

Electronic Supplementary Information

Graphene/semiconductor heterojunction solar cells with modulated antireflection and graphene work function

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1. Device and material modeling

In the main text, the circuit model and some important parameters have been simply demonstrated. It is necessary to show some detailed deductions and expressions that are indispensable in our model, and that is what this section is all about.

1.1 Device principle

The device schematic is shown in Fig. S1a. In the heterojunction, graphene film is coated conformally onto a patterned substrate to form heterojunction with the underlying semiconductor (e.g. Si, CdSe, CdTe, GaAs with band gaps of 1.0~2.5 eV). It is well known that any semiconductor can form a Schottky junction with a certain metal if the difference between their work functions ($\Phi_G - \Phi_S$) is large enough, and the carrier density of the semiconductor is moderate. As shown in the energy band diagram (Fig. S1b), our calculations indicate that graphene makes a Schottky junction with semiconductor, which is favorable for producing a relatively large built-in field $V_0(\Phi_G - \Phi_S)$ and charge separation. A space charge region is formed in the semiconductor near the interface. This indicates that the graphene film not only serves as a transparent electrode for light illumination, but also an active layer for electron/hole separation and hole transport.

Photovoltaic principle: i) light absorption by the semiconductor with appropriate band gaps produces photogenerated carriers (electron/hole pairs); ii) photogenerated holes (h^+) and electrons (e^-) are separated and accelerated by the built-in electric field (V_0); iii) the holes are driven into the graphene film and the electrons are driven into the semiconductor, respectively (bottom of Fig. S1a) to produce electricity.

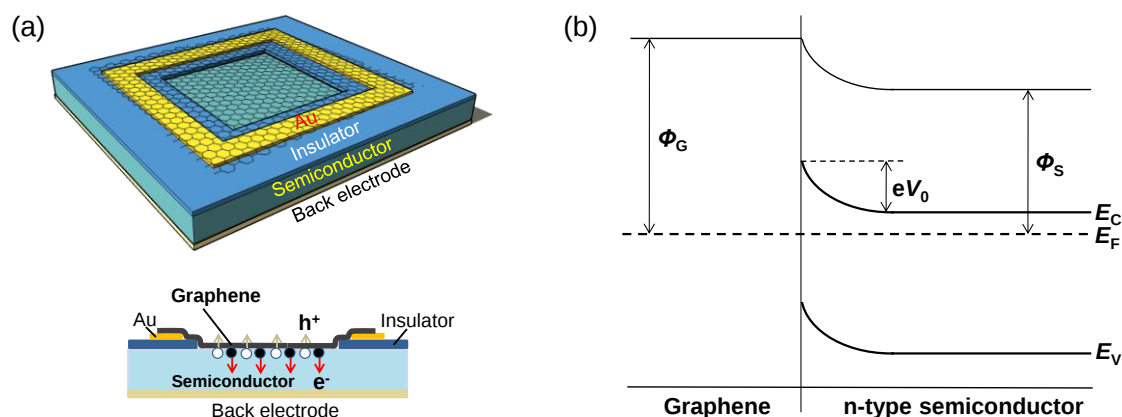


Figure S1 (a) Device schematic of graphene/semiconductor heterojunction. (b) Energy band diagram of graphene/semiconductor heterojunction

1.2 Schottky junction and solar cell parameters

The relation between the current density J and the applied voltage V of an ideal Schottky junction is given by

$$J = -J_{ph} + J_s \cdot (e^{V/nV_t} - 1) \quad (S1)$$

where n is the diode ideal factor, $V_t = k_B T / e$ is a constant related to temperature (k_B is the Boltzmann's constant, e is the elementary charge, and T is the temperature), J_{ph} is the light-generated current density, and J_s is the reverse saturation current density of the diode, given by

$$J_s = A^* T^2 \exp(-\Phi_{B0} / eV_t) \quad (S2)$$

where $A^* \equiv 4\pi e m_n^* k_B^2 / h^3$ is the Richardson constant; $\Phi_{B0} = \Phi_G - \chi$ is called the Schottky barrier height, with Φ_G and χ are the graphene work function and electron affinity of the semiconductor, respectively.

The light-generated current density is calculated using the continuity equations, which is shown later.

The Schottky junction solar cell efficiency can be expressed as

$$\eta = \frac{P_{\max}}{P_{\text{total}}} = \frac{(V I)_{\max}}{P_{\text{total}}} = FF \frac{V_{\text{OC}} I_{\text{SC}}}{P'} \frac{P'}{P_{\text{total}}} = FF \eta_{\text{ph}} T \quad (\text{S3})$$

where $P_{\max} = (V I)_{\max}$ is the maximum electric power per unit area that the device is able to provide; P_{total} is the total energy density of the incident light; FF is the fill factor, a measure of the “squareness” of the I - V curve, defined as

$$FF = \frac{(V I)_{\max}}{V_{\text{OC}} I_{\text{SC}}} \quad (\text{S4})$$

where V_{oc} is the open-circuit voltage, I_{sc} is the short-circuit current. η_{ph} is the photovoltaic transition efficiency, given by

$$\eta_{\text{ph}} = \frac{V_{\text{OC}} I_{\text{SC}}}{P'} \quad (\text{S5})$$

where P' represents the power of the light after passing through the graphene film.

In Eq. (S3), T is the transmittance of the air/graphene/semiconductor optical system, which is divided into two parts in our calculation: (i) T_{G} , which is the percentage of remaining light energy after absorption by the graphene film; (ii) $1-R$ (where R represents the reflectance of the optical system), which is the percentage of the light energy actually getting into the semiconductor considering the reflection loss of the optical system. Therefore,

$$T = T_{\text{G}} (1 - R) \quad (\text{S6})$$

1.3 Parasitic resistance

The series resistance R_{s} is composed of four parts

$$R_{\text{s}} = R_{\text{C-MG}} + R_{\text{C-MS}} + R_{\text{G}} + R_{\text{Sub}} \quad (\text{S7})$$

where R_{C-MG} is the contact resistance between the lead and the graphene, R_{C-MS} is the contact resistance between the semiconductor and the bottom electrode, and R_G and R_{Sub} represent the body resistance of the graphene and the semiconductor, respectively. Regular high-doped semiconductor maintains a negligible R_{Sub} (e.g., for silicon, if the doping concentration is 10^{15} cm^{-3} and the thickness is 0.5 mm, R_{Sub} is smaller than $0.1 \Omega \text{ cm}^2$). R_{C-MS} can be ignored as well if typical low-resistivity metal-Si contact such as Ti/Au or Ti/Pd/Ag is used [S1]. According to previous study, the metal-graphene contact resistivity is independent of metal work function [S2], applied vertical voltage, and the layer number of graphene [S3,S4]. Hence, R_{C-MG} is treated as a constant in our model. The expression of series resistance is thus simplified as

$$R_s = R_{C-MG} + R_G \quad (\text{S8})$$

The parallel resistance (R_p) reflects the leakage current of the junction due to the quantum tunnelling effect. In Ref. [S1], R_p is estimated to be $4.5 \text{ M}\Omega \cdot \text{cm}^2$, which, according to Fig. 1d, can be regarded as infinity.

1.4 Photo-generated current density, J_{ph}

The light-generated current density, J_{ph} , can be divided into two parts, $J_{ph} = J_{dif} + J_{dri}$, where J_{dif} and J_{dri} refer to the light-generated excess carrier's diffusion, due to the concentration gradients, and their drifting, due to the built-in electronic field near the Schottky junction, respectively. The n-Si area is consequently divided into two regions: i) the depletion area with constant built-in electric field, and ii) the uniform region (see Fig. S2). For simplicity, only the variation of the carrier density along the depth (set as the x direction) of the junction is considered, and we set the origin on the interface between graphene and semiconductor. The width of the depletion area is denoted by x_d , given by

$$x_d = \sqrt{\frac{2\epsilon_r\epsilon_0\Phi_{bi}}{eN_d}} \quad (S9)$$

where ϵ_0 and ϵ_r are vacuum permittivity and relative permittivity of the substrate, respectively, N_d is the dopant concentration, and Φ_{bi} is the built-in barrier.

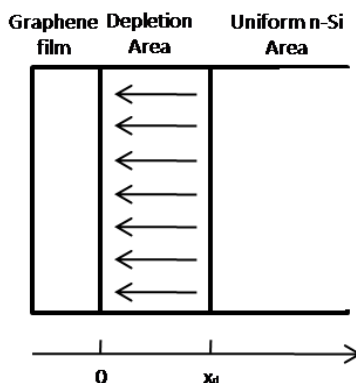


Figure S2 Diagram of the calculation region

We solve continuity equations to determine the current density,

$$\begin{cases} \frac{\partial n}{\partial t} = D_n \frac{\partial^2 n}{\partial x^2} + \mu_n E \frac{\partial n}{\partial x} + \mu_n n \frac{\partial E}{\partial x} - \frac{n - n_0}{\tau_n} + G_n(x) \\ \frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} + \mu_p E \frac{\partial p}{\partial x} + \mu_p p \frac{\partial E}{\partial x} - \frac{p - p_0}{\tau_p} + G_p(x) \end{cases} \quad (S10)$$

where n , p , n_0 , p_0 represent electron and hole actual and equilibrium concentration, respectively; μ_n , μ_p , D_n , D_p , τ_n , τ_p , G_n , G_p are electron's and hole's mobility, diffusion coefficient, carrier lifetime and carrier generation rate, respectively; E is the electric field intensity. We are now dealing with the steady-state conditions, or $\partial n/\partial t = \partial p/\partial t = 0$. In n-type semiconductor, we assume that $n \gg p$, and in such cases, only the latter equation concerning minority carriers would be considered. Regardless of any outer electric field in the uniform n-Si region, the equation is simplified as

$$D_p \frac{d^2 \Delta p_n}{dx^2} - \frac{\Delta p_n}{\tau_p} + G_p(x; \hbar\omega) = 0 \quad (S11)$$

with $\Delta p_n = p_n - p_{n0}$, called excess light-generated carrier density, and the photo-carrier generation rate G_p represented as

$$G_p(x; \hbar\omega) = -\eta_Q(\hbar\omega) \frac{dI(x; \hbar\omega)}{dx} \cdot \frac{e}{\hbar\omega} \quad (\text{S12})$$

where η_Q is the quantum efficiency, defined as the excess carrier number generated by every photon with a certain energy, and $I(x; \hbar\omega)$ the power density of incident light with a certain frequency ω at a certain depth x .

The incident light will be partly absorbed by silicon when passing through it, and under first-order approximation, such attenuated incident light power density can be described as an exponential expression, $I(x; \hbar\omega) = I'(\hbar\omega) \exp(\alpha \cdot x)$, with I' the power density of the light with a certain frequency at origin after transmitting through the graphene film, and $\alpha = \alpha(\hbar\omega)$, called absorption coefficient or absorptance, which reflects a certain material's capacity of absorbing light.

The generation rate is then given by

$$G_p(x; \hbar\omega) = \eta_Q(\hbar\omega) \frac{e\alpha}{\hbar\omega} \cdot I'(\hbar\omega) \quad (\text{S13})$$

In our calculation, the substrate is considered with infinite thickness, thus the boundary condition is quite simple:

$$\begin{cases} \Delta p_n = 0, \text{ when } x = x_d \\ \Delta p_n = 0, \text{ when } x \rightarrow \infty \end{cases} \quad (\text{S14})$$

By solving the continuity equation using the boundary conditions, we obtain

$$\Delta p_n(x; \hbar\omega) = \frac{e}{\hbar\omega} \frac{1}{D_p} \frac{\alpha I'}{\alpha^2 - L_p^{-2}} (e^{-\alpha x} - e^{-\alpha x_d} e^{-(x-x_d)/L_p}) \quad (\text{S15})$$

where L_p is called minority's diffusion length, given by

$$L_p = \sqrt{D_p \tau_p} \quad (\text{S16})$$

The excess minority carrier diffusion current density is proportional to the first derivation of Δp_n : $j_{dif} = -D_p (d \Delta p_n / dx)$, and at the interface between the uniform area and the depletion area,

$$j_{dif}(\hbar\omega) = j_{dif} \Big|_{x=x_d} = \frac{e}{\hbar\omega} \frac{\alpha I'}{\alpha^2 - L_p^{-2}} e^{-\alpha x_d} \quad (\text{S17})$$

The drifting current density is given, neglecting the recombination in the built-in field region, by

$$j_{dri}(\hbar\omega) = e \int_0^{x_d} \frac{1}{\hbar\omega} \left(-\frac{dI(x; \hbar\omega)}{dx} \right) dx = \frac{eI'}{\hbar\omega} (1 - e^{-\alpha x_d}) \quad (\text{S18})$$

Combining the diffusion and drifting current density together, we obtain

$$j_{ph}(\hbar\omega) = j_{dif} + j_{dri} = \frac{eI'}{\hbar\omega} \left(1 - \frac{1}{\alpha L_p + 1} e^{-\alpha x_d} \right) \quad (\text{S19})$$

If the incident light is a color-compound beam (as in the case of solar radiation), the total current density is then calculated by the integration of $j_{ph}(\hbar\omega)$ through the scope of incident photon energy,

$$J_{ph} = \int_{E_g}^{\infty} j_{ph}(\hbar\omega) d(\hbar\omega) \quad (\text{S20})$$

1.5 Band structure of N-layer graphene

A tight-binding Hamiltonian is constructed for N-layer graphene, according to B. Partoens, et al. [S5]:

$$H = \begin{bmatrix} \langle \Psi_{\vec{k}}^{A_1} | H | \Psi_{\vec{k}}^{A_1} \rangle & \langle \Psi_{\vec{k}}^{A_1} | H | \Psi_{\vec{k}}^{B_1} \rangle & \langle \Psi_{\vec{k}}^{A_1} | H | \Psi_{\vec{k}}^{A_2} \rangle & \cdots & \langle \Psi_{\vec{k}}^{A_1} | H | \Psi_{\vec{k}}^{B_N} \rangle \\ \langle \Psi_{\vec{k}}^{B_1} | H | \Psi_{\vec{k}}^{A_1} \rangle & \langle \Psi_{\vec{k}}^{B_1} | H | \Psi_{\vec{k}}^{B_1} \rangle & \langle \Psi_{\vec{k}}^{B_1} | H | \Psi_{\vec{k}}^{A_2} \rangle & \cdots & \langle \Psi_{\vec{k}}^{B_1} | H | \Psi_{\vec{k}}^{B_N} \rangle \\ \langle \Psi_{\vec{k}}^{A_2} | H | \Psi_{\vec{k}}^{A_1} \rangle & \langle \Psi_{\vec{k}}^{A_2} | H | \Psi_{\vec{k}}^{B_1} \rangle & \langle \Psi_{\vec{k}}^{A_2} | H | \Psi_{\vec{k}}^{A_2} \rangle & \cdots & \langle \Psi_{\vec{k}}^{A_2} | H | \Psi_{\vec{k}}^{B_N} \rangle \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \langle \Psi_{\vec{k}}^{B_N} | H | \Psi_{\vec{k}}^{A_1} \rangle & \langle \Psi_{\vec{k}}^{B_N} | H | \Psi_{\vec{k}}^{B_1} \rangle & \langle \Psi_{\vec{k}}^{B_N} | H | \Psi_{\vec{k}}^{A_2} \rangle & \cdots & \langle \Psi_{\vec{k}}^{B_N} | H | \Psi_{\vec{k}}^{B_N} \rangle \end{bmatrix} \quad (\text{S21})$$

In this model, only 6 interactions are considered: the interactions between nearest inplane A-B atoms (γ_0), between nearest-neighbor-plane A-A (γ_1), B-B (γ_2), and A-B (γ_3) atoms, and between next-nearest-neighbor-plane A-A (γ_4) and B-B (γ_5) atoms. The non-zero matrix elements are given by

$$\langle \Psi_{\vec{k}}^A | H | \Psi_{\vec{k}}^A \rangle = E_A \quad (\text{S22a})$$

$$\langle \Psi_{\vec{k}}^A | H | \Psi_{\vec{k}}^{B_i} \rangle = \begin{cases} \gamma_0 f(k_x, k_y) & \text{if } i \text{ is odd} \\ \gamma_0 f^*(k_x, k_y) & \text{if } i \text{ is even} \end{cases} \quad (\text{S22b})$$

$$\langle \Psi_{\vec{k}}^A | H | \Psi_{\vec{k}}^{A_{i+1}} \rangle = \gamma_1 \quad (\text{S22c})$$

$$\langle \Psi_{\vec{k}}^A | H | \Psi_{\vec{k}}^{B_{i+1}} \rangle = \begin{cases} \gamma_3 f^*(k_x, k_y) & \text{if } i \text{ is odd} \\ \gamma_3 f(k_x, k_y) & \text{if } i \text{ is even} \end{cases} \quad (\text{S22d})$$

$$\langle \Psi_{\vec{k}}^A | H | \Psi_{\vec{k}}^{A_{i+2}} \rangle = \gamma_4 \quad (\text{S22e})$$

$$\langle \Psi_{\vec{k}}^{B_i} | H | \Psi_{\vec{k}}^{B_i} \rangle = E_B \quad (\text{S22f})$$

$$\langle \Psi_{\vec{k}}^{B_i} | H | \Psi_{\vec{k}}^{A_{i+1}} \rangle = \langle \Psi_{\vec{k}}^A | H | \Psi_{\vec{k}}^{B_{i+1}} \rangle \quad (\text{S22g})$$

$$\langle \Psi_{\vec{k}}^{B_i} | H | \Psi_{\vec{k}}^{B_{i+1}} \rangle = \begin{cases} \gamma_2 f(k_x, k_y) & \text{if } i \text{ is odd} \\ \gamma_2 f^*(k_x, k_y) & \text{if } i \text{ is even} \end{cases} \quad (\text{S22h})$$

$$\langle \Psi_{\vec{k}}^{B_i} | H | \Psi_{\vec{k}}^{B_{i+2}} \rangle = \gamma_5 \quad (\text{S22i})$$

The function $f(k_x, k_y)$ is given by

$$f(k_x, k_y) = \exp(ik_x a) + 2 \exp(-ik_x a / 2) \cos(k_y a / 2) \quad (\text{S23})$$

where $a = 1.42 \text{ \AA}$ is the in-plane lattice constant of graphene. The values for all the tight-binding parameters are listed below:

Table S1. Parameters used in the tight-binding model [S5]

Parameter	E_A	E_B	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5
Value	0 when $N=1$ 0.01 when $N \neq 1$	0 when $N=1$ -0.206 when $N \neq 1$	3.12	0.377	0.29	-0.120	0.0125	-0.0103

The eigenvalues of the Hamiltonian in different places of k space make up the $E-k$ relations, and the $E-k$ relations of mono-, bi-, and tri-layer graphene are plotted in Fig. S3.

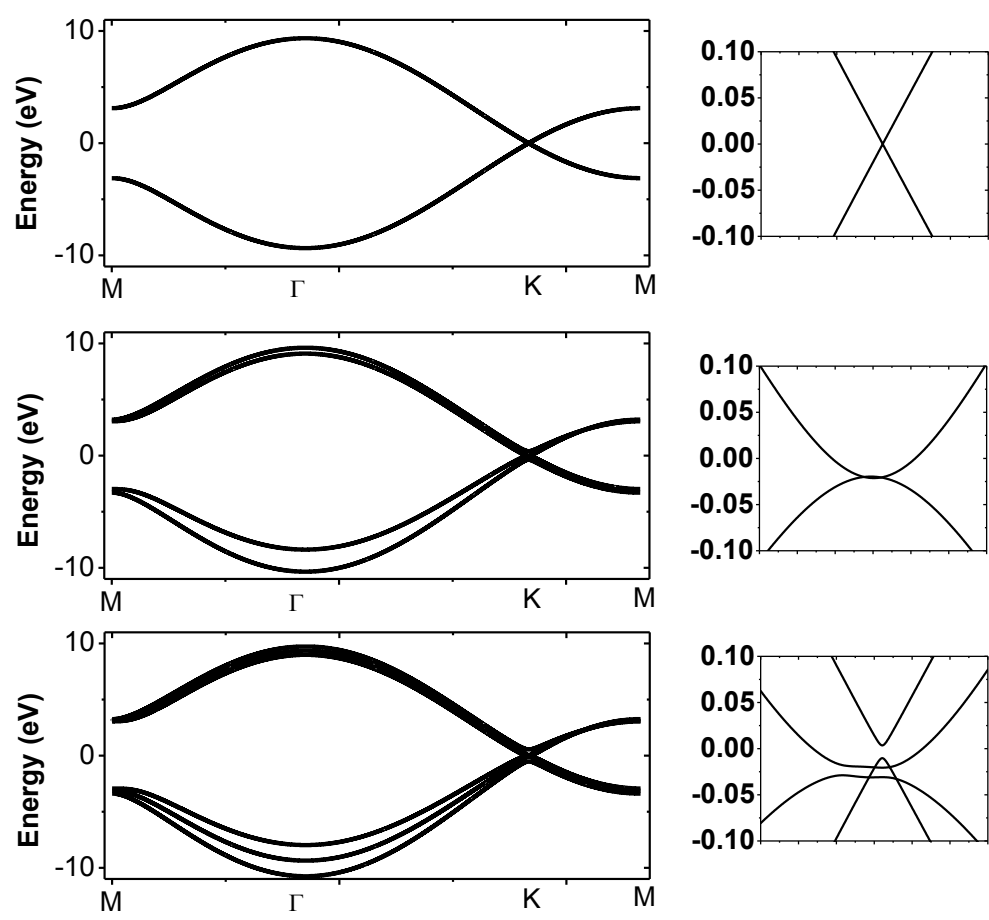


Figure S3 $E-k$ relations of mono-, bi-, and tri-layer graphene. On the right are the amplified corresponding plots near the Dirac point.

1.6 Electric properties of graphene

The carrier state density ρ_{gr} as a function of energy can be calculated from the dispersion relation

derived above using the following equation:

$$\rho_{gr}(E) dE = \int \frac{2}{(2\pi)^2} d^3 \mathbf{k} = \left(\frac{1}{2\pi^2} \int_{\text{constant energy surface}} \frac{1}{|\nabla_{\mathbf{k}} E|} d^2 \mathbf{k} \right) dE \quad (\text{S24})$$

where $2/(2\pi)^2$ is the carrier state density in the 2-dimensional $\mathbf{k}$ -space. The integration should be done within the constant energy surface.

The electron and hole density (N_e and N_h) are obtained by integrating the multiplication of Fermi–Dirac distribution $f_F(E) = (1 + \exp[(E - E_F)/kT])^{-1}$, and the state sheet density of carriers in graphene, and can be expressed as follows:

$$N_e = \int_0^\infty \rho_{gr}(E) f_F(E) dE \quad (\text{S25})$$

$$N_h = \int_0^\infty \rho_{gr}(E) (1 - f_F(E)) dE \quad (\text{S26})$$

The sheet resistance of graphene is given by

$$R_{sh} = \frac{1}{e(\mu_e N_e + \mu_h N_h)} \quad (\text{S27})$$

where μ_e and μ_h are the mobility of electron and hole in graphene, respectively; N_e and N_h are electron and hole density, respectively

1.7 Optical properties of graphene

The optical response of graphene is described by the classic electromagnetic field theory, and the transmittance is expressed as

$$T_G = \left[\sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \frac{4(\varepsilon_1 \varepsilon_0)^2}{(\sqrt{\varepsilon_1 \varepsilon_2} + \varepsilon_1) \varepsilon_0 + \sqrt{\varepsilon_1} \sigma(\omega) / c} \right]^N \quad (\text{S28})$$

where ε_0 , ε_1 , ε_2 represent the permittivity of vacuum, graphene, and the substrate, respectively; $\sigma(\omega)$ is the conductivity of graphene; c is the light velocity; N is the layer number of graphene. The conductivity of graphene is obtained according to Kubo formula, given by

$$\sigma_{xx}(\omega) = \frac{\langle j_x^D \rangle}{iA_s(\omega + i0^+)} + \frac{\Lambda_{xx}(\omega + i0^+)}{i\hbar A_s(\omega + i0^+)} \quad (S29)$$

Detailed discussion and deduction have been reported in Ref. [S6]

1.8 Reflectance of air/graphene/silicon system

According to Ref. [S7], the effective amplitude reflection coefficient $\tilde{r}_{i,i+1}$ of layered planar system can be calculated by

$$\tilde{r}_{i,i+1} = \frac{r_{i,i+1} + \tilde{r}_{i+1,i+2} e^{2jk_{i+1,z} d_{i+1} - d_i}}{1 + r_{i,i+1} \tilde{r}_{i+1,i+2} e^{2jk_{i+1,z} d_{i+1} - d_i}} \quad (S30)$$

where $r_{i,i+1}$ is the amplitude reflection coefficient of the interface between the i th and $(i+1)$ th layer, given by

$$\begin{cases} r_{i,i+1}^{TM} = \frac{\varepsilon_{i+1}k_{i,z} - \varepsilon_i k_{i+1,z}}{\varepsilon_{i+1}k_{i,z} + \varepsilon_i k_{i+1,z}}, & \text{for TM mode} \\ r_{i,i+1}^{TE} = \frac{\mu_{i+1}k_{i,z} - \mu_i k_{i+1,z}}{\mu_{i+1}k_{i,z} + \mu_i k_{i+1,z}}, & \text{for TE mode} \end{cases} \quad (S31)$$

where ε_i , μ_i are the relative permittivity and permeability of the i th layer, and $k_{i,z}$ is the wave vector component of light perpendicular to the layer interface(s) in the i th layer. The energy reflectance is the square of the amplitude of $\tilde{r}_{i,i+1}$, given by

$$R = |\tilde{r}|^2 \quad (S32)$$

The silicon-pillar-array AR film, if any, is treated as a plane-stratified film with various

equivalent refraction indices toward the direction of the thickness [S8], and the effective refraction index of each layer is given by

$$n(z) = [f(z)\tilde{n}_{si}^q + (1-f(z))n_{air}^q]^{1/q} \quad (S33)$$

where $f(z)$ is the geometrical fraction of silicon, and q is called the effective coefficient (in our calculation, $q=2/3$).

2. Simulation results

2.1 Comparison of calculation results to experiments

We compare our simulation results to the experiment data reported in Ref. [S1], and they are fitted with each other very well. Fig. 1(d) has shown the J - V curve matching, and more tests have been conducted, as concluded in Fig. S4.

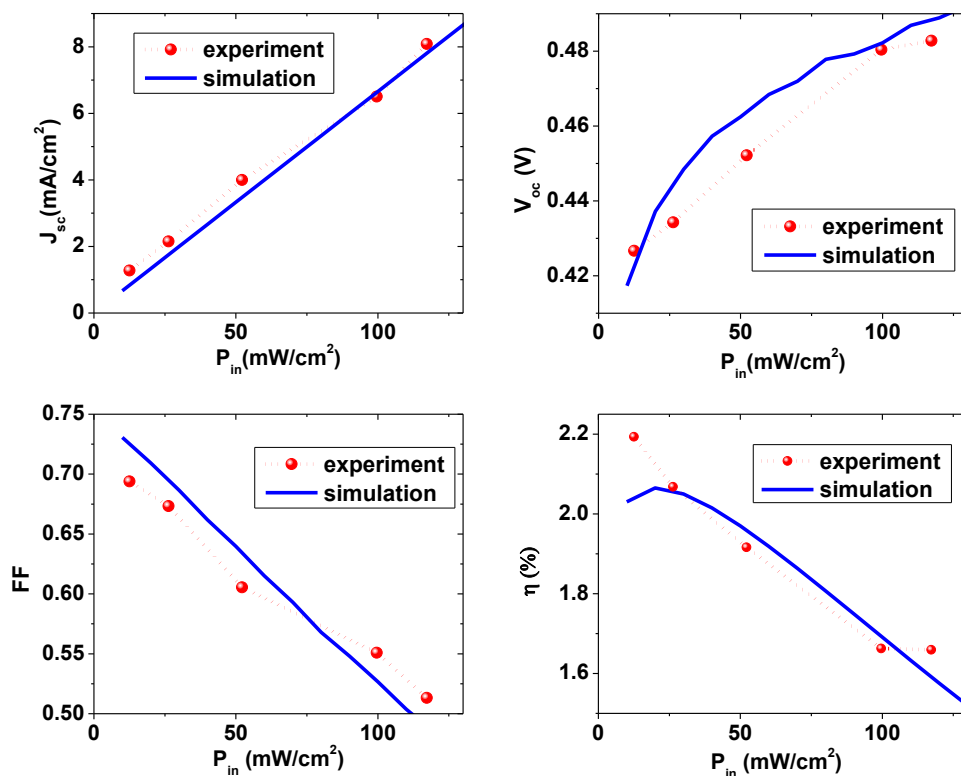


Figure S4 Simulated light-intensity (P_{in}) dependent J_{sc} , V_{oc} , FF , and η plots in comparison with experiments.

The sheet resistance R_s and diode ideality factor n (shown in Fig. 1(d)) is not the same as shown in Ref. [S1], whereas our values fit the J - V curves better than those given in Ref. [S1], so there may be some extraction error in their results.

The reverse saturation current density J_s is found to deviate from ideal Schottky junction expressions

$$J_s = A^* T^2 e^{-\Phi_{B0}/eV_t} \quad (\text{S34})$$

where $A^* \equiv 4\pi m_n^* k_B^2 / h^3$ is the Richardson constant. The reason is mainly because of the deviation of either the Richardson constant or the Schottky barrier, while the relative changes of the Schottky barrier might be more accurate. Therefore, we rewrite J_s as

$$J_s = J_{s0} e^{-\Delta\Phi_{B0}/eV_t} \quad (\text{S35})$$

where J_{s0} is also extracted from experiment.

2.2 The influence of some semiconductor parameters on the device performance

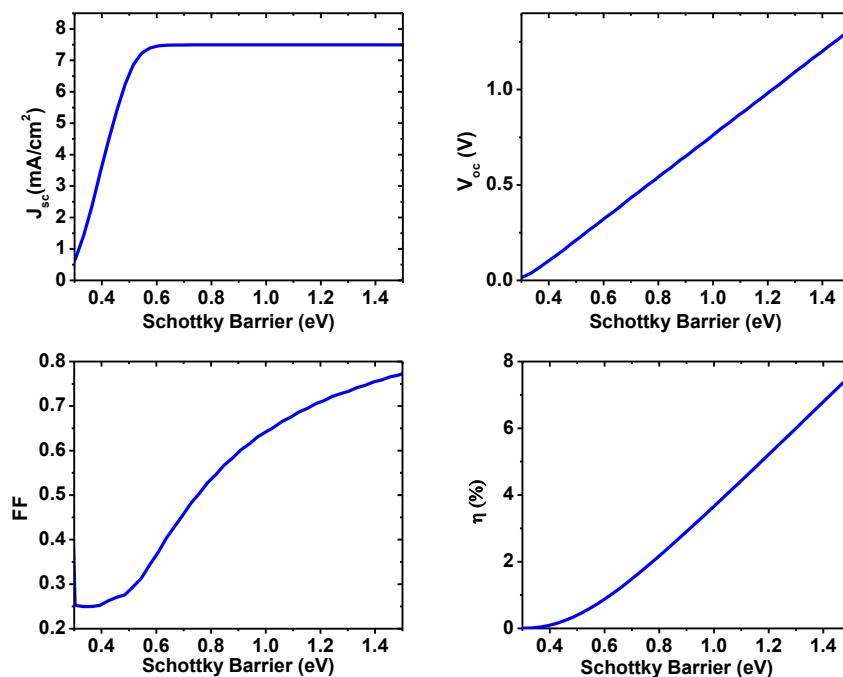


Figure S5 Simulated Schottky barrier (Φ_{B0}) dependent J_{sc} , V_{oc} , FF , and η .

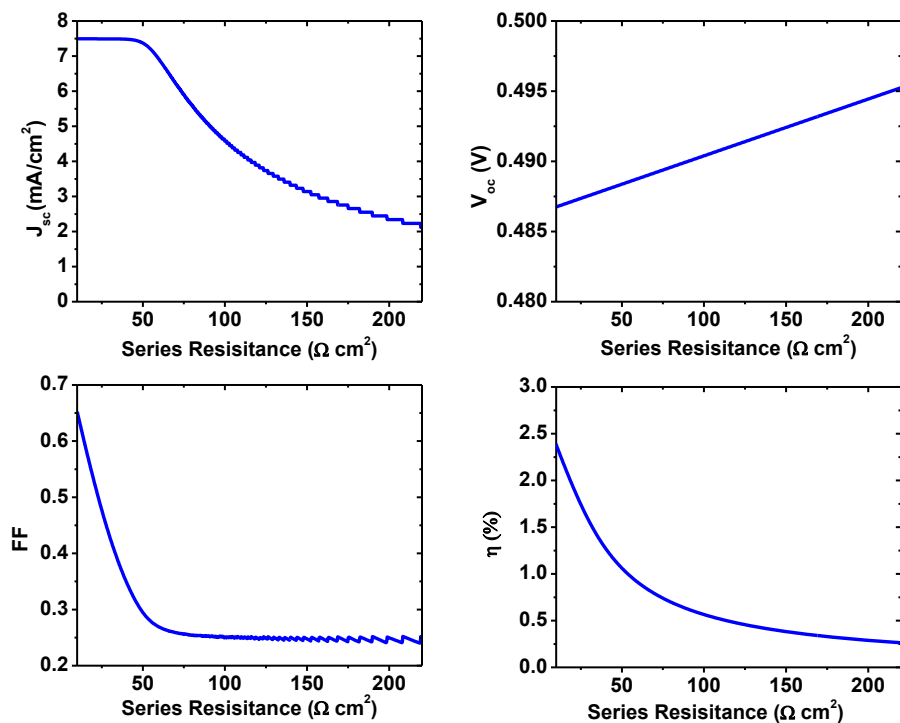


Figure S6 Simulated series resistance (R_s) dependent J_{sc} , V_{oc} , FF , and η .

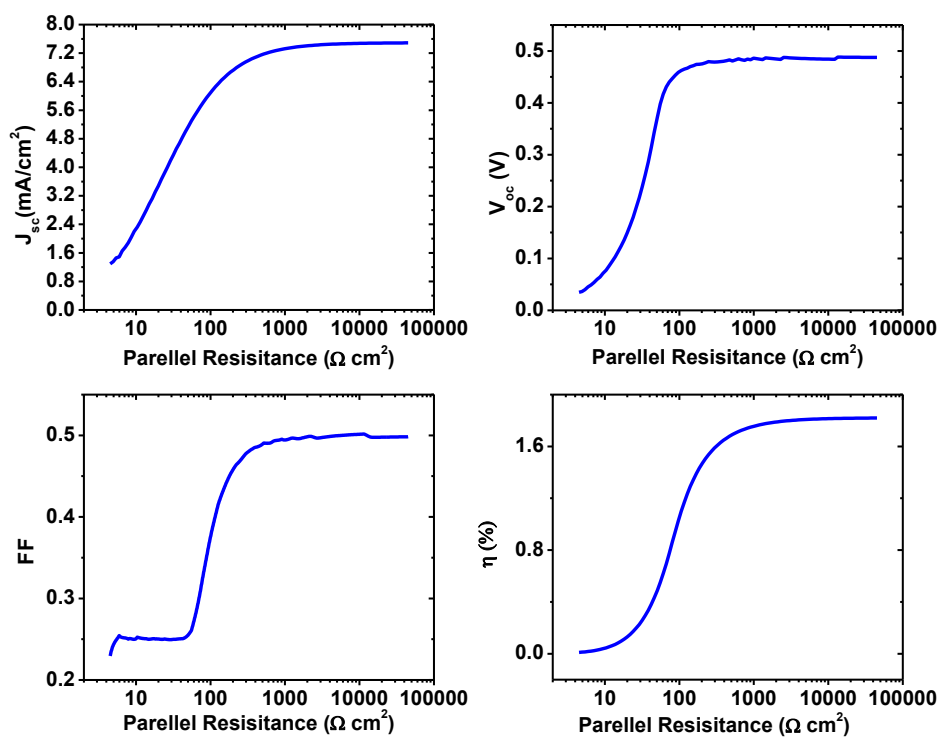


Figure S7 Simulated parallel resistance (R_p) dependent J_{sc} , V_{oc} , FF , and η .

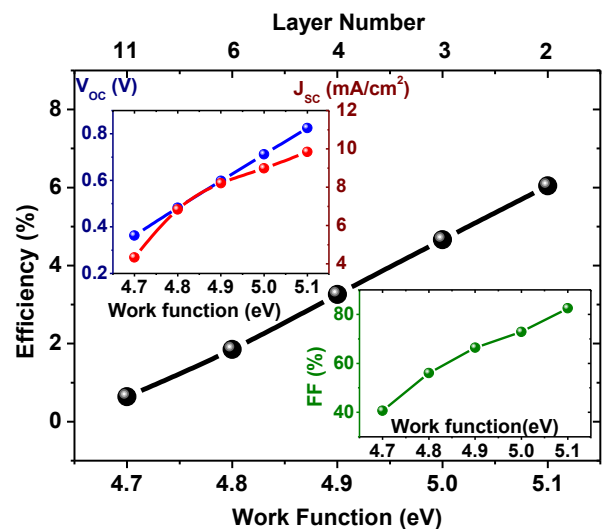


Figure S8 Simulated J_{sc} , V_{oc} , FF , and η along the optimal line in Fig. 3(a).

3. Parameters used in the theoretical model

Table S2. Parameters used in the theoretical model

Parameter	Value	Description
T (K)	300	Temperature
V_t (V)	0.026	The thermal voltage, calculated by $V_t=k_B T/e$
n	Extracted from experiment	The ideality factor of the Schottky junction
J_{s0} (mA·cm ⁻²)	Extracted from experiment	The reverse saturation current density constant
χ (eV)	4.05	The electron affinity of silicon
Φ_G (eV)	4.7~5.1	The work function of graphene
η_Q	Ref. [S1]	The internal quantum efficiency
α (cm ⁻¹)	Ref. [S9]	The absorption coefficient of silicon
E_g (eV)	1.12	The band gap energy of silicon
μ_p (cm ² V ⁻¹ s ⁻¹)	480	Hole mobility of silicon
μ_n (cm ² V ⁻¹ s ⁻¹)	1350	Electron mobility of silicon
τ_p (s)	5E-4	Lifetime of the minority carrier (Hole)

n_0 (cm ⁻³)	1.5E10	Intrinsic carrier concentration of silicon
N_d (cm ⁻³)	2.2E15	Doping concentration of silicon
N_c (cm ⁻³)	2.82E25	Equivalent concentration of conduction band of silicon
ϵ_r	11.9	Relative dielectric constant of silicon
P_{total} (mW/cm ²)	100	Total power density of incident light

4. Application: graphene/Si-pillar-array device as a light sensor.

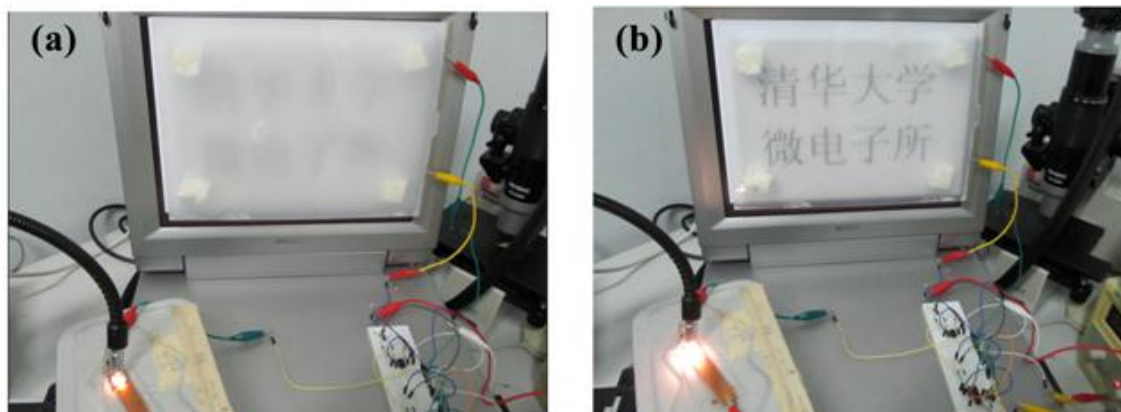


Figure S9. Demonstration of the graphene/Si-pillar-array device as a light sensor. The solar device is connected to a signal amplifier circuit to drive a liquid crystal display screen, which is transparent under high voltage, and opaque under low voltage. (a) The screen is opaque when the illumination is weak; (b) The screen becomes transparent when the illumination is strong.

References

- (S1)Xi. Li, H. Zhu, K. Wang, A. Cao, J. Wei, C. Li, Y. Jia, Z. Li, and D. Wu, *Adv. Mater.* 22, 2743 (2010).
- (S2)Venugopal, A.; Pirkle, A.; Wallace, R. M.; Colombo, L.; Vogel, E. M. Contact resistance studies of metal on HOPG and graphene stacks. In *International Conference on Frontiers of Characterization and Metrology for Nanoelectronics*2009, 1173, 324-327.
- (S3)Venugopal, A.; Colombo, L.; Vogel, E. M. Contact resistance in few and multilayer graphene devices. *Appl. Phys. Lett.* 2010, 96, 013512.
- (S4)Russo, S.; Craciun, M. F.; Yamamoto, M.; Moropurgo, A. F.; Tarucha, S. Contact resistance in graphene-based devices. *Physica E* 2010, 42, 677-679.
- (S5)B. Bartoens, and F. M. Peeters, *Phys. Rev. B* 74, 075404 (2006).

- (S6) T. Stauber, N. M. R. Peres, and A. K. Geim, *Phys. Rev. B* 78, 085432 (2008).
- (S7) W. C. Chew, *Waves and Fields in Inhomogeneous Media*; Wiley – IEEE Press, 1999.
- (S8) C.-H. Sun, P. Jiang, and B. Jiang, *Appl. Phys. Lett.* 92, 061112 (2008).
- (S9) D. E. Aspnes, and A. A. Studna, *Phys. Rev. B* 27, 985-1009 (1983).

References cited in Figure 6:

Graphene-based Organic Photovoltaic Devices:

- (S10) Q. Liu, Z. Liu, X. Zhang, L. Yang, N. Zhang, G. Pan, S. Yin, Y. Chen, and J. Wei, *Adv. Funct. Mater.* 19, 894 (2009).
- (S11) H. Park, J. A. Rowehl, K. K. Kim, V. Bulovic, and J. Kong, *Nanotechnology*, 21, 505204 (2010).
- (S12) X. Wang, L. Zhi, N. Tsao, Z. Tomovic, J. Li, and K. Mullen, *Angew. Chem. Int. Ed.*, 47, 2990 (2008).
- (S13) Q. Liu, Z. Liu, X. Zhang, N. Zhang, L. Yang, S. Yin, and Y. Chen, *Appl. Phys. Lett.*, 92, 223303 (2008).
- (S14) Y. Wang, X. Chen, Y. Zhong, F. Zhu, and K. P. Loh, *Appl. Phys. Lett.* 95, 063302 (2009).
- (S15) Y. Gao, H.-L. Yip, S. K. Hau, K. M. O'Malley, N. C. Cho, H. Chen, and A. K.-Y. Jen, *Appl. Phys. Lett.* 97, 203306 (2010).
- (S16) G. Jo, S.-I. Na, S.-H. Oh, S. Lee, T.-S. Kim, G. Wang, M. Choe, W. Park, J. Yoon, D.-Y. Kim, Y. H. Kahng, and T. Lee, *Appl. Phys. Lett.* 97, 213301 (2010).
- (S17) M. Cox, A. Gorondetsky, B. Kim, K. S. Kim, Z. Jia, P. Kim, C. Nuckolls, and I. Kymissis, *Appl. Phys. Lett.* 98, 123303 (2011).

- (S18) L. Valentini, M. Cardinli, S. B. Bon, D. Bagins, R. Verdejo, M. A. Lopez-Manchado, and J. M. Kenny, *J. Mater. Chem.*, 20, 995 (2010).
- (S19) M. Choe, B. H. Lee, G. Jo, J. Park, W. Park, S. Lee, W.-K. Hong, M.-J. Seong, K. Lee, and T. Lee, *Organic Electron.* 11, 1864 (2010).
- (S20) G. Kalita, M. Matsushima, H. Uchida, K. Wakita, and M. Umeno, *J. Mater. Chem.*, 20, 9713 (2010).
- (S21) J. Wang, Y. Wang, D. He, Z. Liu, H. Wu, H. Wang, Y. Zhao, H. Zhang, and B. Yang, *Synthetic Metals*, 160, 2494 (2010).
- (S22) D. Yu, K. Park, M. Durstock, L. Dai, *J. Phys. Chem. Lett.*, 2, 1113 (2011).
- (S23) S.-S. Li, K.-H. Tu, C.-C. Lin, C.-W. Chen, M. Chhowalla, *ASC Nano*, 4, 3169 (2010).
- (S24) D. Yu, Y. Yang, M. Durstock, J.-B. Baek, and L. Dai, *ACS Nano*, 4, 5633 (2010).
- (S25) L. G. De Arco, Y. Zhang, C. W. Schienker, K. Ryu, M. E. Thompson, and C. Zhou, *ACS Nano*, 4, 2865 (2010).
- (S26) Z. Yin, S. Sun, T. Salim, S. Wu, X. Huang, Q. He, Y. M. Lam, and H. Zhang, *ACS Nano*, 4, 5263 (2010).
- (S27) Z. Liu, D. He, Y. Wang, H. Wu and J. Wang, *Sol. Energy Mater. Sol. Cells*, 94, 1196 (2010).
- (S28) Y. Xu, G. Long, L. Huang, Y. Huang, X. Wan, Y. Ma, and Y. Chen, *Carbon*, 48, 3293 (2010).
- (S29) Z. Liu, D. He, Y. Wang, H. Wu, J. Wang, and H. Wang, *Sol. Energy Mater. Sol. Cells*, 94, 2148 (2010).

Graphene/CdS or CdSe Nanostructured Solar Cells:

- (S30) T. Dufaux, J. Boettcher, M. Burghard, and K. Kern, *Small*, 6, 1868 (2010).

- (S31) Y. Ye, Y. Dai, L. Dai, Z. Shi, N. Liu, F. Wang, L. Fu, R. Peng, X. Wen, Z. Chen, Z. Liu, and G. Qin, *ACS Appl. Mater. Interfaces*, 2, 3406 (2010).
- (S32) G. Zhu, T. Xu, T. Lv, L. Pan, Q. Zhao, and Z. Sun, *J. Electroanal. Chem.*, 650, 248 (2011).
- (S33) S. Sun, L. Gao, Y. Liu, and J. Sun, *Appl. Phys. Lett.*, 98, 093112 (2011).
- (S34) Y. Ye, L. Gan, L. Dai, Y. Dai, X. Guo, H. Meng, B. Yu, Z. Shi, K. Shang, and G. Qin, *Nanoscale*, 3, 1477 (2011).
- (S35) J. Chen, C. Li, G. Eda, Y. Zhang, W. Lei, M. Chhowalla, W. I. Milne, and W.-Q. Deng, *Chem. Commun.*, 47, 6084 (2011).

Graphene/Si Schottky Solar Cells:

- (S36) Y. Shi, K. K. Kim, A. Reina, M. Hofmann, L.-J. Li, and J. Kong, *ACS Nano* 4, 2690 (2010).
- (S37) K. Ihm, J. T. Lim, K.-J. Lee, J. W. Kwon, T.-H. Kang, S. Chung, S. Bae, J. H. Kim, B. H. Hong, and G. Y. Yeom, *Appl. Phys. Lett.* 97, 032113 (2010).
- (S38) The same as Ref. S1.