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DOI:

[10.1039/c8nr05285a](https://doi.org/10.1039/c8nr05285a)

Document Version

Accepted author manuscript

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Citation for published version (APA):

Selvi, H., Hill, E., Parkinson, P., & Echtermeyer, T. (2018). Graphene-Silicon-On-Insulator (GSOI) Schottky Diode Photodetectors. *Nanoscale*, 10(40), 18926-18935. <https://doi.org/10.1039/c8nr05285a>

Published in:

Nanoscale

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Cite this: DOI: 10.1039/xxxxxxxxxx

Received Date
Accepted Date

DOI: 10.1039/xxxxxxxxxx

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Graphene-Silicon-On-Insulator (GSOI) Schottky Diode Photodetectors

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Graphene-silicon (GS) Schottky junctions have been demonstrated as an efficient architecture for photodetection. However, the response speed of such devices for free space light detection has so far been limited to 10's-100's of kHz for wavelength $\lambda > 500\text{nm}$. Here, we demonstrate graphene-silicon Schottky junction photodetectors fabricated on a silicon-on-insulator substrate (SOI) with response speeds approaching 1GHz, attributed to the reduction of the photo-active silicon layer thickness to $10\mu\text{m}$ and with it a suppression of speed-limiting diffusion currents. Graphene-silicon-on-insulator photodetectors (GSOI-PDs) exhibit a negligible influence of wavelength on response speed and only a modest compromise in responsivities compared to GS junctions fabricated on bulk silicon. Noise-equivalent-power (NEP) and specific detectivity (D^*) of GSOI photodetectors are 14.5pW and $7.83 \times 10^{10} \text{ cm Hz}^{1/2}\text{W}^{-1}$, respectively, in ambient conditions. We further demonstrate that combining GSOI-PDs with micro-optical elements formed by modifying the surface topography enables engineering of the spectral and angular response.

1 Introduction

Graphene is an appealing material to realize ultrafast and broadband photodetectors (PDs) due to its versatile electronic and optical properties such as high carrier mobility¹, ultrafast carrier dynamics² and broadband optical absorption^{3,4}. However, graphene's low optical absorption of $\sim 2.3\%$ and small photo-active area of devices are a bottleneck for photodetectors solely based on graphene. Photoresponsivities of graphene-based photodetectors based on metal-graphene-metal architectures (MGM) are typically below 10mAW^{-1} for visible (VIS) and near-infrared (NIR) wavelengths⁵⁻⁷ and the photoactive area is restricted to the periphery ($\sim 100\text{-}200\text{nm}$) of the graphene contact^{8,9}. Various strategies have been exploited to enhance light absorption in graphene, e.g. by integrating graphene into optical microcavities^{10,11} or combining graphene with plasmonic nanostructures^{12,13}. More recently, graphene-silicon (GS) Schottky junction photodiodes have been demonstrated as an efficient platform for photodetection¹⁴⁻³² and photovoltaic³³⁻³⁸ applications.

The co-integration of graphene with silicon technology allows the realization of a hybrid platform that is suitable for large scale fabrication due to the possible integration of graphene into back end-of-line (BEOL) complementary metal-oxide-semiconductor (CMOS) processing^{39,40}.

GS Schottky PDs exhibit a dual operating regime where both graphene and silicon act as active light absorbing materials for different wavelength ranges²⁵. Devices can show high responsivities on the order of hundreds of mA/W , comparable to commercial silicon photodiodes for wavelength ranges with photon energies above the silicon bandgap ($\lambda < 1.1\mu\text{m}$) which is facilitated by the high optical transmittance of graphene ($\sim 97.3\%$). Detection of light with energies below the silicon band gap is enabled by the broadband absorption of graphene³ and responsivities reduce to a few mAW^{-1} or less for $\lambda > 1.1\mu\text{m}$ ³¹. One important advantage of GS devices is their large photoactive area due to the vertical nature of the graphene-silicon junction as opposed to the lateral junction as in MGM photodetectors.

To date, the performance of GS PDs in terms of response speed remains far below that of MGM and commercial silicon photodetectors which exhibit cut-off frequencies (f_c) on the order of GHz for free space light detection^{41,42}. Conversely, GS PDs demonstrated response speeds of 10's-100's of kHz for wavelengths $\lambda > 500\text{nm}$ ^{16,17,20,22,27,30,31}. This limitation can be attributed to speed-limiting diffusion currents due to photo-generated carriers deep within the silicon substrate of typically employed thicknesses ($\sim 500\mu\text{m}$). A solution to improve the response speed of GS devices is replacing commonly employed bulk silicon with a

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† Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/b000000x/

silicon-on-insulator (SOI) substrate. SOI, a thin silicon layer on top of a buried silicon oxide layer (BOX), is frequently used to implement CMOS electronics because of many advantages compared to their bulk silicon counterparts; SOI allows full dielectric isolation between neighboring devices, reduced leakage currents and reduced capacitive coupling, full depletion of the active silicon layer and 3-dimensional device architectures⁴³ which makes SOI suitable for high speed and low power applications. SOI substrates additionally provide processing advantages since the BOX acts as a well-defined etch-stop and substrates can further be employed for micro-electro-mechanical-systems (MEMS)⁴⁴. However, in this device configuration, employed thin top silicon layer may act as an optical microcavity due to possible multiple round-trips of the incident light, especially for silicon's reduced optical absorption coefficient at longer wavelengths. This formed microcavity makes the device responsivity sensitive to the wavelength and angle of incident light. We demonstrate that these dependencies can be controlled by the integration of micro-optical elements into the top silicon surface.

SOI wafers with a 10 μm thick, lightly-doped (1-10 Ωcm) n-type silicon device layer (100) were employed to fabricate two sets of devices, a planar GSOI Schottky diode (GSOI-planar) and GSOI Schottky diode with a grating surface topography (GSOI-grating). The architecture of both device types is shown in Fig. 1. A metal frame to electrically contact graphene has been designed around the graphene-silicon junction of the GSOI-planar device to minimize series resistance potentially arising from the relatively large junction area of the device. The GSOI-grating device has a smaller junction area than the GSOI-planar device and the metal-graphene contact was placed to one side of the junction only. This minimizes interfering with the optical paths close to the junction by avoiding highly reflective metal contacts close to it and facilitates characterizing the angle dependent photoresponse of the GSOI-grating device. For the GSOI-planar device, graphene is transferred onto the flat (100) oriented silicon surface. For the GSOI-grating device, graphene is transferred onto an array of self-terminated V-grooves formed by anisotropic wet etching of silicon in KOH solution, exposing both the (100) and (111) silicon surfaces with an angle of 54.7° between them⁴⁵. To pattern the silicon surface of the GSOI-grating device, 100nm of SiN_x were deposited on the silicon surface by inductively coupled plasma enhanced chemical vapor deposition (ICP-PECVD, Oxford Instruments). A grating structure consisting of an array of trenches (~5.5 μm wide) is patterned in the SiN_x layer employing optical lithography and subsequent dry etching (reactive ion etching). This grating structure formed in the SiN_x layer then serves as a hard mask for the anisotropic etching of silicon along the grating trenches carried out in 30wt% KOH solution at 80°C. As a result, 3 μm deep (111)-self-terminated V-grooves are etched into the silicon surface. The substrate is then dipped in acetic acid to remove the KOH residues and the SiN_x mask is completely removed by dry etching.

After the substrate fabrication for the GSOI-grating device, the device fabrication process is identical for both the GSOI-planar and GSOI-grating devices. The previously fabricated grating substrate and un-processed substrate (planar) are both coated with

a 100nm thick silicon-dioxide (SiO₂) layer by ICP-PECVD (Oxford Instruments). Subsequently, two areas are opened in the SiO₂ layer for the formation of the GSOI junction and the metal-silicon contact. These areas are defined by optical lithography and the oxide layer in these areas is removed by wet etching in a buffer-oxide-etch (BOE) solution. In the case of the GSOI-grating device, the GSOI junction area corresponds to the previously patterned region. Right after the BOE of the oxide, contacts to the top silicon layer are fabricated by an additional lithography step followed by thermal evaporation of Au/Cr/Al (50nm/3nm/50nm) and lift-off. Aluminum is chosen as the metal contact to the silicon substrate as it forms an ohmic contact to silicon due to its low work function⁴⁶. The additional layers of Au/Cr on top of Al serve as protective layers for Al during subsequent BOE etching processes.

Commercially sourced graphene grown by chemical vapour deposition (CVD) on copper foil is spin coated with a 200nm thick poly-methyl-methacrylate (PMMA, 950K A4) layer before being etched in ammonium persulfate solution to remove the copper foil. The PMMA/graphene membrane is rinsed in de-ionised (DI) water twice before the final transfer to remove etchant and copper residues. The substrates are dipped in BOE for five seconds to remove any native oxide layer formed on the silicon area for the graphene-silicon junction window, before the wet transfer of CVD graphene. The substrates with the PMMA/graphene membrane are baked at 140°C for 5 minutes to enhance graphene adhesion to the substrate before removing the PMMA layer in an acetone bath. The shape of graphene is defined by optical lithography and subsequent O₂/Ar plasma etching (60s at 8W, Moorfield NanoETCH). A further optical lithography step is used to define the electrical contact to graphene and Au/Cr (50nm/3nm) are evaporated as contact metals with a following lift off step. Optical images of the finalized devices are shown in Fig. 1c,d). The quality of graphene on top of SiO₂ and on top of the silicon window is examined by Raman spectroscopy under 532nm laser excitation after completion of the device fabrication. Obtained Raman spectra (ESI) show a negligible D peak and a single Lorentzian 2D peak with a full width at half maximum (FWHM) below 35cm⁻¹, confirming the successful transfer of monolayer CVD-grown graphene.

2 Results and Discussions

The current density-voltage (J-V) characteristics of both the GSOI-planar and GSOI-grating devices are shown in Fig. 2. Devices were tested under dark conditions, at room temperature and in ambient atmosphere. Both device types exhibit a rectifying behavior with current on- to off-ratios ($I_{\text{on}}/I_{\text{off}}$, at $\pm 2\text{V}$), exceeding 10⁵ and 10² for the GSOI-planar and the GSOI-grating device, respectively. It is notable that the GSOI-grating device exhibits a reduced forward and an increased dark current density under reverse bias compared to the GSOI-planar device. The exact reason for this is unknown so far but we suspect that both the inhomogeneous stress, strain and doping profile of graphene due to the patterned substrate as well as the differences in silicon surfaces in contact with graphene, (100) vs (111), will play a role. Various factors need to be considered. The higher number of silicon atoms of the silicon (111) surface compared to the (100)

Fig. 1 a) Schematic structure of the GSOI-planar device where graphene is transferred on the planar silicon (100) surface. b) Schematic structure of the GSOI-grating device where graphene is transferred on the structured silicon surface that consist of an array of V-grooves with (111) silicon facets separated by unpatterned planar (100) silicon lines of $3\mu\text{m}$ width. The V-grooves are $3\mu\text{m}$ deep and $5.5\mu\text{m}$ wide. c,d) Optical images of the fabricated devices. The active area of the GSOI-planar device is $4\times 4\text{mm}^2$ and for the GSOI-grating is $0.5\times 0.5\text{mm}^2$. Inset: Scanning electron micrograph (SEM) image of the grating structure formed by the V-grooves.

surface enables a faster oxidation of the (111) surface⁴²; this interfacial oxide layer has been demonstrated to influence the properties of GS Schottky PDs³¹. On the other hand, the reduced number of dangling bonds of the (100) compared to the (111) surface promotes less impurity accumulation and thus less defects which influence charge carrier tunneling processes⁴². Additionally, the Richardson constant A^* determines the leakage current density and is dependent on the effective mass of the electrons (m^*)^{47,48}. m^* is dependent on the crystal orientation and slightly higher for the $\langle 111 \rangle$ direction compared to the $\langle 100 \rangle$ direction in silicon^{47,48}. This difference in effective mass further leads to a difference in charge carrier mobilities for different crystal orientations^{42,48}. Determining the precise physical reason for the observed behaviour requires further studies and is not scope of this work. However, the differences in junctions formed between graphene and silicon's (100) and (111) surfaces in the GSOI-grating device effectively lead to an electrical equivalent circuit representing a parallel circuit of Schottky diodes with different series resistances, ideality factors, Schottky barrier heights and built-in voltages. Further, the effective area through which current transport is taking place is not exactly known for the SOI-grating device due to e.g. possible imperfect contact and interfaces between graphene and the silicon substrate. We utilize the total lateral area of the junction, not taking into account the increased area due to the facets of the grooves, to calculate the current density.

The J-V characteristic of an ideal diode can be described by the Shockley equation⁴² which allows the extraction of the ideality

factor (n) and series resistance (R_s)

$$I = AA^*T^2 \exp\left(\frac{-q\phi_B}{k_B T}\right) \left[\exp\left(\frac{q(V - IR_s)}{nk_B T}\right) - 1 \right] \quad (1)$$

Fig. 2 J-V characteristics of the GSOI-planar and GSOI-grating devices in the dark and the fitted Shockley equation (eq.1).

Here, A is the Schottky diode contact area, A^* is the effective Richardson constant ($112\text{ A cm}^{-2}\text{K}^{-2}$ for n-type silicon) and ϕ_B is the Schottky barrier height (SBH) for a given voltage (V), k_B is the Boltzmann constant, q the electron charge, and T is the temperature in Kelvin. The values of n and R_s obtained through

fitting eq.1 to the experimental data are 2.03 and 1.7k Ω for the SOI-planar device, respectively, and 5.23 and 1.21k Ω for the SOI-grating device, respectively. We intentionally employ a fit of eq.1 over the whole forward bias voltage range despite deviations of the experimental data from ideal diode characteristics. This avoids vastly different results for n and R_s depending on which voltage region the experimental data has been fitted to. It further allows a fair comparison with other devices since it prevents choosing a sweet spot in the J-V characteristics to optimize n and R_s as can be done e.g. using Cheung's method⁴⁹. The built-in voltages and Schottky barrier heights can be estimated to V_{bi} =0.61V and SBH=0.9eV for the GSOI-planar device and V_{bi} =0.27V and SBH=0.56eV for the GSOI-grating device²⁹.

Subsequently, J-V measurements of both device types have been carried out under optical excitation at different wavelengths and varying optical powers. Fig.3a) shows the J-V characteristics of the GSOI-planar device under illumination with $\lambda = 635$ nm laser light at optical powers varying from $P = 2$ nW..0.5mW (device area 4×4 mm²). As expected for a well-behaved photodiode, the forward current remains unchanged under illumination, however, the reverse current increases with increasing incident light powers due to generated photocurrents at the junction³¹. The time dependent measurement of the current of the GSOI-planar device under intermittent illumination at a reverse bias of $V_b = 2$ V (Fig.3b)) shows that light powers as low as 500pW, corresponding to an intensity of ~ 3 nW/cm², can be clearly detected. It demonstrates the high sensitivity of the GSOI-planar device due to the low dark current of ~ 4 nA (~ 25 nA/cm²). Fig.3c) shows transient measurements conducted with different laser wavelengths at constant power ($P = 1$ μ W) when the device is operated at $V_b = 2$ V reverse bias. The responsivity of the device is 0.23A/W, 0.26A/W and 0.029A/W for 520, 635 and 980nm laser light, respectively. Fig.3d) demonstrates the bias voltage dependence of the photoresponse of the GSOI-planar device under $\lambda = 635$ nm laser light illumination. Higher reverse biases increase the depletion width of the Schottky junction and increase the electric field in the depletion region which facilitates separation of photogenerated carriers^{31,42}. In comparison with the GSOI-planar device, the GSOI-grating device shows an increasing reverse current density with increasing reverse bias under illumination, similar to its behaviour in the dark (Fig.3e)). However, despite the increased dark current of the GSOI-grating device it exhibits a clearly distinguishable photoresponse for sub- μ W illumination (Fig.3f)).

Sensitivity is an important metric that represents the performance of a photodetector by quantifying the ultimate capability to detect weakest signals. Achieving high sensitivity requires both large responsivity R and low noise. Noise-equivalent-power (NEP) and specific detectivity (D^*) quantify the detection limit of a photodetector and are defined as⁵⁰

$$NEP = \frac{Noise_{RMS}}{R} \quad (2) \quad D^* = \frac{\sqrt{A_d \Delta f}}{NEP} \quad (3)$$

where NEP is the incident optical power that results in a signal-to-noise ratio (SNR) of one, R is the responsivity of the device at a given wavelength and bias conditions, A_d is the photoactive

Fig. 3 Photoresponse of the GSOI-planar (a-d) and GSOI-grating devices (e-f) in various conditions. a) J-V characteristics under different light powers. b) Transient measurement under decreasing light powers. c) Photocurrent response for different wavelengths. d) Photocurrent response at different reverse biases. e) J-V characteristics under different light powers. f) Transient measurement at $P = 400$ nW.

device area and Δf is the electrical bandwidth. The NEP is determined by the ratio of the root-mean-square (RMS) noise and responsivity R of the photodetector at a given wavelength. To extract NEP and D^* , the time-dependent response of the GSOI-planar device has been recorded with 8 Hz sampling rate at bias voltages of $V_b = 0$ and 2V, respectively, under optical excitation at a wavelength of $\lambda = 520$ nm, chopped at 0.5s intervals. Fig.4a) shows the I-V characteristics of the GSOI-planar device in the dark and under periodic optical excitation with decreasing optical power at a bias voltage of $V_b = 0$ V. The RMS noise is extracted from the measurement in the dark, equating to 2.89pA. NEP and D^* of the GSOI-planar device are calculated to be 14.5pW and 7.83×10^{10} cm Hz^{1/2}W⁻¹, respectively. Under an applied reverse bias of $V_b = 2$ V, shown in Fig.4b), the rise in the dark current leads to an increase in the RMS noise to 4.06pA. The NEP increases by $\sim 20\%$ to 17.7pW and D^* decreases to 6.41×10^{10} cm Hz^{1/2}W⁻¹. Fig.4c) shows the I-V characteristics for the GSOI-grating device under periodic optical excitation with decreasing optical power at a bias voltage of $V_b = 2$ V. The increased dark current of the GSOI-grating device compared to the GSOI-planar device leads to an increase of the RMS noise to 0.65nA and NEP to 3.8nW. Subsequently, the detectivity D^* decreases to 3.71×10^7 cm Hz^{1/2}W⁻¹. For comparison, our graphene-bulk silicon Schottky photodiodes exhibit a RMS noise of 40pA and NEP and D^* of 190pW and 1×10^{10} cm Hz^{1/2}W⁻¹, respectively. As such, a reduction of the photoactive silicon thickness from 500 μ m (bulk) to 10 μ m (SOI) leads to a ~ 10 times improved NEP for the GSOI-

planar compared to the bulk device due to reduced noise. We anticipate that a passivation/encapsulation of the graphene surface will improve the sensitivity of GSOI photodetectors further. Passivation will prevent the adsorption of e.g. H₂O and O₂ from the ambient environment onto graphene and reduce electronic noise⁵¹. The passivation/encapsulation layer can further be utilized to tailor the reflectivity of the device surface to engineer e.g. wavelength selectivity of the detectors. Additional sensitivity enhancement can be achieved through engineering of the graphene-silicon interface to further reduce dark currents^{22,31}.

Fig. 4 Time dependent current of the GSOI-planar and GSOI-grating device under low light power in ambient condition. The device is intermittently illuminated with laser light of $\lambda = 520\text{nm}$ wavelength of sub-nanowatt intensity to characterize $\text{Noise}_{\text{RMS}}$, NEP and D^* under different reverse bias voltages. a,b) GSOI-planar device at $V_b = 0\text{V}$ and 2V , respectively. c) GSOI-grating device at $V_b = 2\text{V}$.

The high-speed optical response of both devices has been evaluated for wavelengths ranging from the near UV to NIR employing a picosecond white light laser source (Fianium, pulse duration $\tau_{\text{pulse}} < 80\text{ps}$ at all wavelengths) and optical bandpass filters ($\text{FWHM} \leq 10\text{nm}$). The electrical response was recorded using a transimpedance preamplifier (Phillips Scientific 6954) and an oscilloscope (WaveJet 354-A) while the devices were operated under zero bias conditions ($V_b = 0\text{V}$). The current response I of the devices to the picosecond light pulses is shown in Figs.5)a,b) and has been fitted with a biexponential function

$$I = I_{\text{max}} \times \left(1 - e^{-\frac{t-t_0}{\tau_r}}\right) \times e^{-\frac{t-t_0}{\tau_f}} \quad (4)$$

with I_{max} the peak response, τ_r and τ_f the rise- and fall-times and t_0 the time-offset at which the photoresponse occurs. The

rise- and fall-times of the GSOI-grating device are $\tau_r < 4\text{ns}$ and $\tau_f \sim 10\text{-}15\text{ns}$ for all tested wavelengths ($\lambda = 420\text{-}900\text{nm}$) and are moreover almost constant for all wavelengths. The GSOI-planar device exhibits slightly increased rise- and fall-times in the orders of $\tau_r \sim 10\text{ns}$ and $\tau_f \sim 20\text{-}70\text{ns}$, attributed to the larger average thickness of the active silicon layer of the GSOI-planar device compared to the GSOI-grating device with a patterned surface. The increased spread of the fall time τ_f of the GSOI-planar device compared to the GSOI-grating device stems from the larger junction area of the GSOI-planar device. Even though the laser spot has been fully focused inside the junction area for all measurements, dispersive effects of the different optical bandpass filters used to select a wavelength from the white light source can cause minor shifts of the illuminated position that can lead to variations in the fall time τ_f . Note that rise- and fall-times can be further decreased upon application of a bias voltage V_b to facilitate extracting charge carriers out of the device. We anticipate that the speed can be increased at least twice by an applied bias³¹; due to restrictions in our characterization setup application of a bias voltage is not possible in present experiments.

Fig. 5 Time-resolved photoresponse of a) the GSOI-planar and b) the GSOI-grating device under illumination with a picosecond white light source at various wavelengths. Note change of scale of time-axis.

The temporal response of a photodiode to an instant injection of excess carriers upon photon absorption depends mainly on three independent components which can be expressed⁵² by

$$\tau_r = \sqrt{\tau_{\text{RC}}^2 + \tau_{\text{dr}}^2 + \tau_{\text{diff}}^2} \quad (5)$$

with τ_r the overall 10% to 90% response time of the photodiode, τ_{RC} the resistor-capacitor (RC) time constant of the photodiode, τ_{dr} the electric-field driven drift time of the carriers in

the depletion region and τ_{diff} the diffusion time of carriers in the non-depleted region of the substrate. The wavelength dependent optical absorption coefficient of silicon determines the penetration depth of incident light into the silicon substrate according to Beer-Lambert law⁴². Generally, incident light of short wavelengths optically excite charge carriers in the silicon close to the substrate surface while long wavelengths create charge carriers deep within the silicon substrate. Considering a depletion region length L_D of the Schottky junction for employed low doped silicon on the order of 1-2 μm ³¹, this implies complete absorption of short wavelength light (e.g. $\lambda = 450\text{nm}$) within the depletion region while only $\sim 50\%$ and $\sim 15\%$ of light of $\lambda = 550\text{nm}$ and $\lambda = 700\text{nm}$ wavelengths, respectively, are absorbed within the depletion region. The light absorbed deeper within the silicon substrate, outside the depletion region length of the Schottky junction, thus creates charge carriers that contribute to the photoresponse by a diffusion process. The transit time for charge carriers within the depletion region for zero external bias condition depends on the depletion region length L_D and the electric field E due to the built in potential V_{bi} of the Schottky junction and can be estimated by $\tau_{\text{dr}} = \frac{L_D}{\mu E} = \frac{L_D^2}{\mu V_{\text{bi}}}$ to $\sim 82\text{ps}$ for holes and $\sim 26\text{ps}$ for electrons based on mobilities for holes and electrons of $\mu_p = 450 \frac{\text{cm}^2}{\text{Vs}}$ and $\mu_n = 1400 \frac{\text{cm}^2}{\text{Vs}}$, respectively. However, charge carriers contributing to diffusion currents from deep within the silicon substrate need to travel far longer distances. The required time for diffusion can be calculated via $\tau_{\text{diff}} = \frac{L_p^2}{2D_p}$. In the case of a bulk silicon substrate, the diffusion length L_p for holes is determined by the thickness of the active silicon layer. The diffusion coefficient $D_p = \mu_p \frac{kT}{q}$ can be evaluated from the mobility of holes ($\mu_p \sim 450 \frac{\text{cm}^2}{\text{Vs}}$) in lowly n-doped silicon. Using a recombination time of $\tau_p = 2 \times 10^{-4}\text{s}$ for n-type silicon with a doping level of $N_d = 3.5 \times 10^{14} \text{ cm}^{-3}$ ^{53,54}, the diffusion length L_p is calculated as $L_p = \sqrt{D_p \tau_p} = 480 \mu\text{m}$ which is comparable to the thickness of a standard silicon substrate.

In a straight forward manner, the necessary time τ_{diff} for a hole to diffuse $10\mu\text{m}$ and $480\mu\text{m}$, representative of employed SOI wafers and typically employed bulk silicon wafers with identical doping concentration of $N_d \sim 3.5 \times 10^{14} \text{ cm}^{-3}$, can be calculated as $\sim 42\text{ns}$ and $\sim 98\mu\text{s}$, respectively. As such we argue that the decrease of the active optical silicon layer thickness to $10\mu\text{m}$ in our devices based on SOI material and with it a reduction of speed limiting diffusion currents is the major reason for an increase of the operating speed of both the GSOI-planar and GSOI-grating device by more than two orders of magnitude compared to GS devices based on bulk silicon.

The argument of diffusion currents being the speed limiting component is further supported by comparing the 3-dB cut-off frequency (f_c) of our GSOI devices fabricated on an SOI substrate with GS junction diodes fabricated on bulk silicon substrates in the literature, including our previous report (Fig.6)³¹. The corresponding cut-off frequencies of the GSOI-grating, GSOI-planar and reference devices are determined from the measured and reported rise times τ_r as $f_c = 0.34/\tau_r$ ⁵⁵. Fig.6 shows the cut-off frequency (f_c) vs photoactive device area for various wavelengths of our own devices and devices reported in the literature. It can

be seen that despite an active area of our devices comparable to or greater than devices fabricated on bulk silicon, our devices fabricated on SOI substrate exhibit an increase in cut-off frequency of several orders of magnitude. It further demonstrates that the increase in cut-off frequency f_c of our devices cannot be attributed to a simple decrease of the RC-time constant due to down scaling contact and junction areas. The RC-time constant of the junction of the GSOI-grating device can be estimated from the measured series resistance $R_s = 1.2\text{k}\Omega$ and calculated junction capacitance C ⁴²

$$C = \sqrt{\frac{q\epsilon_0\epsilon_{\text{Si}}N_d}{2(V_{\text{bi}} + V_r)}} \quad (6)$$

with ϵ_0 and ϵ_{Si} the free space and silicon permittivity, respectively, N_d the donor concentration of silicon, V_{bi} the built-in potential and V_r the applied reverse bias. The junction capacitance equates to $C = 19\text{pF}$ for $N_d = 3.5 \times 10^{14} \text{ cm}^{-3}$, $V_{\text{bi}} = 0.5\text{V}$ and $V_r = 0\text{V}$, yielding an RC-time constant of $\tau_c = 23\text{ns}$ which is smaller than the diffusion time of $\tau_{\text{diff}} = 42\text{ns}$. As such the RC-time constant does not present a bottle-neck for the speed of the GSOI-grating device. To the best of our knowledge, our graphene-silicon Schottky photodetectors on SOI substrate are the fastest to date for free space light detection, especially in the VIS and NIR wavelength range $\lambda > 500\text{nm}$.

Fig. 6 Comparison of the 3dB cut-off frequency f_c versus photoactive device area of our GSOI-photodetectors with GS Schottky photodetectors fabricated on bulk silicon photodiodes at various wavelengths.

The spectral response of the photodetectors on SOI substrate in comparison with a device fabricated on $500\mu\text{m}$ thick bulk n-type silicon with identical doping level is shown in Fig.7a). All three device types show similar responsivities for shorter wavelengths $\lambda < 450\text{nm}$ since incident light in this wavelength range is totally absorbed within the first top $10\mu\text{m}$ of silicon. Light of longer wavelengths $\lambda > 450\text{nm}$ can penetrate deeper into the silicon substrate due to the reduced absorption coefficient. For longer wavelengths, only part of the incident light is absorbed within the active top silicon layer of the SOI substrate and the remaining light power is transmitted into the BOX and silicon handle

wafer where it does not contribute to the photoresponse. This is manifested in Fig.7a) as a reduced responsivity of the GSOI devices compared to GS devices fabricated on bulk silicon for longer wavelength light $\lambda > 900\text{nm}$. It is further noticeable that the spectral response of the GSOI-grating device is almost flat in the wavelength range $\sim 400\text{--}800\text{nm}$ compared to both the GSOI-planar and bulk silicon device, easier recognizable in the plot of the spectral dependence of the responsivities for each device type normalized to their respective peak responsivities (Fig.7b)). This flat spectral photoresponse of the GS-grating device can be attributed to the surface topography of the device. The V-grooves form micro-optical elements that allow direct transmission of incident light into the silicon substrate but also reflect light that is unused in planar devices back into the substrate^{56–58}. We would like to point out that even though the top silicon layer forms an optical microcavity for the GSOI-planar device that should lead to an oscillating wavelength dependent responsivity, this cannot be observed in our measurements. The spectral width of the light at our monochromator output of $\Delta\lambda \sim 8\text{nm}$ at a wavelength of 980nm corresponds to a coherence length $\lambda^2/\Delta\lambda$ of $\sim 120\mu\text{m}$ in free space⁵⁹. The coherence length is further reduced to $\sim 35\mu\text{m}$ in the silicon substrate due to the higher refractive index. Comparing derived coherence length of the light employed in our setup to the top silicon layer thickness of $10\mu\text{m}$ implies that light with broad spectral width will lose its coherence after a few reflections within the formed optical microcavity already. As such, oscillating, wavelength dependent responsivity effects are smeared out and cannot be observed for the GSOI-planar device. Fig.7c,d) show the simulated electromagnetic power loss for a unit cell of the grating and planar device, respectively, for normal incident light (p-polarized) at a wavelength of $\lambda = 980\text{nm}$. The blue arrows indicate the transmitted and reflected light paths. Light incident on the GSOI-grating device with 54.7° sloped facets will be partially transmitted into the silicon substrate after undergoing refraction. However, the reflected light component is directed towards the opposite facet and also partially absorbed by the substrate. Additionally, the active silicon layer of the SOI substrate of both the GSOI-grating and the GSOI-planar device forms an optical cavity where multiple reflections between the topmost air-silicon, silicon-BOX and BOX-handle silicon interfaces lead to optical interference effects. This is clearly visible in the zoom-in on the electromagnetic losses in the GSOI-planar device (Fig.7d)). The surface topography of the GSOI-grating device leads to greater electromagnetic power losses (absorption) within the active silicon layer compared to the GSOI-planar device and allows tailoring the spectral response of GS photodetectors. However, we note that optical absorption on its own does not fully describe the electrical responsivity. Optically excited charge carriers contribute to the photocurrent via diffusion and drift processes subject to electric fields in the formed junction which can be particularly complex, especially for the grating device.

Devices fabricated on SOI substrate are further sensitive to the angle of incident light. Fig.7e) shows a measurement of the angular dependence of the responsivity for the GSOI-planar and GSOI-grating device, respectively, for p-polarized light of $\lambda = 980\text{nm}$ wavelength. A laser light source has been employed due its high

Fig. 7 Effect of substrate thickness, surface topography, and incident angle on the spectral response of GS Schottky photodiodes. a) Spectral responsivity. b) Normalized responsivity. c,d) Simulated relative electromagnetic power loss density in the grating and planar device, respectively (normal incidence light, $\lambda = 980\text{nm}$). Blue arrows indicate light reflection and transmission, respectively. Zoom-in: Interference effects in the planar device. e) Measured angular dependence of the responsivity of the GSOI-planar and -grating device, respectively.

coherence length and silicon's reduced absorption coefficient at this wavelength compared to visible light. This allows multiple light reflections within the top silicon layer and probing interference and thus angle dependent effects. The GSOI-planar device, in which all interfaces between different materials are parallel, exhibits a strong angular dependence. Constructive and destructive interference effects due to multiple reflections within the optical cavities formed by the active silicon layer and the BOX result in an oscillating behavior of the responsivity. The GSOI-grating device, however, does not show this oscillatory behavior but instead exhibits a smoother angular dependence and an increased responsivity at higher incident angles due the surface topography of the device. The micro-optical elements formed by the slanted facets allow more efficient coupling of incident light into the silicon substrate at higher incident angles. Furthermore, parallel air-top silicon and top silicon-BOX interfaces that would result in well defined interference effects are strongly reduced in the GSOI-grating device. Light entering the top silicon through the slanted surfaces can be incident on the top silicon-BOX interface above the critical angle of $\sim 25^\circ$ which results in total internal reflection (TIR) of the light rays at this interface.

3 Conclusions

In conclusion, we have demonstrated that graphene-silicon Schottky photodetectors fabricated on SOI substrate exhibit a significant improvement in operating speeds compared to their bulk silicon counterparts, approaching cut-off frequencies of $f_c \sim 1\text{GHz}$. The speed improvement can be attributed to a suppression of speed limiting diffusion currents due to the reduced thickness of the photoactive silicon layer. We anticipate that down scaling of the junction area to decrease the RC-time constant as well as decreasing the active silicon layer thickness can further improve operating speeds. Ultimately, the thickness of the silicon substrate determines the trade off between responsivity and speed for GSOI-PDs. We demonstrated that an active silicon layer thickness of $10\mu\text{m}$ significantly improves the speed of the GSOI device with only a modest decrease in the responsivity. The integration of micro-optical elements through surface patterning allows control of the spectral responsivity and angular dependence of GSOI devices. These micro-optical elements might further pave the way towards GSOI photodetectors operating in a total internal reflection (TIR) architecture⁶⁰, particularly for wavelengths beyond $\lambda > 1.1\mu\text{m}$ for which silicon is fully optical transparent and absorption is taking place in the graphene only.

Methods

Device characterization.

All electrical measurements were conducted in ambient atmosphere at room temperature. The current-density-voltage (J-V) measurements were performed using a computer-interfaced Keithley 2400 source-meter. As convention, the bias voltage is applied to the silicon substrate and graphene is grounded in all measurements. Laser diodes of wavelength $\lambda = 520, 635$ and 980nm as well a monochromator (Spex 500M) with white light source (Thorlabs OSL1EC) were used to record the spectral response of devices under illumination. Neutral density (ND) filters

were used to vary the light intensity. The high photoresponsivity of the diodes from near UV to IR allowed performing measurements at DC without need for a lock-in amplifier.

Acknowledgement

H.S. acknowledges funding from the Turkish government (MEB-YLSY). P.P. acknowledges funding from the Royal Society (RG140411). T.J.E acknowledges funding from the Huawei Innovation Research Program (HIRP).

Supporting information

Additional information including Raman characterization of graphene, surface topography of the GSOI-grating device, extraction of ideality factors and series resistances from the electrical diode characteristics, and optical simulations.

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