to 0.75 THz, there was an obvious tradeoff between bandwidth and responsivity. Metallic metamaterials with large scale offer high response but with limited bandwidth. Metallic metamaterials with small scale offer broader bandwidth but with comparatively weaker response.

In this work, we used graphene as a channel of the detectors. Dual-side metallic gates (DSMG), i.e., one deposited below and the other above graphene, were adopted. Devices with only one set of DSMG showed a response caused by the PTE effect. The responsivity monotonically changes as the gate voltage changes and showed a peak responsivity of 13.8 V/W at 0.082 THz. However, little response was found

for incidence with frequencies > 0.1 THz. For devices with multiple sets of DSMG, the responsivity showed monotonic and non-monotonic changes within certain frequency ranges, which were attributed to the sole PTE effect and a combination of the PTE effect and plasmon rectification effect, respectively. The peak responsivity was 462 V/W at 0.082 THz when the top gate voltage (V_{tg}) was 6 V. Devices with multiple sets of DSMG also showed a responsivity of 198 V/W at 2.52 THz, at which frequency the devices with only one set of DSMG showed no response. Higher responsivity, as we estimated, can be obtained by simultaneously applying opposite voltages on the top gate and the back gate. These observations are important for realizing terahertz detectors covering a large terahertz frequency range with high responsivity.

Experiment and Discussion

Figure 1a schematically shows the structure of the samples. Graphene micro-ribbon was used as the channel. The zoom-in images highlighting the graphene channel are shown in Fig. S1. Two sets of metallic gates were used to control the Fermi level of different parts of the graphene channel. The length L_1 of the top gate was $6 \text{ }\mu\text{m}$, and the length L_2 of the back gate was $6.1 \text{ }\mu\text{m}$. The little difference in width compensated for the different dielectric environment, as mentioned in our previous work [34]. The top gate and the back gate overlapped by $2.5 \text{ }\mu\text{m}$ to break the symmetry and to guarantee the excitation of the even order plasmon modes, which are usually dark modes [34]. The spacing between adjacent DSMG (if there is) was designed to be $0.1 \text{ }\mu\text{m}$ to efficiently excite graphene plasmons. Both gates were separated from the graphene channel by an ultrathin SiO_2 layer with $h_1 = h_2 = 10 \text{ nm}$. Trapezoid metals were used as the source and drain, respectively. The trapezoids were $70 \text{ }\mu\text{m}$ in the x coordinate and $100 \text{ }\mu\text{m}$ in the y coordinate. The distance between source(/drain) and top gate(/back gate) was $1 \text{ }\mu\text{m}$. Three devices were designed and fabricated. Sample 1 had only one set of DSMG, as shown in Fig. 1b, with a channel length of $11.6 \text{ }\mu\text{m}$ and a width of $6 \text{ }\mu\text{m}$. Sample 2 also had only one set of DSMG, as shown in Fig. 1c, but the channel length was $21.7 \text{ }\mu\text{m}$. Sample 3 had 16 sets of DSMG, as shown in Fig. 1d, with a channel length of $164.6 \text{ }\mu\text{m}$ and a width of $10 \text{ }\mu\text{m}$.

Figure 2a shows the transfer characteristic curve of Sample 3 as the back gate voltage (V_{bg}) swept forward and backward from -7 to 7 V and the source-drain bias fixed at 0.1 V . The transfer characteristic curve of Samples 1 and 2 is given in Fig. S2. The current minimum emerged at $\sim 4.5 \text{ V}$ during the forward-sweeping and $\sim -3.4 \text{ V}$ during the backward-sweeping, respectively. The average of the two points is positive, corresponding to the p-doped

Fig. 1 **a** Cross section of the designed devices. **b–d** Microscopic images of **b** Sample 1, **c** Sample 2, and **d** Sample 3

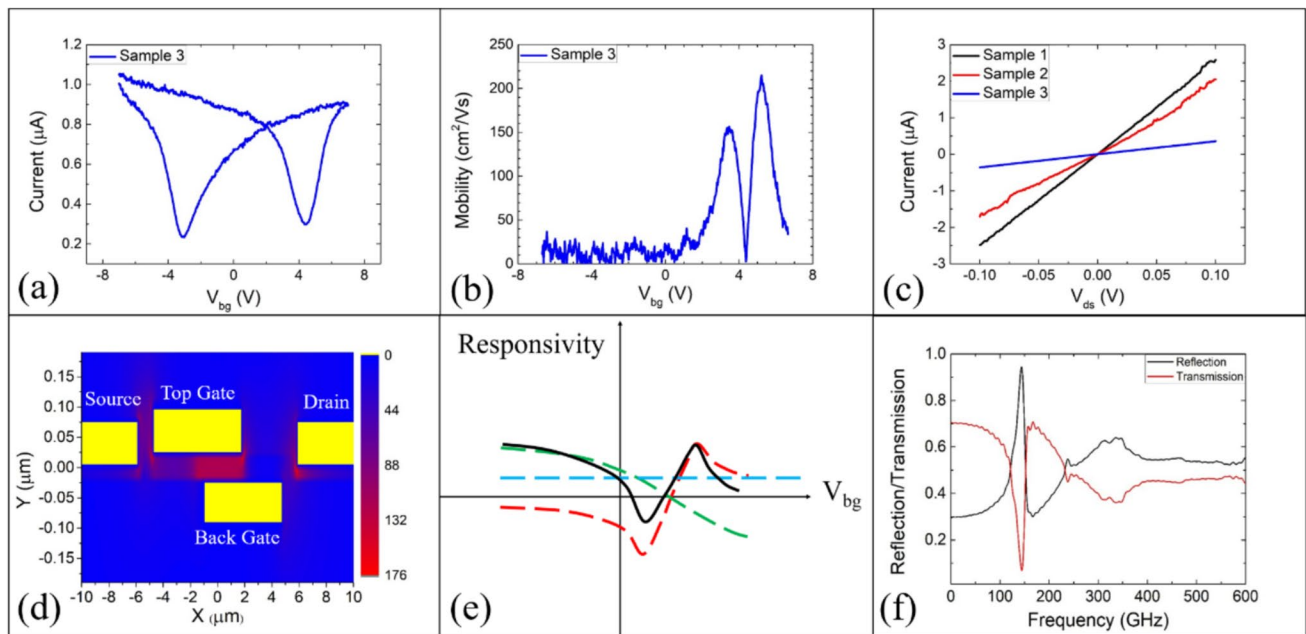
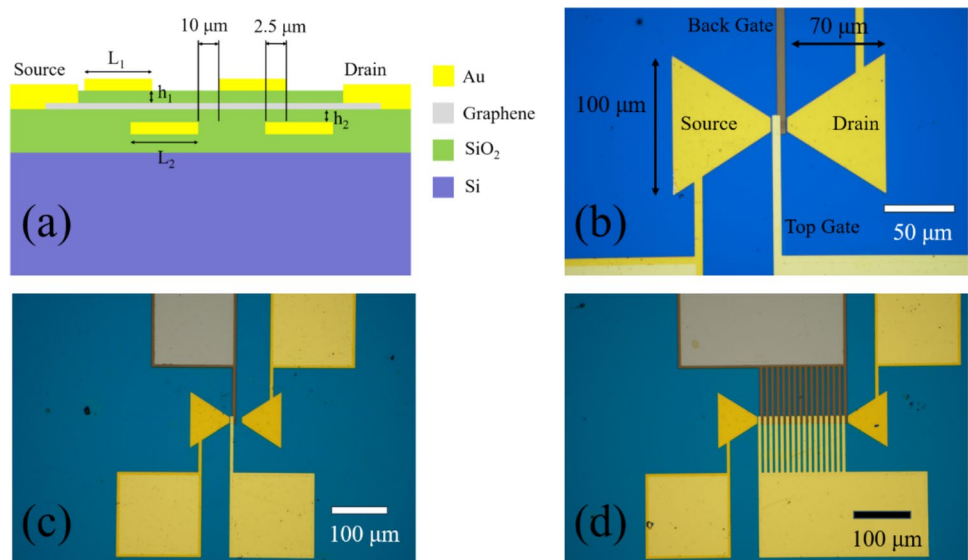


Fig. 2 **a** The transfer characteristic curve of Sample 3. **b** The extracted mobility of Sample 3 from **a**. **c** The output characteristic curve of all three samples. **d** Simulated electric field distribution $|E_z|$ by FDTD method. **e** Illustration of the combination of the PTE effect (green dashed curve) and the plasmon rectification effect in top

(blue dashed curve)/back (red dashed curve) gated channel forms the observed responsivity as a function of V_{bg} (black solid curve). **f** Simulated reflection and transmission spectra of Sample 1 (at the absence of graphene)

nature of graphene. The hysteresis is generally caused by charge trapping and de-trapping at the graphene/SiO₂ interfacial [35–37]. The post-fabrication mobility was extracted to peak at $V_{lg} = 5.4$ V with a peak value of 215 cm²/Vs, as shown in Fig. 2b. The method of estimating graphene mobility is given in the “Experimental Section.” Fig. 2c shows the output characteristic curve of Sample 3 when both gate voltages were 0 V. The resistance of

graphene was extracted to be $\sim 279,470 \Omega$, and the square resistance was calculated to be $16,979 \Omega$. Compared with our previous works [33, 38], in which graphene showed square resistance from 1600 to 2500 Ω and peak mobility of ~ 2600 cm²/Vs, both the mobility and the resistance degraded by more than an order. The reason for the great degradation in post-fabrication graphene mobility was likely to be the rough surface onto which graphene was

transferred, brought by the back gate process, as introduced in the “[Experimental Section](#).”

Sample 1 showed a negative response when both gate voltages were 0 V, as shown in Fig. 3a. It might seem strange that devices with such a symmetric structure show a non-zero response. However, it should be pointed out that Sample 1 was, in fact, asymmetric. As shown in Fig. 1a, the back gate and source/drain were not on the same plane, but the top gate was. Therefore, when the THz radiation impinged on Sample 1, the electric field between the source and the top gate was much higher than that between the drain and the back gate, and the electric field in the top gated channel is higher than that in the back gated channel, which was demonstrated by FDTD simulation, as shown in Fig. 2d. Therefore, it could be anticipated that V_{tg} dominated the response. Figure 3a showed that the responsivity of Sample 1 increased monotonically from negative to positive, with the peak value at 0.028 THz from -2.15 to 5.05 V/W as V_{tg} increased from -2 to 5 V. On the contrary, as V_{bg} changed from -2 to 5 V, the responsivity was always negative and reduced monotonically, with the peak value at 0.028 THz

from -0.75 to -4.21 V/W. The larger change in responsivity as V_{tg} changed demonstrated that V_{tg} dominated the response. Both PTE effect and plasmon rectification effect were potential candidates responsible for the observed response [19]. As the response changed monotonically, it was difficult to judge the dominant contributor from Sample 1.

Similar to Sample 1, Sample 2 also showed a negative response when both V_{tg} and V_{bg} were 0 V. Figure 3d shows that the responsivity of Sample 2 increased from -1.07 to 4.01 V/W at 0.027 THz as V_{tg} increased from -2 to 5 V. As V_{bg} increased from -2 to 5 V, however, the responsivity of Sample 2 only changed a little from -0.78 to -1.05 V/W, as shown in Fig. 3e. Note that a major difference of Sample 2 was that the back gate was on the left side of the channel. If the PTE effect was the dominating effect in the back-gated channel for both Samples 1 and 2, the responsivity would have changed positively in Fig. 3e instead of negatively, since the hot holes diffuse from the right side of the channel to the left side for Sample 1, while from the left side to the right side for Sample 2. Therefore, the plasmon

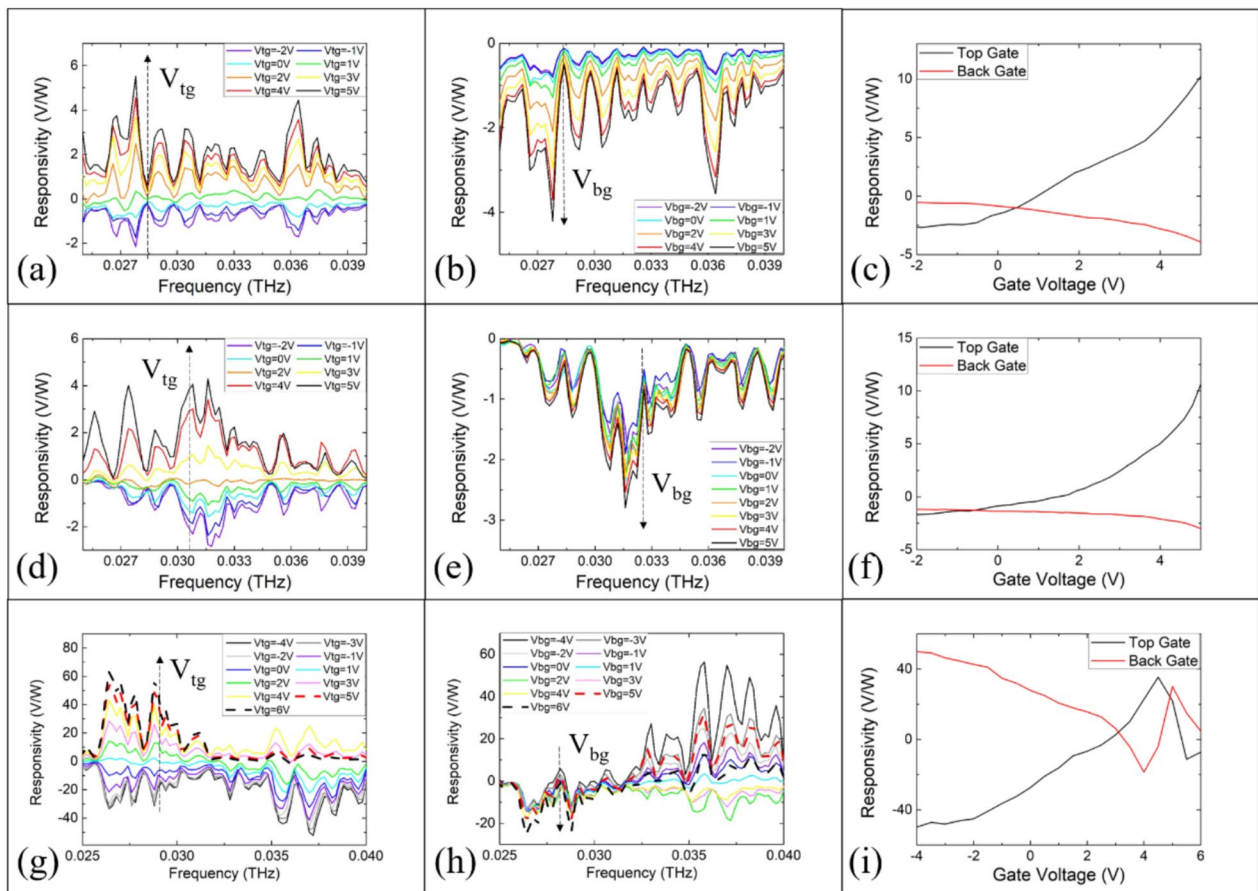


Fig. 3 Responsivity of **a** Sample 1, **d** Sample 2, and **g** Sample 3 at different V_{tg} ($V_{bg} = 0$ V), and responsivity of **b** Sample 1, **e** Sample 2, and **h** Sample 3 at different V_{bg} ($V_{tg} = 0$ V). Responsivity of **c** Sample

1, **f** Sample 2, and **i** Sample 3 as a function of the top gate and back gate at 0.028 THz, 0.027 THz, and 0.036 THz, respectively

rectification effect dominated in this case. Such a weak rectification effect, however, could not account for the much larger change in responsivity, as shown in Fig. 3a, b, and d. Then, the change in responsivity could be explained as follows. Graphene was naturally p-doped due to impurities. For Sample 1, when both gate voltages were 0 V, since the top gate dominated and the PTE effect dominated, the holes in the top-gated channel were heated more than those in the back-gated channel, and then more hot holes diffused from source to drain, creating a built-in electric field from drain to source and generating a negative response. When V_{tg}/V_{bg} was negative, the change in hole density and Seebeck coefficient generated more hot holes at the top/(back) gate side, which would enhance/(weaken) the built-in electric field, so that the responsivity changed negatively/(positively). When the top gate/(back) voltage was positive, less hot holes or more hot electrons diffused toward drain/(source), so that the responsivity changed positively/(negatively). For Sample 2, the explanation to the change of responsivity was same as that of Sample 1 when V_{tg} changed. When V_{bg} changed from negative to positive, since the back gate was far away from the drain, the electric field between the back gate and the drain was greatly suppressed, and thus the PTE effect was weakened and became even weaker than the plasmon rectification effect, so that the weak plasmon rectification effect dominated.

The responsivity of Sample 3 at different V_{tg} was quite different from those of Samples 1 and 2, as shown in Fig. 3g. Firstly, when V_{tg} was 2 V (green curve), there were both positive response peaks within 0.032 THz and negative ones above 0.032 THz. Secondly, the response peaks within 0.032 THz kept changing positively, while the response peaks above 0.032 THz changed positively as the top gate increased from -4 V (black solid curve) and reached a maximum when V_{tg} was 4 V (yellow solid curve), and then changed negatively as V_{tg} further increased from 4 to 6 V (black dashed curve). For the response peaks within 0.032 THz, the dominating effect was still attributed to the PTE effect, as the change of the response peaks was similar to that of Sample 1. For the response peaks above 0.032 THz, however, the two points mentioned above indicated that the PTE effect could not be the dominating effect. The responsivity as a function of V_{bg} , as shown in Fig. 3h further supported the suspicion. For the response peaks within 0.032 THz, the change of the response peaks was also similar to that of Sample 1. For the response peaks above 0.032 THz, however, the response peaks were initially positive instead of negative (black solid curve). As V_{bg} increased, the response peaks changed negatively and reached a negative maximum when V_{bg} was 2 V (green dashed curve), and then increased to a positive maximum when V_{bg} was 5 V (red dashed curve), and then the response peaks reduced again (black dashed curve). Compared with the top gate tuning, the back gate

tuning clearly showed a negative maximum and a positive maximum, corresponding to the plasmon rectification effect [16, 19]. Considering that the negative maximum showed up before the positive maximum as V_{bg} increased from -4 to 6 V, the response of the plasmon rectification effect in the back gated channel was negative when the majority was hole and positive when the majority was electron.

Then, the responsivity of Sample 3 at different V_{bg} could be explained as a combination of the plasmon rectification in the top and back gated channel, and the (plasmon-enhanced) PTE effect, as schematically shown in Fig. 2e. When the Fermi level was tuned close to the Dirac point, the PTE effect (green dashed curve) in the back gated channel would be weak while the plasmon rectification effect (red dashed curve) in the back gated channel dominated, such that negative/positive maximum showed up when the majority was holes/electrons. When the Fermi level was tuned far away from the Dirac point, the plasmon rectification effect in the back gated channel yielded weak response current/voltage, while the PTE effect in the back gated channel was strong and dominated, yielding positive/negative response when the majority was holes/electrons. In the region gated only by the top gated channel, the response of the plasmon rectification effect (blue solid curve) was nearly constant. As a result, the sum of the PTE effect, the plasmon rectification effect in the back gated channel and the top gated channel, the response peaks above 0.032 THz were dominated by the PTE effect in the back gate channel and showed positive response when V_{bg} was -4 V, and then dominated by the plasmon rectification effect in the back gate channel and showed negative/positive maximum when V_{bg} was 2 V/5 V, and then reduced because the responsivities of both the PTE effect and the plasmon rectification effect changed negatively. For the responsivity as a function of V_{tg} as shown in Fig. 3g, since all of these effects show opposite response, the change in responsivity was also opposite.

One might be curious about why the (plasmon-enhanced) PTE effect yielded strong/weak response, while the plasmon rectification effect yielded weak/strong response when the Fermi level is far away from/close to the Dirac point. Here, we would like to stress that strong plasmon excitation would result in strong absorption and thus enhance the PTE effect, but would not necessarily result in a strong response of its own. The reason was that the response of the plasmon rectification effect not only relied on the total absorption of THz waves but also depended on the phase difference of plasmons at the two boundaries of the resonance cavity. When the carrier density was high, the phase difference was close to 0. Therefore, even if plasmons were more efficiently excited when the carrier density was high, the plasmon rectification effect would not yield a high response, while the plasmon-enhanced PTE effect definitely would because of increased total absorption. On the contrary, when the carrier density is

low, the phase difference would become larger, but the total absorption decreased; the tradeoff between the larger phase difference and the decreased total absorption would result in a maximum response for the plasmon rectification effect at certain carrier density, while the plasmon-enhanced PTE effect would just be weaker.

When a $3 \times$ multiplier was equipped onto the microwave source, the responsivity at different gate voltages of all these samples (as shown in Fig. 4) was similar to that shown in Fig. 3. Samples 1 and 2 showed monotonic change in response because the dominating effect was the PTE effect. Sample 3 showed monotonic change in response below 0.091 THz, while non-monotonic change (due that the dominating effect changed between the PTE effect and the plasmon rectification effect) above 0.091 THz, nearly 3 times the frequency when the non-monotonic response showed up (above 0.032 THz, as shown in Fig. 3g). Since plasmons are excited only when the wavevector match $k_p = n\pi/W$ is realized, where k_p represents the plasmon wavevector, W is the gate length, n is an integer, the frequency ranges where the response changed non-monotonically seemed to

correspond to the excitation of the 1st and the 3rd order plasmon modes. In the frequency ranges between two adjacent plasmon modes, the broadening of a resonance mode is responsible for the THz response. In these frequencies, although plasmons quickly cancelled themselves because of the mismatch in phase, their energy will be transferred to heat because of the high scattering rate (which caused the low mobility), and then the PTE effect dominates. Therefore, the dominating effect on the response of Sample 3 was always the PTE effect in some frequency ranges, while the dominating effect varied between the PTE effect and the plasmon rectification effect in the other frequency ranges.

A main difference when the $3 \times$ multiplier was equipped was that Samples 1 and 2 showed decreasing responsivity, and finally undistinguishable when the frequency was larger than 0.1 THz, while Sample 3 showed high responsivity even when the frequency was larger than 0.1 THz. The reason for such difference lied in their different coupling mechanisms. For Samples 1 and 2, the trapezoid source-drain antennas were responsible for coupling the terahertz waves. FDTD simulation in Fig. 2f showed a transmission dip/reflection

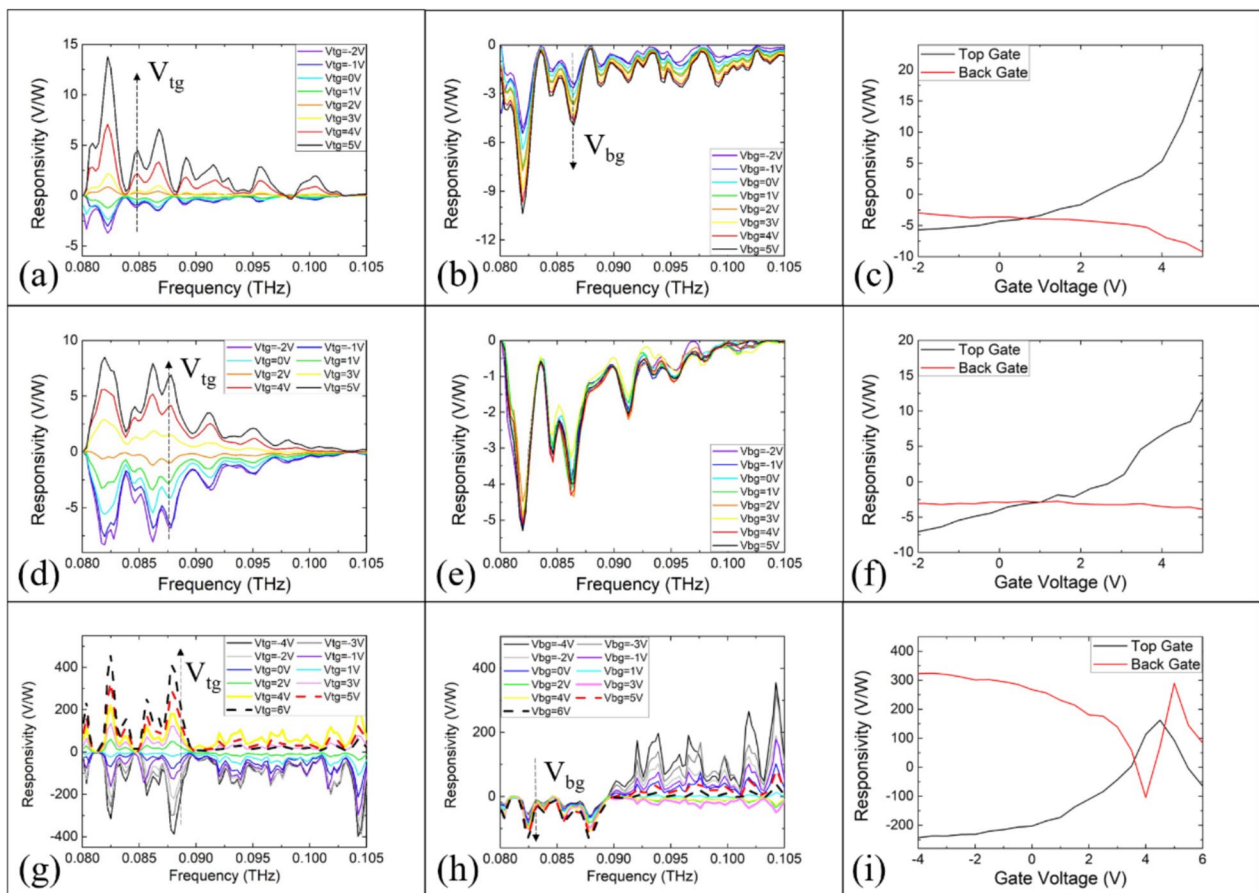


Fig. 4 Responsivity **a** of Sample 1, **d** Sample 2, and **g** Sample 3 at different V_{tg} ($V_{bg} = 0$ V), and responsivity of **b** Sample 1, **e** Sample 2, and **h** Sample 3 at different V_{bg} ($V_{tg} = 0$ V). Responsivity of **c** Sample

1, **f** Sample 2, and **i** Sample 3 as a function of the top gate and back gate at 0.082 THz, 0.082 THz, and 0.104 THz, respectively

peak at 0.144 THz, which meant that the trapezoid antenna could only offer good coupling within 0.144 THz. For Sample 3, however, the dual side grating gates instead of the source/drain antenna offered the coupling. According to our previous work [34], such coupling could excite plasmon modes up to the 21 st order, generating broadband terahertz absorption, so that the responsivity of Sample 3 did not drop quickly as Samples 1 and 2 did.

Finally, the samples were illuminated by a FIR laser (2.52 THz). Samples 1 and 2 showed no response, while Sample 3 did. As shown in Fig. 5a, the responsivity as a function of V_{bg} was similar to that shown in Figs. 3i and 4i, with negative maximum and positive maximum around the Dirac point. The peak responsivity was 198 V/W when V_{bg} was 4.32 V. Different from the profile shown in Figs. 3i and 4i, the responsivity of the positive maximum, which mainly came from the plasmons rectification effect, was larger than the responsivity when V_{bg} was -5 V, which mainly came from the plasmon-enhanced PTE effect. The reason was that the degradation of plasmon resonances was proportional to $(\omega\tau)^{-1}$. At higher frequencies, the degradation of plasmons was weaker, so that plasmon resonance was stronger, generating a stronger plasmonic response. The response time when both top gate and V_{bg} were 0 V, to our surprise, was ~ 190 μ s, with a rise time of ~ 126 μ s and a fall time of ~ 46.5 μ s, as shown in Fig. 5b. Such response time, especially the rise time, was about an order higher than those reported in our previous works [29, 38], which was likely to be induced by the low graphene mobility of 215 cm^2/Vs .

Conclusion

To conclude, we fabricated three DSMG graphene THz detectors. Samples 1 and 2 had only one set of DSMG, showing peak responsivity < 12 V/W and quickly diminished after 0.1 THz, which was mainly attributed to the PTE effect by the source/drain antenna coupling. Sample 3 had multiple sets of DSMG, showing peak responsivity of 462 V/W at 0.082 THz and no trend of weakening after 0.105 THz. The responsivity changed monotonically as the gate

voltage changed in some frequency ranges while non-monotonically in other frequency ranges. The dominant mechanism was attributed to the PTE effect where the responsivity changed monotonically, while the dominant mechanism altered between the plasmon rectification effect and the PTE effect at different gate voltages where the responsivity changed non-monotonically. Sample 3 also showed responsivity at 2.52 THz. The high responsivity and broad response bandwidth were attributed to the excitation of graphene plasmons up to high order.

Experimental Section

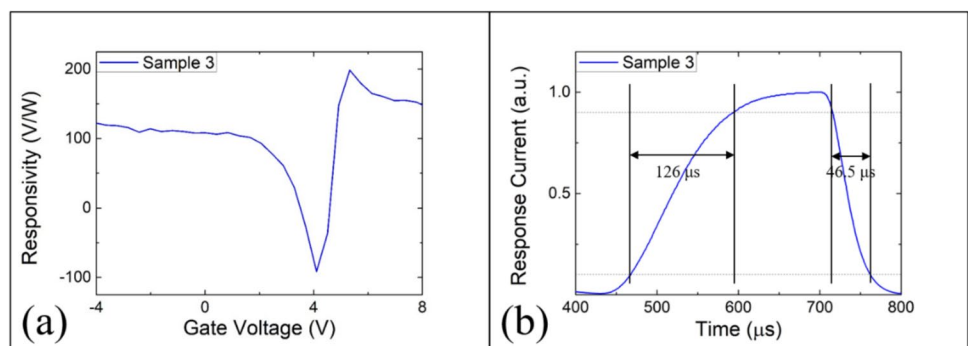
Device Fabrication

The devices were fabricated on a Si/SiO₂ substrate, with Si thickness of 500 μ m and resistivity $> 5 \times 10^3$ $\Omega\cdot\text{cm}$ and SiO₂ thickness of 300 nm. The substrate was wet-etched, and then back gates were deposited by thermal evaporation in the etched grooves. After that, an ultrathin SiO₂ layer of 10 nm was deposited to separate the back gate and the channel, followed by wet transfer of CVD-grown graphene. Graphene was patterned into channel by O₂ ion, and then source and drain (Cr/Au 20/60 nm) were deposited by magnetron sputtering. Another ultrathin SiO₂ layer of 10 nm was deposited to separate the graphene channel and top gate. Finally, top gate (Cr/Au 20/60 nm) was deposited by magnetron sputtering.

Measurements

The devices were measured under ambient environment and at room temperature. The measure system included a Source/Measurement Unit (Agilent B2912 A), a microwave source (Agilent E8257D, for 0.02–0.04 THz measurement), a VDI multipliers (WR 2.8 Tripler for 0.08–0.11 THz measurement), a FIR terahertz laser (FIRL-100, for 2.52 THz measurement), a preamplifier (SR570), a lock-in amplifier (SR830) and a high-speed sampling oscilloscope. The samples were fixed on a printed circuit board (PCB), and the

Fig. 5 **a** Responsivity of Sample 3 as a function of the back gate at 2.52 THz. **b** Response current as a function of Sample 3 with chopping frequency of 2.5 kHz



pads of the samples were wire-bonded to the pads on the PCB. In measuring the THz response, the incidence is linearly polarized with the electric field perpendicular to the metallic gate, and no source-drain bias is applied. Graphene mobility was calculated by $Gm \cdot L / (C_{\text{eff}} \cdot V_{\text{ds}} \cdot W)$, where $Gm = d(I_d)/d(V_{\text{bg}})$ is the transconductance, L is the spacing between source and drain contacts as indicated in Fig. S1, $C_{\text{eff}} = \epsilon_0 \cdot \epsilon_{\text{ox}} / d_{\text{ox}}$ is the effective capacitance, with ϵ_0 is the dielectric constant of vacuum, $\epsilon_{\text{ox}} = 3.9$ is the relative dielectric constant of SiO_2 , and $d_{\text{ox}} = 10$ nm is the designed thickness of SiO_2 , $V_{\text{ds}} = 0.1$ V is the applied source-drain bias, W is the width of the graphene micro-ribbon, as indicated in Fig. S1. Responsivity was calculated by $R = V/P \cdot S_{\text{eff}}$, where V is the measured response voltage, P is the power density of THz signal and was 2.5 mW/cm^2 for 0.02 to 0.04 THz, and 1 mW/cm^2 for 0.08–0.11 THz and 5.7 mW/cm^2 for 2.52 THz, S_{eff} is the effective area calculated by $S_{\text{eff}} = \max\{S_{\text{dev}}, S_{\text{THz}}\}$, where $S_{\text{dev}} = 0.424 \text{ mm}^2$ is the detector envelop area, and $S_{\text{THz}} = \lambda^2/4\pi$ is the diffraction-limited area.

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Author Contribution A.Y. conceived the idea and prepared figures 2–5. S.M. and N.Z. wrote the main manuscript text and prepared figure 1. S.M., X.P., H.Z., X.S., Y.M. and Y.Z. tested the samples. A.Y., Y.Y., Y.S., A.V.B., A.P.S. and Y.M.Z. conducted the experiment. All authors reviewed the manuscript.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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