High-Speed Graphene–Silicon–Graphene Waveguide PDs with High Photo-to-Dark-Current Ratio and Large Linear Dynamic Range

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2D materials (2DMs) meet the demand of broadband and low-cost photodetection on silicon for many applications. Currently, it is still very challenging to realize excellent silicon-2DM photodetectors (PDs). Here, graphene–silicon–graphene waveguide PDs operating at the wavelength bands of 1.55 and 2 μm, showing the potential for large-scale integration, are demonstrated. For the fabricated PDs, the measured responsivities are ≈0.15 and ≈0.015 mAW⁻¹ for the wavelengths of 1.55 and 1.96 μm, respectively. In particular, the PDs exhibit a high bandwidth of ≈30 GHz, an ultra-low dark current of tens of pico-amperes, a high normalized photo-to-dark-current ratio of 1.63 × 10⁶ W⁻¹, as well as a high linear dynamic range of 3 μW to 1.86 mW (and beyond) at 1.55 μm. According to the measurement results for the wavelength bands of 1.55/2.0 μm and the theoretical modeling for the silicon–graphene heterostructure, it is revealed that internal photoemission and photo-assisted thermionic field emission dominantly contribute to the photoresponse in the graphene–silicon Schottky junctions under moderately high bias voltage, which helps the future work to further improve the performance.

1. Introduction

2D materials (2DMs) feature the wide-range bandgaps, high mobility, and flexible integration, meeting the demands on wide-spectrum, high-performance, and integration-friendly photodetection on silicon photonic chips. Currently there have been several typical silicon-2DM photodetectors (PDs) developed, including metal–2DM–metal PDs, metal–2DM+X–metal PDs, and 2DM–heterostructure PDs. It is still very challenging to realize silicon–2DM PDs with high overall performances on bandwidth, sensitivity, as well as linearity by using low-cost and reproducible fabrication technologies.

A popular strategy is using the dual-gate field-effect transistor configuration with graphene p-n homojunction, in which way these devices can operate at zero bias with a bandwidth of >10 GHz based on the photo-thermoelectric effect. Meanwhile, more efforts are still needed to suppress the thermal noise and enhance the photoresponse. The silicon–graphene heterostructure provides another promising option for the near/mid-IR photodetection, because of its potential advantages of easy fabrication and low dark current. Currently various surface-illuminated and waveguide-integrated silicon–graphene heterostructure PDs have been demonstrated, while most of them have bandwidths below MHz. As an exception, Li et al. demonstrated a waveguide-integrated silicon–graphene p-i-n photodiode with a high radio frequency (RF) bandwidth estimated from the measured microwave spectrum of the converted photoelectric signal with a center frequency of 40 GHz. In order to improve the PD performances, in the past years the carrier transport mechanisms in various 2DM–2DM and 2DM/bulk-material heterostructures have drawn much attention from academia, including silicon–graphene Schottky diodes. For a graphene–semiconductor/insulator interface, if light is absorbed by graphene only, the photoresponse mechanisms can be classified to two types, depending on whether the thermal relaxation process of the photo-induced carriers involves. The first type is for the case with the photo-thermionic (PTI) effect. Here, the photoexcited carriers may form a Fermi–Dirac distribution with an increased temperature T higher than the lattice temperature. The high-energy tail of the distribution of the carriers (called “hot carriers”) contributes to the photo-thermionic current. For instance, the PTI effect was found in the graphene/WSe₂/graphene heterostructure, and the plasmonics-enhanced PTI was observed in the graphene/hBN/graphene heterostructure. The
second type is similar to the internal photoemission (IPE) effect in the conventional metal–semiconductor Schottky PDs, in which case the photoexcited carriers may go over or tunnel through the energy barrier and then contribute to the photocurrent directly. For the second type, the mechanisms include the prompt IPE (PIPE) in a graphene/SiC Schottky junction,\cite{21} the direct tunneling in a graphene/hBN/graphene tunneling junction,\cite{22} the photovoltaic effect in a graphene/2D-semiconductor junction,\cite{23} as well as the hot-electron emission in a graphene/vacuum system.\cite{24} Furthermore, it has been shown that the bias voltage,\cite{21,22,24} the incident optical power,\cite{21,23,24} and the photon energy\cite{22,21} usually play important roles in the competition of different photoelectric conversion pathways. In order to further develop high-performance silicon–graphene heterostructure PDs, more efforts are still desired to obtain a clearer physical image for light-induced carrier dynamics and photoresponse mechanisms.

In this work, we propose and demonstrate a graphene–silicon–graphene heterostructure PDs with few-layer graphene (FLG). A thin silicon photonic platform is adopted for enhancing light absorption in graphene. In particular, we introduce a multimode-interference-based wavelength-division-multiplexer in photonic integrated circuits, so that the present PD working for both wavelength bands of 1.55/2 μm can be characterized conveniently. The fabricated graphene–silicon–graphene PD typically has a high bandwidth of \( \approx 30 \) GHz, benefiting from short transit time and small RC time constant. The normalized photo-to-dark-current ratios (NPDRs) are as high as \( 1.63 \times 10^6 \) and \( 2.66 \times 10^5 \) W\(^{-1}\) at 1.55 and 1.96 μm, respectively. According to the experimental results and the theoretical modeling, it is revealed that the IPE effect and the photo-assisted thermionic field emission (PTFE) dominate the photoresponse in the present graphene–silicon–graphene Schottky junctions, showing the potential pathway of the internal quantum efficiency (IQE) improvement in the future.

2. Results

2.1. Design and Simulation

Figure 1a illustrates the schematic configuration of the present FLG-Si-FLG heterostructure waveguide PD. The FLG is divided into two parts with a gap between them (where the gap width is chosen as \( w_{\text{gap}} = 300 \) nm in the present design), covering...
the silicon photonic waveguide symmetrically and forming an FLG-Si-FLG structure. Meanwhile, the FLG parts connect with the corresponding metal electrodes, where the metal–graphene–metal sandwiched contact-structures are introduced for low contact resistance.\(^{[25]}\) In order to enhance the light-graphene interaction, here the thin-silicon ridge waveguide\(^{[25,26]}\) is adopted with a silicon height of \(h_s = 100 \text{ nm}\), an etching height of \(h_{\text{etch}} = 50 \text{ nm}\), and a silicon ridge width of \(w_s = 1300 \text{ nm}\).

Figure 1b shows the present silicon photonic integrated circuit (PIC) consisting of a PD, a pair of \(\approx 1.55/2 \mu m\) two-channel wavelength-division (de)multiplexers, and the corresponding grating couplers for \(\approx 1.55/2 \mu m\). Such a PIC configuration supports convenient experimental measurement for the two wavelength bands of \(1.55/2 \mu m\). For each wavelength band, light is coupled from the fiber to the fundamental transverse electric (TE) mode of the input strip silicon photonic waveguide by using the corresponding grating couplers. Then light is routed to the input port of the PD through the wavelength-division multiplexer.

More details on the calibration and the normalization for the optical power are given in Section S1 of Supporting Information. The mode field is calculated from a finite-element method mode-solver tool (COMSOL). For FLG, the optical conductivity is set to the universal guarantee full optical absorption ability, in which case the real part of the optical conductivity per layer is close to the universal optical conductivity of \(\sigma_0 = 60.8 \mu S\) for both 1.96 and 1.55 \(\mu m\).\(^{[26]}\) In the simulation, we set \(|\mu| = 0.2 \text{ eV}\) to give an estimation. More details about the simulation modeling were given in our previous work.\(^{[25]}\) Figure 1c shows the calculated fundamental TE mode fields at the two wavelengths of 1.55/1.96 \(\mu m\). Regarding that light is absorbed by graphene only in the present case, the graphene absorbance is given by \(\eta(L) = 1 - 10^{-\alpha L}\), where \(\alpha\) is the mode absorption coefficient in dB \(\mu m^{-1}\) and \(L\) is the length of the graphene sheet. Figure 1d shows the calculated absorbance \(\eta\) at the wavelengths of 1.55/1.96 \(\mu m\) for the cases with different graphene layers \(N\) as the length \(L\) varies. For the present thin silicon ridge waveguide, the mode fields (see Figure 1c) and the graphene optical conductivities are similar for the two wavelengths. As a result, the absorption \(\alpha\) at the two wavelengths is close. For example, the one-layer graphene has an absorption loss of \(\approx 0.111\) and 0.107 dB \(\mu m^{-1}\) at 1.55 and 1.96 \(\mu m\), respectively. As shown in Figure 1d, the absorption coefficient \(\alpha\) is proportional to the layer number of graphene. For the case with one-layer graphene, the graphene absorbance \(\eta\) reaches \(> 90%\) when the length \(L > 90 \mu m\). In contrast, when the layer number \(N\) increases to 3, one has \(\eta > 90%\) even with the length as short as 30 \(\mu m\).

### 2.2. Experimental Results and Analyses

The present FLG-Si-FLG heterostructure waveguide PDs were fabricated by the processes of electron-beam lithography (EBL), inductively coupled plasma (ICP) etching, graphene transfer, and metal deposition (see details in the Experimental Section). Figure 2a shows the fabricated PIC with a 30 \(\mu m\) long FLG-Si-FLG waveguide PD. The commercial chemical vapor deposition (CVD)-grown graphene with a few layers was used. As the Raman peak intensity ratio provides a convenient way for graphene number identification, the Raman scattering measurement was carried and the results are given in Figure 2b. One can see the G peak at 1584.71 \(\text{cm}^{-1}\) and the 2D peak at 2691.99 \(\text{cm}^{-1}\), and the intensity ratio of 2D peak to G peak is about \(I_{2D}/I_G \approx 2\), suggesting that the graphene layer number is \(\approx 4\).\(^{[28]}\) Besides, we characterized the output optical powers from the PIC covered by the graphene sheets with different lengths, and the measured absorption coefficient is estimated to be \(\approx 0.4\) dB \(\mu m^{-1}\) by the cutoff method, which further confirms the conclusion that the graphene layer number is 4. Note that there is usually a native oxide (SiO\(_2\)) layer formed during the graphene transfer process at the silicon–graphene interface,\(^{[29]}\) and our ellipsometer measurement shows that the oxide layer thickness is \(\approx 1 \text{ nm}\). The input optical power \(P_{in}\) of the PD is estimated by removing the fiber-chip coupling loss and the excess losses from the other passive...
2.2.1. Photoresponse in the Silicon–Graphene Heterostructure

In order to investigate the photoresponse at the silicon–graphene heterostructure, we also fabricated an FLG-Si waveguide PD for testing on another chip with similar processes.\cite{30} Figure 3a,b shows the band diagrams for two types of mechanisms in the silicon–graphene Schottky diode, including the PTI effect and the IPE effect. Here, the spontaneously formed SiO$_2$ oxide layer is included, n-doped silicon was used, and the electron behavior is mainly considered. Particularly, we define the following two barrier heights, i.e., the Fermi surface barrier height $\Phi_B$ and the Dirac point barrier height $\Phi_D$, which are, respectively, the barriers referring to the Fermi surface and the Dirac point of graphene. In practice, since the image force lowering (IFL) should be considered, the barriers $\Phi_B$ and $\Phi_D$ become $\Phi_B-\text{IFL}$ and $\Phi_D-\text{IFL}$, respectively.\cite{8,31} Apparently, one has $\Phi_D = \Phi_B + \mu_g$ and $\Phi_D-\text{IFL} = \Phi_B-\text{IFL} + \mu_g$, where $\mu_g$ is the chemical potential of graphene.\cite{8}

For the PTI effect shown in Figure 3a, the photoexcited carriers form a Fermi–Dirac distribution with an increased temperature $T_e$ due to the carrier–carrier scattering, and the hot carriers with sufficient energy can be emitted over the barrier and then contribute to the photoresponse. In this process, the distribution of hot carriers is determined by the Fermi level of the FLG, the density of state of the FLG, and the hot carrier temperature $T_e$ jointly. Therefore, the absorbance-normalized responsivity (i.e., $R/\eta$) of the PTI photoresponse is sensitive to $\Phi_B-\text{IFL}$, other than the energy of the absorbed photons.\cite{19}

Figure 3b shows the direct photon-excited carrier detection mechanisms. Note that the photoexcited carriers have energy $hv/2$ (i.e., half of the photon energy $hv$) higher than the graphene Dirac point due to the unique band structure of graphene; Thus, the IQE of the silicon–graphene PD is determined by $\Phi_D$ (or $\Phi_D-\text{IFL}$) instead of $\Phi_B$ (or $\Phi_B-\text{IFL}$), which is totally different from the traditional metal–semiconductor Schottky PDs. As shown in Figure 3b, only the carriers excited by photons with an energy $hv > 2\Phi_D-\text{IFL}$ have the chance to be emitted over the Schottky barrier in the IPE process. The photo-carriers without sufficient kinetic energy (strictly speaking, out-plane kinetic energy) still can contribute to the photoresponse by another pathway of tunneling through the barrier, which is named as PTFE process in this paper.

Figure 3c shows measured I–V curves for the fabricated silicon–graphene PD,\cite{30} which has an FLG-Si Schottky diode in the active region. In particular, a subwavelength grating structure is introduced to electrically connect the silicon ridge waveguide devices integrated in the PIC. More details about the calibration are given in Section S1 of the Supporting Information.
and the metal pad, in which way there is no influence on the light propagation in the active region almost. From Figure 3c, one sees that the $I$–$V$ curves show standard rectifier behaviors. The current saturation at a high forward bias is attributed to the series resistance and the barrier height increase caused by the graphene doping. When operating with increased reverse bias, the photocurrent increases quickly to be saturated. Here, the dark current $I_{D\text{dark}}$ is about 0.1 nA.

Figure 3d shows the measured responsivity as the reverse bias increases. It can be seen that the results for the wavelengths of 1.55/1.96 μm are with very different responsivities but similar trends. When operating at 1.55 μm, the responsivity increases from 0.02 to 0.029 mA W$^{-1}$ as the bias $|V_{bias}|$ increases from 0 to 1 V, and then reaches $\approx$0.031 mA W$^{-1}$ at 5 V. In contrast, for the 1.96 μm wavelength, the measured responsivity increases from $\approx$0 to 6.44 × 10$^{-4}$ mA W$^{-1}$ as the bias $|V_{bias}|$ increases from 0 to 0.6 V, and then reaches 0.008 mA W$^{-1}$ at 5 V reserve bias. It shows that the saturated responsivity at 1.55 μm is about four-fold of that at 1.96 μm. The calculation shows that the light absorptions in the active region (which is 15 μm long) are 89.95% and 85.76% for the wavelengths of 1.55 and 1.96 μm, respectively. It indicates that the absorbance-normalized responsivity and the IQE are very sensitive to the photon energy. On the other hand, as shown in the inset of Figure 3d, the photocurrent exhibits a linear dependence on the input optical power $P_{in}$ for both wavelengths.

The strong wavelength-dependence of the IQE suggests that the PTI effect is not likely to be the dominated mechanisms for the photoresponse (as discussed above). One may notice that the IQE is pretty low even considering the existence of the 1 nm thick SiO$_2$ layer. To further figure out the photo-assisted carrier dynamics, we built the band-diagram modeling of the silicon–graphene Schottky diode with the initial parameters confirmed by the Kelvin probe force microscopy (KPFM) measurement (see Section S2, Supporting Information). As shown in Figure S1d, Supporting Information, the barriers $\Phi_{D\text{IFL}}$ and $\Phi_{B\text{IFL}}$ are, respectively, 0.357 and 0.484 eV considering the IFL effect at $-5$ V.

For the wavelengths of 1.55 and 2 μm, their half photon energies $h\nu/2$ are 0.4 and 0.31 eV, which are, respectively, higher and lower than the barrier $\Phi_{D\text{IFL}}$. As a result, the IPE effect and the PTFE process are the dominant mechanisms in the graphene–silicon heterostructure PD for the wavelengths of 1.55 and 1.96 μm, respectively. One should note that the PTFE effect has quite limited quantum efficiency as a tunneling process when compared to the IPE effect. Nevertheless, these two mechanisms both show strong wavelength sensitivity. At the longer wavelength, less photoexcited carriers are excited over the Schottky barrier due to smaller photon energy for the IPE effect, and longer tunneling length leads to lower quantum efficiency for the PTFE process. As the reserve bias increases to $>1.5$ V, the barrier $\Phi_{D\text{IFL}}$, and the depletion width in silicon decrease slowly, and consequently the responsivity grows slowly to be saturated for both wavelengths of 1.55 and 1.96 μm, as shown in Figure 3d.

### 2.2.2. The Graphene–Silicon–Graphene PD

As it is well known, traditional silicon–graphene PDs usually need high-quality metal–silicon Ohmic contact, which actually is not easy due to the imperfection in the fabrication. Fortunately, no metal–silicon contact is needed for the present graphene–silicon–graphene PD with a simple and fabrication-friendly heterostructure. Furthermore, the present graphene–silicon–graphene PD enables a short carrier transit distance in silicon, providing the potential for high-speed operation because the carrier transit in graphene is usually very fast. Figure 4 shows the measured static results of the fabricated graphene–silicon–graphene PD (Device A) with a 60 μm long graphene sheet for the wavelengths of 1.55 and 1.96 μm. The $I$–$V$ curve maps in Figure 4a,b can be divided to the gray region and green region which represent low bias condition and high bias condition, respectively. As it can be seen, the measured $I$–$V$ curves are basically symmetric for both wavelengths of 1.55 μm (Figure 4a) and 1.96 μm (Figure 4b). Here, we focus on the forward bias operation for more discussions. In low bias condition, e.g., when $V_{bias} = 1$ V, we found that the photocurrents at two wavelengths are similar in magnitude under the same input optical power. This phenomenon indicates that PTI effect may dominate the photoresponse in low bias condition. In this case, the linearity of photocurrent is found to be not good for both wavelengths. When $V_{bias}$ increases to over a threshold bias voltage, the device operates in high bias condition. Figure 4c shows the measured photocurrent $I_{ph}$ at 1.55 μm as the optical power $P_{in}$ varies from 3.10 μW to 1.86 mW (which is the maximal power coupled into the PD with the present measurement setup). As shown in Figure 4c, the photoresponse for this graphene–silicon–graphene PD has a very nice linearity in high bias condition, e.g., when operating at different bias voltages of 2, 4, and 6 V. When operating at the wavelength of 1.96 μm, the measured photoresponse for the PD also has a good linearity when the input power ranges from 0.17 to 1.96 mW, as shown in Figure 4d. By fitting the $I_{ph}$–$P_{in}$ curve, Figure 4e shows the responsivity for the wavelength of 1.55 μm. One sees that the responsivity increases from 7.2 × 10$^{-3}$ to 0.147 mA W$^{-1}$ as the bias $V_{bias}$ increases from 1 to 6 V. In contrast, when operating at the wavelength of 1.96 μm, the responsivity increases from 3.5 × 10$^{-3}$ to 0.0148 mA W$^{-1}$ as the bias $V_{bias}$ increases from 1 to 6 V, as shown in Figure 4f. Given that the optical absorbances for the wavelengths of 1.55 and 1.96 μm are similarly high as $\approx$99.8%, the absorbance-normalized responsivity of the graphene–silicon–graphene PD is very sensitive to the wavelength, which is similar to the silicon–graphene PD discussed above. This suggests that the IPE or PTFE processes dominate the photoresponse in the high bias condition. In this case, the photoexcited carriers are directly collected to contribute to the photocurrent, and the quantum efficiency can keep stable when optical power varies.$^{[22,24]}$ Therefore, large linear dynamic range can be observed.

Figure 4e,f also shows the NPDR, calculated by NPDR = $R/I_{dark}$ (where $R$ is the responsivity). For the wavelength of 1.55 μm, the NPDR increases from $3.11 \times 10^3$ to $1.67 \times 10^4$ W$^{-1}$ as the bias $V_{bias}$ increases from 1 to 2.5 V. As the bias $V_{bias}$ further increases to 6 V, the NPDR varies slightly with a peak value of $1.85 \times 10^3$ W$^{-1}$ at 5.5 V. Similarly, the NPDR at 1.96 μm increases from $2.95 \times 10^3$ to $2.22 \times 10^3$ W$^{-1}$ as the bias $V_{bias}$ increases from 1 to 2 V. When the bias $V_{bias}$ increases further from 2 to 6 V, the NPDR changes slightly with a peak value of $2.91 \times 10^3$ W$^{-1}$ at 5.5 V (see Figure 4f).
The measured results of a typical graphene–silicon–graphene device (Device A). a,b) The I–V curves at a) 1.55 and b) 1.96 μm. c,d) The results of I_ph–P_in (dotted line: the fitting curves) at c) 1.55 and d) 1.96 μm. e,f) The responsivity and the NPDRA as a function of V_bias at e) 1.55 and f) 1.96 μm. The gray region: low bias condition. The green region: high bias condition.

In order to have a deep look at the PD, here we give an analysis on the band structure of the graphene–silicon–graphene structure qualitatively with a 1D model. As shown in Figure 5a, a graphene–silicon–graphene structure consists of a pair of con-directional silicon–graphene Schottky junctions (strictly speaking, silicon–SiO2–graphene Schottky junctions). Here, the case with a forward bias V_bias is considered. In this case, the photoexcited electrons in the FLG at the left and the photoexcited holes in the FLG at the right may contribute to the photocurrent, facing the electron Dirac point barrier Φ_De-IFL and the hole Dirac point barrier Φ_Dh-IFL, respectively. Note that Φ_De-IFL is Φ_D-IFL mentioned in Figure 3. Since the bias voltage for the narrow-sandwiched silicon region is usually negligible, the total bias voltage V_bias is given approximately as |V_bias| = |V_SL_L|+|V_SL_R|, where V_SL_L and V_SL_R are, respectively, the reserve bias voltage for the Schottky junction at the left and the forward bias voltage for the Schottky junction at the right. In terms of the bias-polarity definition in this work, in a unidirectional graphene-nSi Schottky diode, the silicon side corresponds to the negative electrode. Most of the electric potential difference is generated at the left Schottky junction, and thus one has |V_SL_L|>|V_SL_R|. The voltages can be estimated according to the current continuity condition. The electron current density J_e can be written as

\[ J_e(V_{SL}) = A^{**}T^2 e^{-\frac{qΦ_{De-IFL}(V_{SL})}{k_B T}} \left[ \exp \left( \frac{qV_{SL}}{n_f k_B T} \right) - 1 \right] \]

where A^{**} is the effective Richardson constant, T is the temperature, χ is the mean tunneling barrier height presented by the oxide, δ is the interfacial oxide thickness, Φ_{De-IFL} is the Schottky barrier height (written as Φ_{D-IFL} in Figure 3 and Figure S1d in the Supporting Information), k_B is Boltzmann’s constant, q is the elementary charge, and n_f is the diode ideality factor. Here, n_f is about 5.11 according to the analysis of the silicon–graphene I–V curve based on the Cheung method. In a symmetric structure, the current density J_e for the two Schottky junctions are equal, i.e., |J_e(V_{SL_L})| = |J_e(V_{SL_R})|. In high bias condition, when V_bias = 6 V, one has V_SL_L = −4.59 V and V_SL_R = 1.41 V, while the depletion widths are, respectively, 256 and 104 nm based on this 1D model. When simplifying the actual graphene–silicon–graphene structure with a coplanar stripline configuration to the 1D model, it is well known that the equivalent separation...
between the two Schottky junctions (Figure 5a) is significantly larger than the minor separation between two Schottky junction interfaces, i.e., $W_{gap} = 300$ nm here. Since the equivalent separation is estimated to be larger than sum of the depletion widths (360 nm), silicon should not be fully depleted for the present case according to the 1D model estimation. Then we can analyze the two Schottky junctions separately.

Figure 5b exhibits the results of the simulated barriers, where $\Phi_{De}$ and $\Phi_{De,IFL}$ are obtained directly from the modeling results in Section S3 of the Supporting Information. The Dirac point barrier height $\Phi_{De}$ (ignoring the IFL effect) is given by $\Phi_{De} = E_g - \mu \nu$, where $E_g$ is the silicon bandgap of 1.12 eV.[37] As a result, $\Phi_{De,IFL}$ can be calculated by Equation (S7) in the Supporting Information (see the details in Section S3, Supporting Information), while the IFL effect on the hole barrier should be considered only when the silicon built-in potential $\varphi_i < 0$. Correspondingly, one has $V_{De} > 0.56$ V in this case (see region III in Figure 5b). Correspondingly, $\Phi_{De,IFL}$ is calculated only when $\varphi_i > 0$, where the electron barriers are calculated for the left reverse barrier with $V_{De} < 0$ (see Figure 5b in Section S1d).

When $V_{bias} = 6$ V, as shown in Figure 5b, the two Schottky junctions have $\Phi_{De} = 0.363$ eV ($\Phi_{De} = -4.59$ V) and $\Phi_{De,IFL} = 0.479$ eV ($\Phi_{De,IFL} = 1.41$ V), respectively. As shown in Figure S1d in the Supporting Information, the chemical potentials $\mu$ for the graphene sheets at the left and right sides are, respectively, −0.129 and −0.17 eV, indicating that both parts of FLGs have full optical absorption ability. Similarly to the silicon–graphene PD, the photoresponse mechanisms for the graphene–silicon junction at the left are, respectively, the IPE and PTFE processes at wavelengths of 1.55 and 1.96 μm. For the graphene–silicon junction at the right, half of the photon energy ($h\nu/2$) is still below $\Phi_{De,IFL}$ and $\Phi_{De,IFL}$, the PTFE mechanism is the dominating mechanism at both wavelengths of 1.55 and 1.96 μm. Since $\Phi_{De,IFL} < \Phi_{De,IFL}$, the photoexcited electron current is the main component here. When $V_{bias} = 2$ V, the left Schottky junction has local voltage $V_{SL,L} = -1.12$ V and $\Phi_{De,L} \approx 0.4$ eV, while the right Schottky junction has local voltage $V_{SL,R} = 0.88$ V and $\Phi_{De,R} \approx 0.5$ eV. When $V_{bias}$ decreases further, the Schottky barriers become higher, which can explain why the photoresponse generates from PTI effect instead of direct detection of photoexcited carriers in the low bias condition. In theory, the threshold bias voltage that distinguishes the low bias condition and the high bias condition should be higher for longer wavelength with lower photon energy. According to the experimental results in Figure 4a,b, the threshold bias voltages are slightly lower than 2 V for both wavelengths of 1.55 and 1.96 μm. Note that the photoresponse measured in the low bias condition is too weak to make the threshold voltage hard to be evaluated accurately. Nonetheless, the measured results in the high bias condition (which is mainly focused in this work) are stable and well repeatable. It should be noted that the 1D model does not give a precise modeling but nevertheless provides a simple method to reveal how the photocurrent generates in different conditions.

Figure 6a shows the experimental setup for the high-frequency measurement, including a commercial modulator and a vector network analyzer (VNA, see the Experimental Section). Figure 6b gives the normalized high-frequency response of the graphene–silicon–graphene PD (Device A). The measured 3 dB bandwidth $f_{3dB}$ is about 30 GHz, which is owing to the small RC time constant as well as the short carrier transit time in the present PD. Here, we carry a simple RC bandwidth analysis. The shunt capacitance $C_s$ of the graphene–Si–graphene can be calculated by the capacitance evaluation method used in metal–semiconductor–metal PDs,[38] and one has $C_s = 11.3$ fF for the present device. As introduced in our previous work,[25] one can extract the device series resistance $R_s = 355$ Ω by fitting the impedances from the measured $S_{11}$ response. Accordingly, the RC-limited bandwidth is estimated as $f_{3dB,RC} = 1/2\pi (R_s + R_C)C_s = 36.1$ GHz.[37] In addition, the transit time limited bandwidth $f_{tr}$ can be roughly evaluated by the equation for metal–semiconductor–metal PDs, i.e., $f_{tr} = \frac{V_s}{s \tau}$, where $V_s$ is the electron saturation velocity in silicon (e.g., $V_s = 10^7$ cm s$^{-1}$).[37] $s$ is the carrier transit distance estimated to be 300–600 nm. As a result, one has $f_{tr} = 51.9$–103.7 GHz. Finally, the theoretical 3 dB bandwidth given by $f_{3dB} \approx \left( f_{3dB,RC}^{-2} + f_{tr}^{-2}\right)^{-1/2}$ is 29.6–34.1 GHz, which is...
Fig. 6. The high-frequency measurement. a) Setup. b) normalized response of Device A at 1.55 μm. Red dot line: origin data, blue line: 6th-order polynomial fitting data for the bandwidth evaluation.

consistent with the experimental result. As a conclusion, one sees that the bandwidth is mainly RC-limited.

In this work, we fabricated several graphene–silicon–graphene waveguide PDs and the measured results are summarized in Section S3 of the Supporting Information. At the wavelength of 1.55 μm, the responsivity is 0.13–0.33 mA W⁻¹, while the directly measured bandwidth from the VNA is 19–30 GHz. And the NPDRs are 1.5 × 10⁵ to 6.5 × 10⁶ W⁻¹. In addition, these devices exhibit large linear optical power ranges of 3 μW to 1.86 mW (and more) at 1.55 μm and 0.17–1.96 mW (and more) at 1.96 μm, respectively (see Table S2, Supporting Information).

2.3. Discussions and Perspective

In graphene–silicon–graphene PDs, high energy barrier faced by the photoexcited holes may lead to a low IQE compared to silicon–graphene PDs in theory. Interestingly, the present graphene–silicon–graphene PDs exhibits higher responsivity and higher bandwidths than the silicon–graphene PDs in our experiments. The performance of our fabricated silicon–graphene PD in ref. [30] may be limited by the imperfection Al–Si contact with a high contact resistance and a high Schottky barrier. In contrast, there is no metal–silicon contact introduced for the graphene–silicon–graphene PDs presented in this paper. In this work, the FLG has graphene layer N of 4. When N changes, it is found that the Schottky barrier height Φ_De-IFL under large bias changes little, which means the IQE may be similar. Besides, thicker graphene can lead to shorter graphene length for the same light absorbance, which may have some beneficial influences on the performance of device RC-limited bandwidth.

In Section S4 of the Supporting Information, we give a summary for the performances of the representative waveguide-integrated Si-2DM PDs. As shown in Table S3 in the Supporting Information, the graphene bolometers with the metal–graphene–metal structure can operate with a high bandwidth but a very large dark current, which results in low NPDRs of 10–10⁵ W⁻¹ (see Table S3, Supporting Information). Besides, graphene bolometers usually have poor linearity performances. The metal–2DM–metal PDs have improved NPDRs when using nonzero bandgap 2DMs instead of graphene, as shown in Table S3 in the Supporting Information. However, currently it has never achieved a large NPDR over 10⁵ W⁻¹ and a large bandwidth over 1 GHz simultaneously. Alternatively, a graphene p-n homojunction PD is interesting because it is possibly with zero-bias operation, in which case the dark current and the dark-current shot noise is zero (but the thermal noise remains). And the bandwidth is possible as high as >67 GHz as the state of the art. Another ring-resonator PD exhibited a bandwidth of 12 GHz and a high responsivity of 90 V W⁻¹, resulting in a high sensitivity on par with Ge/Si PDs. However, its lindynamic range (LDR) is limited to be 0.01–0.2 mW. More recently, an Au–MoS₂ Schottky PD using an Au active region exhibited a responsivity of 15.7 mA W⁻¹, an NPDR of 1.05 × 10⁸ W⁻¹, and a bandwidth of 1.37 GHz at 1.55 μm.
The 2DM heterostructure PDs have shown the potential to feature overall high performances. For instance, a MoTe₂-graphene heterostructure PD has an NPDR of $10^8 – 10^9$ W⁻¹ and bandwidths of 12–46 GHz at the wavelength band of 1.31 μm. Another MoS₂/G-hBN-G heterostructure PD was reported with a high NPDR of $10^9$ W⁻¹ and a bandwidth of 28 GHz at 1.55 μm. However, the linearity performance is unknown yet. In contrast, the silicon–graphene heterostructure PD based on the wet-transferred CVD-grown graphene have the advantages of easy fabrication and high feasibility of large-scale photonic integration, as discussed in Section S4 of the Supporting Information. Currently very few waveguide-integrated silicon–graphene heterostructure PDs have been reported. An Au–silicon–graphene heterostructure PD has shown a relatively high responsivity of 85 mA W⁻¹. Another waveguide-integrated silicon–graphene p-i-n photodiode for the 1.55 μm light exhibited a responsivity of 3.4 mA W⁻¹ at zero bias and a high RF bandwidth estimated from the converted photoelectric signal with a center frequency of 40 GHz. In the present work, several graphene–silicon–graphene heterostructure PDs are demonstrated with a responsivity of 0.13–0.33 mA W⁻¹, a bandwidth of 19–30 GHz, and a large NPDR of 1.5 × 10⁶ to 6.5 × 10⁶ W⁻¹. Our PDs exhibit large LDGs of 3 μm to 1.86 mW (and beyond) at 1.55 μm and 0.17–1.96 mW (and beyond) at 1.96 μm, respectively (see Table S2, Supporting Information).

According to the comparison shown in Table S3 in the Supporting Information, the present PD shows excellent overall performances of the NPDR, the bandwidth, and the linearity among the counterparts. Moreover, the fabrication-friendly graphene–silicon–graphene heterostructure PDs have excellent reproducibility and stability. Apparently, for the present silicon–graphene heterostructure PDs, one of the most important works in the future is to further improve the quantum efficiency. More efforts should be made in the photoresponse modeling for better understanding the photoelectric conversion dynamics and the evaluation of the photoresponse IQE. Here, the reveal of the photoresponse mechanisms at the silicon–graphene interface provides the potential solution for the performance improvements. For example, the doping engineering of silicon may be helpful. Heavier doping in silicon can reduce the depletion region width and further reduce the tunneling length for photocreated carriers, which is possibly to significantly increase the IQE. On the other hand, the dark current would probably increase simultaneously. Fortunately, the NPDR performance would be still very acceptable.

3. Conclusion

In this work, we have demonstrated graphene–silicon–graphene heterostructure waveguide PDs for the wavelength bands of 1.55/2 μm. The fabricated PDs have exhibited excellent linearity in the power range of 0.17–1.96 mW and a high NPDR of 2.66 × 10⁶ W⁻¹ when operating at 1.96 μm. At the wavelength of 1.55 μm, the present PDs also show excellent linearity in the power range of 3 μW to 1.86 mW (limited by the maximal power coupled to the chip) and a high NPDR of 1.63 × 10⁶ W⁻¹. The measured 3 dB bandwidth is as high as ≈30 GHz, which is attributed to the small RC constant, the short transit time in silicon, as well as the fast carrier dynamics in the silicon–graphene junction. On the other hand, the PDs still have limited responsivities of ≈0.15 and ≈0.015 mA W⁻¹ for the wavelength bands of 1.55 and 2 μm, respectively. According to the theoretical model established for the silicon–graphene heterostructure, the dominant mechanisms for the photoreponse of the present PDs include the IPE and the PTFE effect when moderately high bias voltage applied, and thus it is possible to improve the responsivity performance by utilizing some strategies such as doping engineering. More efforts should be made to develop graphene–silicon–graphene waveguide PDs with high overall performances to satisfy the demands for large-scale photonic integration in the future.

4. Experimental Section

Device Fabrication: A silicon-on-insulator (SOI) wafer with a 100 nm thick top-silicon layer was obtained from a 220 nm thick SOI wafer (p-type with a doping concentration of 10¹⁴ cm⁻³) by the processes of thermal oxidation and wet etching. The n-doped silicon was formed with an ion implantation process. The processes of EBL and ICP were then carried for the fabrication of silicon ridge waveguides. The buffered-oxide-etch (BOE) cleaning was carried, and the 50/35 nm Al/Au electrodes were fabricated by using the processes of electron beam evaporation, EBL, and lift-off. The Al/Au electrodes were used as the bottom layer of the sandwiched metal–graphene–metal electrodes. Then, graphene was transferred and patterned by the processes of EBL and ICP. Finally, a 40 nm thick Au layer was deposited and patterned to form the top layer of the metal–graphene–metal electrodes.

Transfer Process of Graphene: The CVD-grown graphene was obtained from SUNANO Group (few layers, on copper foil). A 300 nm thick film of poly(methyl methacrylate) (PMMA) was spin-coated on the graphene/copper film at 4000 rpm. The PMMA/graphene/copper film was floated on aqueous ammonium persulfate (60 mg mL⁻¹) to remove the copper and rinsed in deionized water. Then, the film was transferred onto the chip. The graphene-covered chip was dried, baked, soaked in acetone and rinsed with isopropanol.

Device Measurement: The static I–V curves of the PDs were measured by a source meter for different injected optical powers. Light from a laser (a tunable laser @ 1.55 μm or a fiber laser @ >2 μm) was polarization-controlled and then coupled to the on-chip waveguide with the corresponding grating coupler. The photocurrent was then calculated by subtracting the dark current from the total current. The input optical power $P_{in}$ was estimated according to the measured coupling efficiency of the grating coupler and the excess loss of the wavelength multiplexer. More details on the optical power analysis are provided in Section S1 of the Supporting Information. In the high-frequency measurement, the CW light was modulated with a commercial optical modulator (Sumitomo T. MXH1.5DP-40PD-ADC, 22 GHz bandwidth) by the RF signal from a vector network analyzer (ROHDE & SCHWARZ ZVA40, 40 GHz). The modulated light was amplified by an erbium-doped fiber amplifier (Thorlabs EDFA100P) before it was coupled to the chip. The output electrical signal of the test device was then amplified by using an RF amplifier (Centellax OA44VM42) and finally received by the VNA.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

graphene, graphene–silicon heterostructure, internal photoemission, photodetectors, silicon photonics, thermionic field emission

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