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Photovoltaic Effect and Evidence of Carrier Multiplication in Graphene Vertical Homojunctions with Asymmetrical Metal

Contacts

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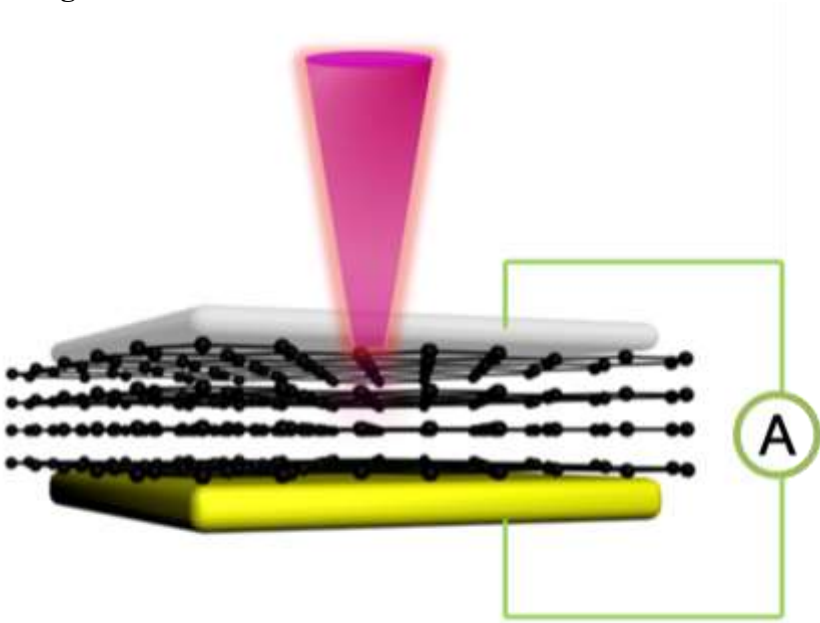
Abstract:

Graphene exhibits exciting potentials for high-speed wideband photodetection and high quantum efficiency solar energy harvest because of its broad spectral absorption, fast photoelectric response and potential carrier multiplication. Although photocurrent can be generated near a metal-graphene interface in lateral devices, the photoactive area is usually limited to a tiny one-dimensional line-like interface region. Here, we report photoelectric devices based on vertical graphene two-dimensional homojunction, which is fabricated *via* vertically stacking four graphene monolayers with asymmetric metal contacts. The devices show excellent photovoltaic output with excitation wavelength ranging from visible light to mid-infrared. The wavelength dependence of the internal quantum efficiency gives direct evidence of the carrier multiplication effect in graphene. The simple fabrication process, easy

scale-up, large photoresponsive active area, and broadband response of the vertical graphene device are very promising for practical applications in optoelectronics and photovoltaics.

Keywords: Graphene, photodetector, carrier multiplication, vertical homojunction, photovoltaics

TOC Figures:



Characterized by its gapless energy dispersion, graphene is known to generate electron-hole pairs over a broad light bandwidth from ultraviolet to the THz range.¹⁻¹⁴ Photocurrent generation has been demonstrated in graphene near metallic contacts,^{6, 7, 15} at the lateral boundary between single-layer and bilayer regions,^{16, 17} and at the edge of lateral p-n junctions.^{8, 18, 19} Nevertheless, the photocurrent away from the contacts or the boundaries is usually very weak and the intrinsically weak absorption of graphene limits the external quantum efficiency (EQE) to the range of merely ~0.1-1%. To overcome the limits of the small photoactive area and the weak absorption, heterostructures of graphene with two-dimensional (2D) semiconductors have been formed by stacking graphene layers and transition metal dichalcogenides.^{20, 21} Although the EQE is enhanced in such heterostructure, the spectral range of the photoelectric response is limited by the band gap of the 2D semiconductors. In this work, we demonstrate graphene-graphene vertical homojunctions that have a much larger photoactive area and maintain the broadband photo response meanwhile. Metal-stacked four layer graphene (SFLG)-metal vertical devices are fabricated *via* a layer-by-layer assembly method, where asymmetric metal contacts are employed to modulate the electronic states in the bottom and the top graphene layers. The as-built graphene-graphene junction is demonstrated as a photovoltaic cell that can be used as a self-powered photodetector without applying a source-drain bias.

RESULTS AND DISCUSSION

A schematic metal-SFLG-metal device is shown in **Fig. 1a**. The structure consists of four stacked graphene monolayers sandwiched between the top Ag electrode and the bottom Pt electrode fabricated on a Si/SiO₂ substrate. The fabricating procedure of the device is described in detail in supporting information **Fig. S1**. A cross-section specimen from the as-built multi-layer graphene photovoltaic cell is prepared and characterized by transmission

electron microscopy (TEM), as shown in **Fig. 1b**. It seems that the graphene layers are well attached to the top and bottom electrodes. When graphene is in contact with the metal, there will be electron transfer at the interface. Previous experiments suggest that the magnitude of the doping not only depends on the difference between the work functions of graphene Φ_G and metal Φ_M , but also on the wave-function hybridization or chemical interaction which may contribute to the electronic doping of graphene.^{22, 23} Theoretical calculations of metal on graphene predict the formation of an interfacial dipole layer, resulting in a potential step ($\Delta V = 0.9$ eV) to favor n-type doping in graphene *via* electron transfer from metal to graphene.²² Due to the existence of the interfacial dipole layer, it was demonstrated that a Pt film can produce either n-type or weak p-type doping of pristine graphene with Fermi level crossing the Dirac point, although Pt has a larger work function than graphene.²³ For our stacked graphene layers, the Fermi level initially locates below the Dirac point due to the possible p-type doping induced in the graphene transfer procedure (**Fig. S2**).²⁴ At the graphene/bottom Pt electrode interface, the electron transfer from Pt to graphene shifts up the Fermi level of the bottom graphene layer. In the case of the top electrode, Ag has a much smaller work function than Pt and therefore more electrons transfer from Ag to the top graphene layer, resulting in a much higher Fermi level of the top graphene layer. In a multilayer graphene system, it has been revealed that the screening effect is non-saturated until the fourth layer.²⁵ The potential profile and the built-in electric field of the Ag-SFLG-Pt vertical device are illustrated in **Fig. 1c**. Upon light absorption, electron-hole pairs can be separated by the built-in electric field within the graphene layers, resulting in a net current flowing from top Ag to bottom Pt through the inner vertical structure.

The configuration of the current-voltage (I - V) measurement and the optical image of a typical device are shown in **Fig. 1d** and **1e**, respectively. The dashed box indicates the Ag-SFLG-Pt junction with an area of $\sim 10 \mu\text{m} \times 10 \mu\text{m}$, and the green dot indicates the focused

laser. The vertical device shows linear I - V curves and a photovoltaic effect under illumination (**Fig. 1f**). The fill factor, which is the ratio of the actual maximum output power to the product of the open circuit voltage and short circuit current, is calculated to be 0.25. The efficiency, which is measured as the ratio of useful output to total input, is calculated to be 1.15×10^{-8} . One of the reasons for such a low efficiency is the top Ag attenuates most light. The open-circuit voltage and short-circuit current switch between on/off states as switching on/off the laser illumination, and polarities of the measured voltage and current are well consistent with the mechanisms of the electron-hole pair separation in the built-in electric field between the graphene layers (**Fig. 2**). The polarities of the photo generated voltage and current reverse when exchanging the electrical connections of the device (**Fig. S3**), indicating that the measured signals are from the device. The response time cannot be directly retrieved from our measurement (**Fig. S4**), and we estimate the intrinsic response time of the vertical graphene detector is below nanosecond according to previous study of graphene based photodetector.^{6, 8}

To separate the photocurrent contributions from different interfaces, we fabricated devices with only a graphene/bottom Pt electrode interface, a top Pt electrode/graphene interface, and Pt/graphene layers/Pt interfaces, respectively (**Fig. S5**). The I-V characteristics of the three devices are shown in (**Fig. S6**), and the minor differences of their resistances will not lead to the significant differences of the open-circuit voltages. For the device with graphene/bottom Pt interface (**Figs. 3a-3c**), the photovoltage shows a negative polarity, which is opposite to the device with a top Pt/graphene interface (**Figs. 3d-3f**). Although the two devices have an equivalent magnitude of photovoltage $\sim 100 \mu\text{V}$, the top Pt/SFLG device has a higher internal quantum efficiency because the top Pt allows only 3.84% light transmission (**Fig. S7**). It suggests that the top Pt-graphene interface produces a sharper potential profile than the graphene-bottom Pt interface. The top Pt electrode was deposited directly on the graphene surface by e-beam thermal evaporation under high vacuum, resulting in a better contact than

that of graphene/bottom Pt interface formed by a transfer technique. Therefore, a symmetrical electrode configuration with Pt-SFLG-Pt structure also has an asymmetric electronic band potential which simplifies the fabrication process of such device.

Twelve Pt-SFLG-Pt devices were fabricated to study their photoelectric properties. The cross-sectional TEM image of the Pt-SFLG-Pt junction is shown in **Fig. 4a**. No clear contaminations can be found, which may be introduced during the graphene transfer process. The measurement configuration is shown in **Fig. 4b**. The mechanism of the photogenerated open-circuit voltage is shown in **Fig. 4c**. All Pt-SFLG-Pt devices show a positive photovoltage, indicating that the photovoltage generation is dominated by the graphene doping from the top Pt electrode, although the graphene/bottom Pt interface tends to decrease the potential slope produced by the top Pt/graphene interface. Surprisingly, as shown in **Fig. 4d**, the vertical Pt-SFLG-Pt device (with 300 μV photovoltage) performed better than the top Pt/SFLG device (with 100 μV photovoltage, **Fig. 3f**) under the same excitation conditions. This implies that the vertical Pt-SFLG-Pt structure makes the carrier collection much more efficient than the top Pt/SFLG structure. The photo-excited electron-hole pairs would typically decay on a timescale of tens of picoseconds,⁹ and the carrier-diffusion length is typically $\sim 15\text{-}70$ nm.²⁶ For our vertical structure, the distance between the electrodes is several nanometers, which is shorter than the carrier-diffusion length, resulting in a more efficient transit of the photo-excited electron-hole pairs towards opposite electrodes.

Furthermore, the metal-SFLG-metal device has a broadband photoelectric response due to the zero bandgap of graphene. **Figure 4e** shows that the device still works well in the mid-infrared region with a wavelength of 4.15 μm . The photoelectric response from visible light to mid-infrared (4.15 μm) is demonstrated and shown in **Fig. S8**. It must be noted that the device is expected to work beyond this wavelength range, but measurements at other wavelengths were limited by the available light source. Unlike the lateral graphene-metal junctions or

graphene p-n junctions that have a rather small photoactive area near the junction, this vertical device can generate a photocurrent throughout the entire area of the metal-SFLG-metal junction, as shown in the scanning photocurrent mapping (**Fig. 4f**). The enhancement of the photocurrent at the corners and edge of Fig. 4f is due to thinning of the Pt contact at the steps between graphene and Al₂O₃ during the Pt deposition process (**Figure S9**) and the enhancement is universal in all devices that are measured. This unique advantage of graphene vertical homojunctions allows us to compare the internal quantum efficiency (IQE) of different photon excitation energy. The wavelength dependent measurement of IQE is performed on a 10μm×10μm Pt-SFLG-Pt device. This active area is slightly larger than the spot size of the laser excitation used in this measurement. The IQE (η) is defined as the number of photo-carriers collected in the external circuits to the number of photons actually

absorbed in graphene, that is, $\eta = \frac{I_{ph}}{e} \left(\frac{h\nu}{\alpha P_{in}} \right)$, where I_{ph} is the photocurrent, e is the electron charge, h is Planck's constant, ν is the frequency of light, α is the ratio of the absorbed light by graphene to the total incident light, and P_{in} is the total incident optical power. Taking into account the light transmission of the top Pt electrode, the incident power arriving at graphene is attenuated and has wavelength dependence as shown in **Fig. S7**. The wavelength dependent absorption rate of the graphene is taken from the measurements by Mak *et al.*,²⁷⁻²⁹ and thus the absorption of 4-layer graphene to different photon energy can be deduced through standard transfer matrix calculation described in the supporting information (**Figure S10, S11**). We can see from **Fig. 5a** that the IQE increases linearly with the excitation photon energy, giving one of the most notable signatures of the carrier multiplication process in graphene,^{10, 30} which plays the key role in enhancing the photon harvest efficiency in the photodetector and solar cell. The carrier multiplication process is schematically shown in **Fig. 5b**. During the relaxation of photon excited hot carriers, instead of losing its energy to the

lattice (phonon), the carrier prefers to transfer its energy to secondary electrons and creates an additional electron-hole pair through interband transition in the undoped layer (II, IV of Fig. 5b, referred as conventional carrier multiplication). Additionally, hot carriers can be created in the doped layer through intraband transition (I, III of Fig. 5b, referred as “hot carrier multiplication” following the reference), leading to the efficient photocurrent generation through photo thermoelectric effect in graphene.^{8,10,16,18} Both processes are highly efficient and can cascade many times due to graphene’s zero bandgap and highly efficient carrier-carrier scattering in linear dispersion band structure.³¹⁻³³ In this scenario, the generation of multiple electron-hole pairs (conventional carrier multiplication) or hot carriers (hot carrier multiplication) from the absorption of a single photon is possible in graphene. As both carrier multiplication and hot carrier multiplication has IQE that is linearly dependent on excitation photon energy,^{10, 30} the wavelength dependent IQE measurement in this work cannot distinguish the dominant mechanism, whether it’s built-in electric field or photo-thermoelectric effect, in the response of the device. The sign of the thermoelectric current in a p^+-p junction can exhibit the same or opposite sign to that of an $p-n$ sample.¹⁸ As shown in Fig. 1c, p^+-p , $p-n$ and $n-n^+$ junctions may coexist in our vertical structure. Thermoelectric current generated by the three junctions may weaken or enhance each other, depending on the carrier densities. In contrast, photocurrent generated by the built-in electric field must enhance each other. The polarity of the photocurrent generated by the built-in electric field is in consistent with the result. At least, the built-in electric field effect makes positive contribution to the total photocurrent. To distinguish the photo-thermoelectric effect and built-in electric field effect, further smoking gun experiment is desired on this vertical device, such as temperature dependence and autocorrelation measurement of the photocurrent.⁸ Here we emphasize that although carrier multiplication and hot carrier multiplication has been theoretically proposed^{31,33} and indirectly measured by pump probe experiments,^{10, 11, 32, 34} time

resolved angle-resolved photoemission spectroscopy,³⁵ our experiment provides direct evidence of this important optoelectronic effect in a real graphene based functional detector, although the IQE is still relatively low in this measurement, possibly due to the gentle slope of the band profile between graphene layers. For future work, a larger built-in electric field throughout the entire vertical device could be designed by applying a proper electrode which can heavily dope the graphene. Besides, the resistance of the thin Pt electrodes (30 nm with 386 Ω) contributes to the majority of the total resistance of the Pt-SFLG-Pt device (450 Ω), which accounts for the 6-fold decrease in photocurrent. A transparent and conductive electrode that favors the doping in graphene and minimizes the series resistance of the electrode is the best choice for the top electrode.³⁶ Finally, a significant improvement could be achieved by enhancing the light absorption of graphene. As a comparative example, a metal-stacked two layer graphene-metal device (**Fig. S12**) was also fabricated, generating about half the amount of the photocurrent compared to the SFLG based device. We attribute this improvement to the enhancement of the light absorption in four-stacked-graphene layers.

The graphene vertical structure based photocell is scalable, demonstrating its potential for solar energy harvest. For a conceptual demonstration, we fabricated a structure composed of four individual cells connected in series, as shown in **Figs. 6a** and **6b**. Fabrication details are shown in **Fig. S13**. The performance of the four individual cells was characterized by a 514-nm laser with an excitation power of ~ 3.79 mW. **Fig. 6c** shows the open-circuit voltage and the short-circuit current when switching the illumination for one Pt-SFLG-Pt cell. The photovoltage and photocurrent are 1.5 mV and 8 μ A, respectively. The responsivity (defined as I_{ph}/P_{in}) was calculated to be 2.1 mA/W. The laser spot was then enlarged to cover the complete area of all four cells, resulting in a decrease in the power density from 134 μ W/ μ m² to 5.36 μ W/ μ m². **Fig. 6d** presents photovoltages for the tandem cells with one to four individual cells connected in series. The photovoltage outputs are 45 μ V, 85 μ V, 140 μ V, and

197 μV for the single cell, double-cell module, triple cell module, and quadruple cell module, respectively, which are well consistent with the series circuit voltage output.

CONCLUSIONS

In summary, we have demonstrated that vertical metal-SFLG-metal can be constructed to generate photocurrent over a broad light bandwidth with a large scalable junction area. Metal electrodes are designed to modulate asymmetrically the graphene Fermi level at the top electrode/graphene and the bottom electrode/graphene interfaces. The device achieves responsivity up to 2.1 mA/W and shows evidence of the carrier multiplication effect. The simple fabrication process, large photoresponsive active area and broadband photoresponse hold great promise for practical applications in photoelectronic devices. Further optimizations of the number of graphene layers and improvement of the top electrodes could open up new vistas of high-performance optoelectronic devices.

MATERIALS AND METHODS

Fabrication of stacked four-layer graphene. A PMMA thin layer was spin-coated onto a monolayer graphene surface grown on a copper foil. The Cu foil was then dissolved by a FeCl_3 saturated solution for 30 min. The graphene/PMMA film was washed three times in 60 °C deionized water. Another monolayer graphene on copper foil was used to fish out the graphene/PMMA film from deionized water. The face-to-face adhesion of the clean graphene surfaces allows no PMMA between the graphene layers. The two-layer graphene/PMMA film was then patterned into microstamps *via* EBL and O_2 plasma etching. After the Cu foil was dissolved and the two-layer graphene/PMMA film was rinsed, the two-layer graphene/PMMA microstamps can be transferred and printed onto the bottom electrode. The fabrication process and the detailed structure are shown in **Fig. S1**. First, the bottom electrode was fabricated

using electron beam lithography (EBL), followed by metal deposition of Ti/Pt (5/15 nm) and a liftoff. Then, the two-layer graphene/PMMA stack was transferred onto the bottom electrode;³⁷ subsequently, the PMMA was dissolved by acetone (**Fig. S1b**). Another two-layer graphene/PMMA was transferred and stacked to form the stacked four layer graphene. Finally, after removing the PMMA by acetone, an insulating Al₂O₃ layer (25nm) with a window of 10 μm \times 10 μm in the center of the graphene was fabricated *via* EBL and film deposition, as shown in **Fig. S1c**. The last step was to fabricate the top electrode by another round of EBL and metal deposition of Pt (30 nm) *via* electron-beam evaporation.

Cross-sectional sample preparation and TEM characterization. After depositing a protective layer of amorphous carbon and subsequently Pt on the device surface, a thin cross-section lamella was prepared by Focused Ion Beam (FIB) using a FEI-Helios NanoLabDualBeam system. Ultra-care is put in when milling the structure in order to protect the graphene layer. High-resolution TEM characterization was performed on a FEI Tecnai G2 microscope operated at 200 kV.

Photocurrent Measurement. All measurements were performed in ambient conditions at room temperature. Except for the wavelength dependent response and the photocurrent mapping, all electrical measurements were performed by Agilent B2912, and the optical excitations were carried out by a 514 nm laser guided by a Renishaw Raman optical system. For wavelength-dependent IQE measurement, a series of bandpass filters is used to select the desired wavelength from an ultrafast fiber laser (Fianium: WhiteLase-Micro) which generates a super-continuum white light with wavelength from 450nm to 2200nm. The repetition rate of the Fianium is 20 MHz and the pulse width is 6 ps. The laser was focused on the device active area by a 20X (Olympus LMPlanFLN 20X/0.40) objective in the visible wavelength or a 40X reflective objective (thorlabs LMM-40X-UVV, 0.5NA) in the near IR wavelength. The spot sizes are all within the 10- μm device active area and the photon fluence is kept around

$10^{13}/\text{cm}^2$. For the 4- μm measurement, 250 kHz Coherent RegA pumped infrared optical parametric amplifier (OPA) followed by a differential frequency generator (DFG) is used to generate Mid-IR pulse with a pulse width of 300 fs. A ZnSe Focusing Objective (0.2 NA) in the Mid-IR range is used to focus the Mid-IR. The laser was modulated with a mechanic chopper with a frequency around 1.5 kHz and the generated photocurrent was converted to voltage using a current preamplifier (DL instruments 1211); then the voltage was read out by a Lock in amplifier (SR 830) referred to the mechanical chopper.

Competing financial interests

The authors declare no competing financial interests.

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Supporting Information Available:

Fabrication of Ag-SFLG-Pt device, doping level of staked graphene monolayers, devices with a graphene/bottom Pt electrode interface, top Pt electrode/graphene interface, top Pt electrode/graphene/bottom Pt electrode interfaces, wavelength-dependent transmission of the 30-nm-thick Pt film, wavelength-dependent photoresponse of the Pt-SFLG-Pt device, performances of the Ag-stacked two layer graphene-Pt and Ag-stacked four layer graphene-Pt devices, fabrication process of a general device consisting of four individual Pt-SFLG-Pt photocells. This material is available free of charge *via* the Internet at <http://pubs.acs.org>.

References

1. Avouris, P.; Xia, F. Graphene Applications in Electronics and Photonics. *MRS Bulletin* **2012**, *37*, 1225-1234.
2. Liu, C.-H.; Chang, Y.-C.; Norris, T. B.; Zhong, Z. Graphene Photodetectors with Ultra-Broadband and High Responsivity at Room Temperature. *Nat. Nanotech.* **2014**, *9*, 273-278.
3. Ju, L.; Geng, B.; Horng, J.; Girit, C.; Martin, M.; Hao, Z.; Bechtel, H. A.; Liang, X.; Zettl, A.; Shen, Y. R.; *et al.* Graphene Plasmonics for Tunable Terahertz Metamaterials. *Nat. Nanotech.* **2011**, *6*, 630-634.
4. Fuhrer, M. S.; Lau, C. N.; MacDonald, A. H. Graphene: Materially Better Carbon. *MRS Bulletin* **2010**, *35*, 289-295.
5. Liu, M.; Yin, X.; Ulin-Avila, E.; Geng, B.; Zentgraf, T.; Ju, L.; Wang, F.; Zhang, X. A Graphene-Based Broadband Optical Modulator. *Nature* **2011**, *474*, 64-67.
6. Xia, F.; Mueller, T.; Lin, Y.-m.; Valdes-Garcia, A.; Avouris, P. Ultrafast Graphene Photodetector. *Nat. Nanotech.* **2009**, *4*, 839-843.
7. Mueller, T.; Xia, F.; Avouris, P. Graphene Photodetectors for High-Speed Optical Communications. *Nat. Photon.* **2010**, *4*, 297-301.
8. Sun, D.; Aivazian, G.; Jones, A. M.; Ross, J. S.; Yao, W.; Cobden, D.; Xu, X. Ultrafast Hot-Carrier-Dominated Photocurrent in Graphene. *Nat. Nanotech.* **2012**, *7*, 114-118.
9. Sun, D.; Wu, Z.-K.; Divin, C.; Li, X.; Berger, C.; de Heer, W. A.; First, P. N.; Norris, T. B. Ultrafast Relaxation of Excited Dirac Fermions in Epitaxial Graphene Using Optical Differential Transmission Spectroscopy. *Phys. Rev. Lett.* **2008**, *101*, 157402.
10. Tielrooij, K. J.; Song, J. C. W.; Jensen, S. A.; Centeno, A.; Pesquera, A.; Zurutuza Elorza, A.; Bonn, M.; Levitov, L. S.; Koppens, F. H. L. Photoexcitation Cascade and Multiple Hot-Carrier Generation in Graphene. *Nat. Phys.* **2013**, *9*, 248-252.
11. Brida, D.; Tomadin, A.; Manzoni, C.; Kim, Y. J.; Lombardo, A.; Milana, S.; Nair, R. R.; Novoselov, K. S.; Ferrari, A. C.; Cerullo, G.; *et al.* Ultrafast Collinear Scattering and Carrier Multiplication in Graphene. *Nat. Commun.* **2013**, *4*, 1987.
12. Novoselov, K. S.; Geim, A. K.; Morozov, S. V.; Jiang, D.; Katsnelson, M. I.; Grigorieva, I. V.; Dubonos, S. V.; Firsov, A. A. Two-Dimensional Gas of Massless Dirac Fermions in Graphene. *Nature* **2005**, *438*, 197-200.
13. Zhang, Y.; Tan, Y.-W.; Stormer, H. L.; Kim, P. Experimental Observation of the Quantum Hall Effect and Berry's Phase in Graphene. *Nature* **2005**, *438*, 201-204.
14. Pospischil, A.; Humer, M.; Furchi, M. M.; Bachmann, D.; Guider, R.; Fromherz, T.; Mueller, T. CMOS-Compatible Graphene Photodetector Covering All Optical Communication Bands. *Nat. Photon.* **2013**, *7*, 892-896.
15. Park, J.; Ahn, Y. H.; Ruiz-Vargas, C. Imaging of Photocurrent Generation and Collection in Single-Layer Graphene. *Nano Lett.* **2009**, *9*, 1742-1746.
16. Xu, X.; Gabor, N. M.; Alden, J. S.; van der Zande, A. M.; McEuen, P. L. Photo-Thermoelectric Effect at a Graphene Interface Junction. *Nano Lett.* **2009**, *10*, 562-566.
17. Wang, F.; Zhang, Y.; Tian, C.; Girit, C.; Zettl, A.; Crommie, M.; Shen, Y. R. Gate-Variable Optical Transitions in Graphene. *Science* **2008**, *320*, 206-209.
18. Gabor, N. M.; Song, J. C. W.; Ma, Q.; Nair, N. L.; Taychatanapat, T.; Watanabe, K.; Taniguchi, T.; Levitov, L. S.; Jarillo-Herrero, P. Hot Carrier-Assisted Intrinsic Photoresponse in Graphene. *Science* **2011**, *334*, 648-652.
19. Lemme, M. C.; Koppens, F. H. L.; Falk, A. L.; Rudner, M. S.; Park, H.; Levitov, L. S.; Marcus, C. M. Gate-Activated Photoresponse in a Graphene p-n Junction. *Nano Lett.* **2011**, *11*, 4134-4137.
20. Yu, W. J.; Liu, Y.; Zhou, H.; Yin, A.; Li, Z.; Huang, Y.; Duan, X. Highly Efficient Gate-Tunable Photocurrent Generation in Vertical Heterostructures of Layered Materials. *Nat. Nanotech.* **2013**, *8*, 952-958.
21. Britnell, L.; Ribeiro, R. M.; Eckmann, A.; Jalil, R.; Belle, B. D.; Mishchenko, A.; Kim, Y.-J.; Gorbachev, R. V.; Georgiou, T.; Morozov, S. V.; *et al.* Strong Light-Matter Interactions in Heterostructures of Atomically Thin Films. *Science* **2013**, *340*, 1311-1314.
22. Giovannetti, G. a. K., P. A. and Brocks, G. and Karpan, V. M. and van den Brink, J. and Kelly, P. J. Doping Graphene with Metal Contacts. *Phys. Rev. Lett.* **2008**, *101*, 026803.
23. Pi, K.; McCreary, K. M.; Bao, W.; Han, W.; Chiang, Y. F.; Li, Y.; Tsai, S. W.; Lau, C. N.; Kawakami, R. K. Electronic Doping and Scattering by Transition Metals on Graphene. *Phys. Rev. B* **2009**, *80*, 075406.
24. Chen, J.-J.; Meng, J.; Zhou, Y.-B.; Wu, H.-C.; Bie, Y.-Q.; Liao, Z.-M.; Yu, D.-P. Layer-by-Layer Assembly of Vertically Conducting Graphene Devices. *Nat. Commun.* **2013**, *4*, 1921.
25. Sun, D.; Divin, C.; Berger, C.; de Heer, W. A.; First, P. N.; Norris, T. B. Spectroscopic Measurement of Interlayer Screening in Multilayer Epitaxial Graphene. *Phys. Rev. Lett.* **2010**, *104*, 136802.

26. Mueller, T.; Xia, F.; Freitag, M.; Tsang, J.; Avouris, P. Role of Contacts in Graphene Transistors: A Scanning Photocurrent Study. *Phys. Rev. B* **2009**, *79*, 245430.
27. Mak, K. F.; Matthew, Y. S.; Wu, Y.; Lui, C. H.; Misewich, J. A.; Heinz, T. F. Measurement of the Optical Conductivity of Graphene. *Phys. Rev. Lett.* **2008**, *101*, 196405.
28. Mak, K. F.; Shan, J.; Heinz, T. F. Seeing Many-Body Effects in Single- and Few-Layer Graphene: Observation of Two-Dimensional Saddle-Point Excitons. *Phys. Rev. Lett.* **2011**, *106*, 046401.
29. Mak, K. F.; Ju, L.; Wang, F.; Heinz, T. F. Optical Spectroscopy of Graphene: from the Far Infrared to the Ultraviolet. *Solid State Communications* **2012**, *152*, 1341.
30. Winzer, T.; Malic, E. Impact of Auger Processes on Carrier Dynamics in Graphene. *Phys. Rev. B* **2012**, *85*, 241404.
31. Basko, D. M. Effect of Anisotropic Band Curvature on Carrier Multiplication in Graphene. *Phys. Rev. B* **2013**, *87*, 165437.
32. Plotzing, T.; Winzer, T.; Malic, E.; Neumaier, D.; Knorr, A.; Kurtz, H. Experimental Verification of Carrier Multiplication in Graphene. *Nano Lett.* **2014**, *14*, 5371-5375.
33. Winzer, T.; Knorr, A.; Malic, E. Carrier Multiplication in Graphene. *Nano Lett.* **2010**, *10*, 4839-4843.
34. Tielrooij, K. J.; Piakowski, L.; Massicotte, M.; Woessner, A.; Ma, Q.; Lee, Y.; Myhro, S.; Lau, C. N.; Jarillo-Herrero, P.; van Hulst, N. F.; *et al.* Generation of Photovoltage in Graphene on a Femtosecond Timescale through Efficient Carrier Heating. *Nat. Nanotech.* **2015**, *10*, 437-443.
35. Gierz, I.; Petersen, J. C.; Mitrano, M.; Cacho, C.; Turcu, I. C. E.; Springate, E.; Stohr, A.; Kohler, A.; Starke, U.; Cavalleri, A. Snapshots of Non-Equilibrium Dirac Carrier Distributions in Graphene. *Nat. Mater.* **2013**, *12*, 1119-1124.
36. Wu, H.; Kong, D.; Ruan, Z.; Hsu, P.-C.; Wang, S.; Yu, Z.; Carney, T. J.; Hu, L.; Fan, S.; Cui, Y. A Transparent Electrode Based on a Metal Nanotrough Network. *Nat. Nanotech.* **2013**, *8*, 421-425.
37. Bie, Y.-Q.; Zhou, Y.-B.; Liao, Z.-M.; Yan, K.; Liu, S.; Zhao, Q.; Kumar, S.; Wu, H.-C.; Duesberg, G. S.; Cross, G. L. W.; *et al.* Site-Specific Transfer-Printing of Individual Graphene Microscale Patterns to Arbitrary Surfaces. *Adv. Mater.* **2011**, *23*, 3938-3943.

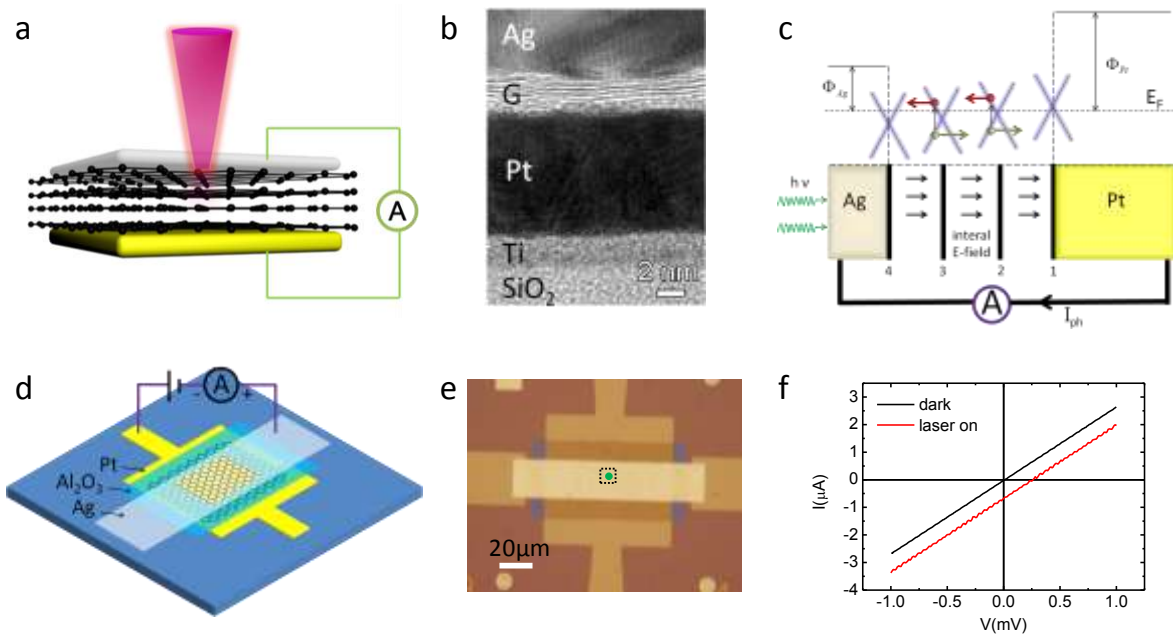


Figure 1 | Structure and mechanism of the vertical Ag-stacked graphene layers-Pt photovoltaic cell. **a**, Schematic of the vertical device. **b**, Cross-section HRTEM image of the Ag-SFLG-Pt junction. **c**, Schematic band diagram of the vertical structure. Red and green spots represent photoexcited electrons and holes, respectively, and the corresponding arrows indicate the transport directions. Φ_{Ag} and Φ_{Pt} are the work function of Ag and Pt, respectively. I_{ph} is the photocurrent. The four graphene layers are denoted by the numbers “1, 2, 3, 4”, and the black arrows present the built-in electric field. **d**, Sketch of the measurement configuration of a vertical Ag-SFLG-Pt device. **e**, Optical image of a typical device. The dashed box denotes the Ag-SFLG-Pt junction with an area of $\sim 10 \mu\text{m} \times 10 \mu\text{m}$, and the green dot indicates the focused laser spot. **f**, I–V characteristics recorded in the dark and under laser irradiation.

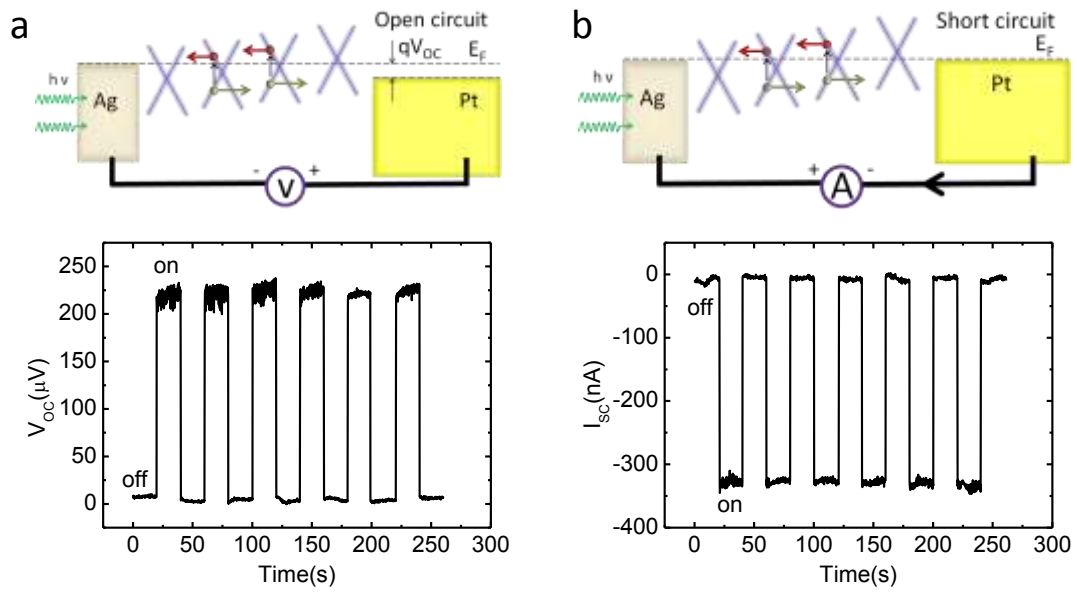


Figure 2 | Performances of vertical Ag-SFLG-Pt device. The photoelectrical properties were measured under laser irradiation with 514 nm wavelength. (a) The mechanisms of the photogenerated open-circuit voltage (V_{OC} , upper panel) and the V_{OC} outputs under on-off light modulation (lower panel). (b) The mechanisms of the photogenerated short-circuit current (I_{SC} , upper panel) and the I_{SC} outputs under on-off light modulation (lower panel).

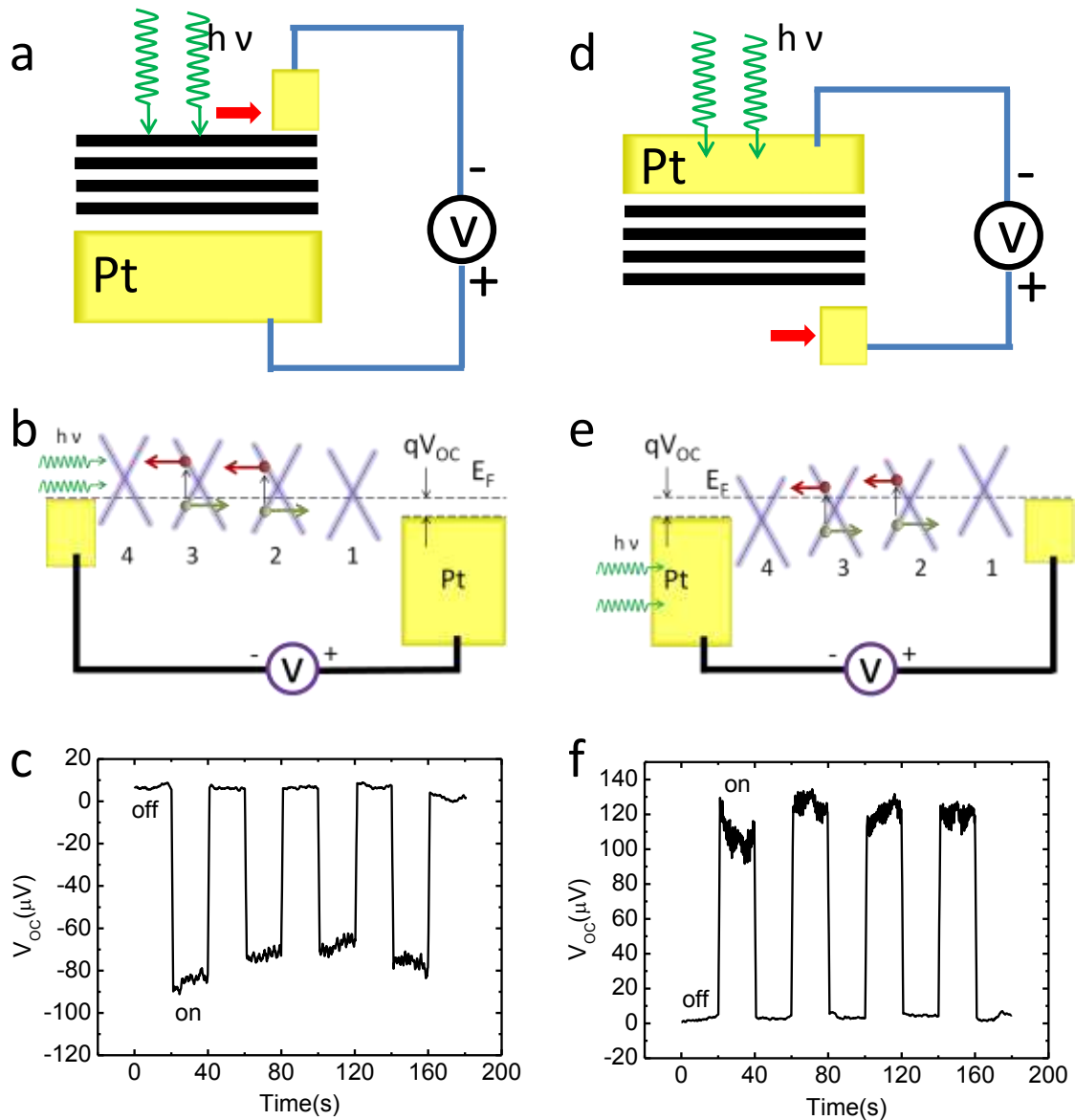


Figure 3 | The role of interface on the photovoltage generation. Structures, mechanisms and photovoltages of two devices with graphene/bottom Pt interface, top Pt/graphene interface. (a) (b) (c) Structure, mechanism and photovoltage of the device with graphene/bottom Pt interface, respectively. (d) (e) (f) Structure, mechanism and photovoltage of the device with top Pt/graphene interface, respectively. The red arrows in (a) and (d) indicate that carriers away from the electrode must diffuse laterally to the electrode to be collected.

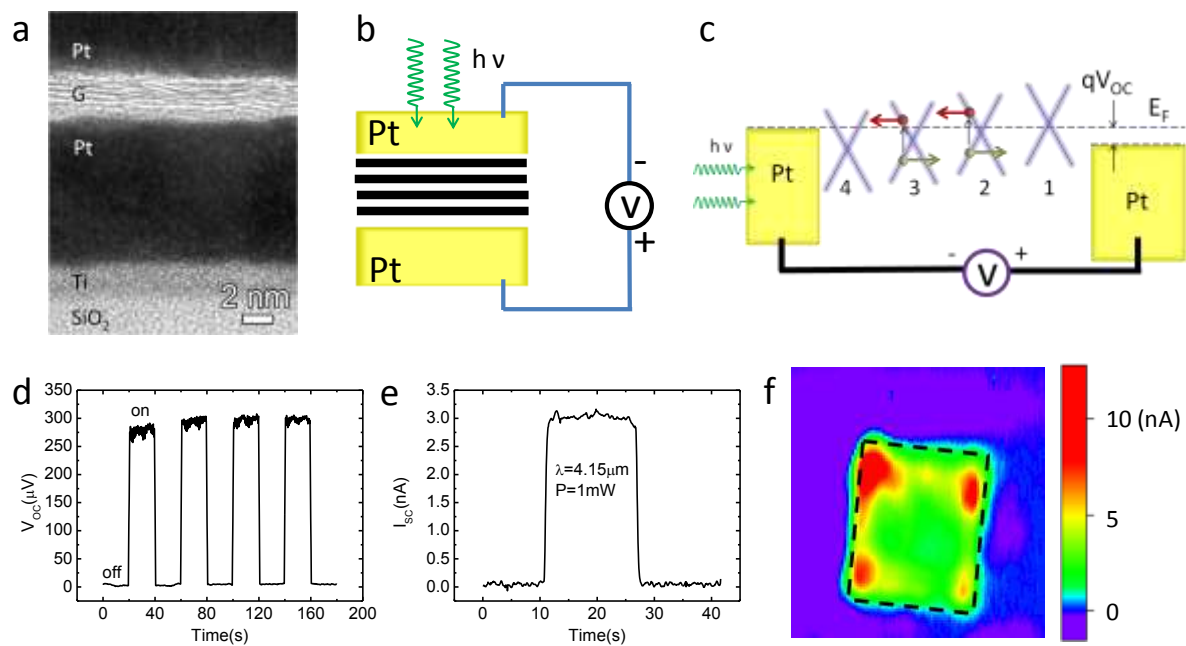


Figure 4 | Vertical Pt-four-stacked-graphene-Pt device. **a**, A cross-section TEM image of the Pt-SFLG-Pt junction. **b**, **c**, **d**, Measurement configuration, mechanism and photovoltage with excitation by a 514 nm laser, respectively. **e**, Photocurrent generation excited by a 4.15 μm laser. **f**, Scanning photocurrent mapping of the device under a 800 nm laser excitation.

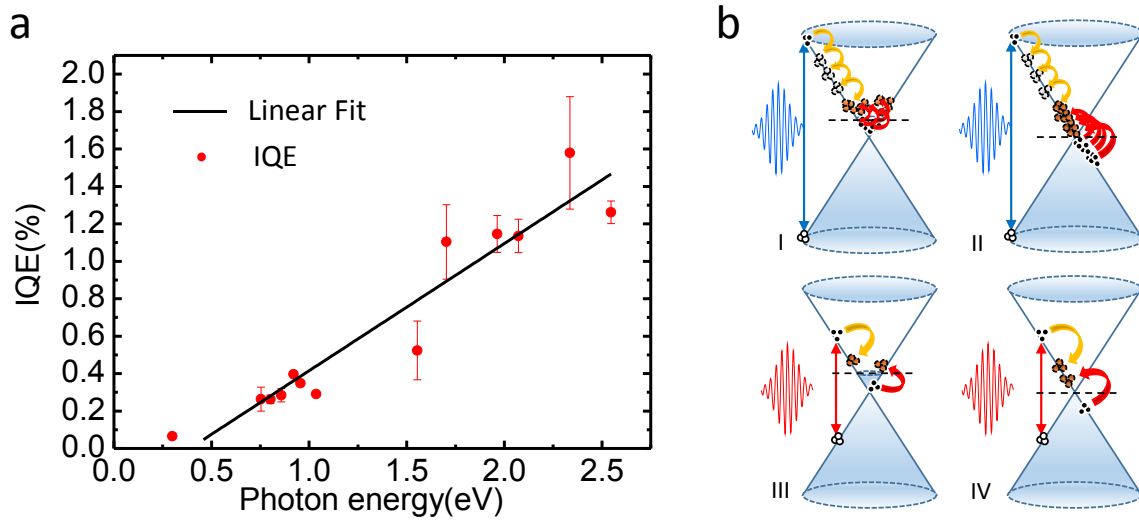


Figure 5 | Carrier multiplication effect in the Pt-SFLG-Pt device. **a**, Photon energy dependence of the internal quantum efficiency from 488 nm to 1650 nm, the excitation photon fluence on the device is kept around $10^{13}/\text{cm}^2$. The measured photon energy dependent IQE can be fit linearly. **b**, Illustration of the carrier multiplication process under different excitation photon energy in doped (I,III) and undoped graphene layers (II,IV). Yellow arrows show the cascade relaxation steps of photoexcited carriers. Red arrows show intraband impact excitation in doped layers and interband impact excitation in undoped layers. Higher photo excitation (I,II) can induce more steps of impact excitation cascade and thus result in larger internal quantum efficiency.

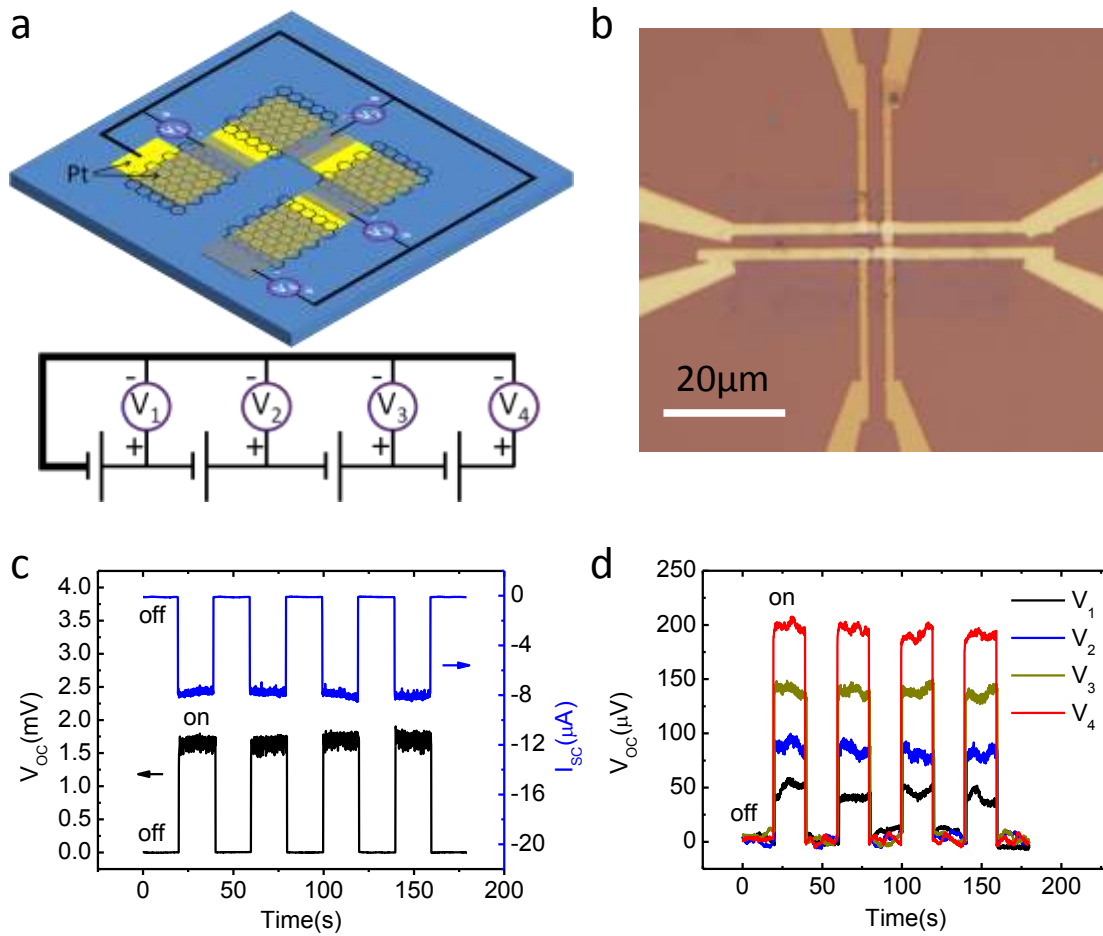


Figure 6 | Four individual cells connected in series. **a**, Schematic of a general device consisting of four individual Pt-SFLG-Pt cells. V_1 , V_2 , V_3 , V_4 measure the tandem cells with one, two, three and four individual cells connected in series, respectively. **b**, Optical image of a typical device composed by four Pt-SFLG-Pt cells. **c**, Photoreponse of a single Pt-SFLG-Pt cell under on-off light modulation of a 514-nm laser with an excitation power of ~ 3.79 mW. **d**, Photovoltage for the tandem cells with one (V_1), two (V_2), three (V_3) and four (V_4) individual cells connected in series, as the laser spot is expanded to cover all four individual cells with reduced power density.