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Graphene–semiconductor heterojunction sheds light on emerging photovoltaics

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Electronic coupling of graphene atop a bulk semiconductor and the resultant interfacial energy-band reorganization create a light-sensitive junction only one atom below the front surface. Uniquely, this architecture leads to the surface being in extremely close proximity to the depletion region (typically buried several micrometres under the surface for a conventional wafer-based p–n junction solar cell), thus providing direct access to the photosensitive junction, which can be modified by surface functionalization and/or incorporation of plasmonic nanoparticles. The surface-based heterojunction, tunable carrier transport and relatively enhanced optical absorption in such 2D-layer-interfaced 3D semiconductor systems will have a transformative impact in the field of 2D optoelectronics, photovoltaics, photonics and nanoelectronics.

Two-dimensional crystals, such as graphene, are effectively 'surfaces' and exhibit superior electronic, mechanical and optical properties suitable for efficient photonic interactions in optoelectronic circuits. The contact of the basal plane of a graphene layer with a 3D semiconductor enables the origin of a 'surface junction' with an intrinsic driving potential to transport the electrons and holes across the 2D/3D junction (Fig. 1)[1]. Several unique functionalities of the 2D/3D device architecture have emerged over the past decade with a sustained focus on heterojunction photovoltaics and continued innovation in their surface/interfacial science, materials chemistry and device physics. Graphene or other optically transparent and active absorber 2D layers, including reduced graphene oxide, three-atom-thick semiconducting transition metal dichalcogenides and two-atom-thick phosphorene, are interfaced with direct- or indirect-bandgap 3D bulk semiconductors for photovoltaic phenomena. To establish the charge-transport mechanism and to amplify the performance efficiency of such 2D-on-3D photovoltaics, several routes have been employed, including (1) chemical doping or surface functionalization of 2D layers (to tune the chemical potential and work function), (2) interfacing metallic nanoparticles on the 2D surface junction (to plasmonically boost the photon absorption and the short-circuit current density (J_{SC})), (3) employing antireflection coating (ARC) layers (to optically manage the light absorption), (4) inclusion of hole-transporting insulating 2D layers (to increase the surface-junction barrier, and with it the open-circuit voltage (V_{OC})), and (5) interfacing graphene or other 2D materials with III–V compound semiconductors.

Low-dimensional *sp*^{2} carbon materials for solar cells

Functional 2D nanomaterials (2DNs) have shown great promise in optoelectronic applications[2], including photovoltaic solar cells, photosensors, photodiodes and photodetectors. Graphene, a *sp*^{2}-hybridized carbon monolayer, has been extensively investigated for photovoltaic energy conversion, owing to its robust in-plane intrinsic strength, high charge-carrier mobility and relatively high optical transparency. The graphene layer has been employed for different purposes in the various generations of photovoltaic technologies: (1) transparent conducting film for amorphous silicon (Si)-based[3] and indium gallium nitride (InGaN)-based solar cells[4], (2) active light-harvesting material for Si-based heterojunction photovoltaic cells[5], (3) counter cathode electrode for dye-molecule solar cells[6], (4) photoanode electrode for organic solar cells[7], and (5) high-performance hole-transporting material for hybrid organic–inorganic perovskite solar cells[8]. Broadly, the graphene film has dual functionality and is employed as a transparent conductor and as an atomically thin photoabsorber sheet in the photovoltaic cells. Currently, doped metal oxides, including indium tin oxide and fluorine-doped tin oxide transparent electrodes, are employed for charge injection or collection in thin-film solar cells. These transparent conductive oxide thin films are typically brittle (ceramic materials) and expensive (indium is scarcely available), which makes them unsustainable for optoelectronic or photonic devices. In contrast, low-dimensional *sp*^{2}-hybridized carbon nanostructures, including fullerenes, carbon nanotubes and graphene, have been utilized as optically transparent, electrically conductive and mechanically flexible electrodes in organic-, polymer–fullerene- and dye-molecule-sensitized (Grätzel cells)-based solar cells.

In this Perspective, we focus on the concept of the 'surface junction': the photojunction only one atom below the front surface, which is produced due to the interfacing of 2D layers (graphene) with bulk 3D semiconductors (Si). Here, graphene functions as both a light transparent electrode and a charge-separating, transport-active layer. In these 2D/3D heterojunction-based emerging photovoltaic cells, a light energy to electricity conversion efficiency of 15–17% can be achieved with improved nanoarchitectures and combined surface/interface engineering[9]. Figure 1 shows a schematic of a graphene/semiconductor heterojunction and the charge-carrier transport across the ångström-scale surface junction.

Energy-band structure engineering

To enhance the performance of graphene-on-semiconductor heterojunctions in optoelectronic applications, a uniquely accessible route is to engineer the interfacial band structure to control the electron- and hole-transport phenomena. For the heterojunction solar cell operation, the built-in voltage across the depletion region of the surface junction (here, the 2D/3D heterojunction) plays an important role, as it not only drives the photoexcited charge

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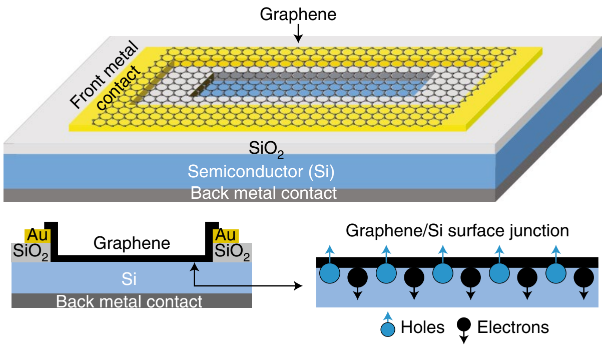

Fig. 1 | Schematic of a graphene-on-semiconductor (Si) heterojunction photovoltaic cell. Top: top view of the heterojunction. Bottom: side view of the heterojunction (left) and charge-carrier transport across the surface junction (right).

carriers towards the contact electrodes, but also avoids charge-carrier recombination. Therefore, it is essential to understand the transport of charge carriers, potential barrier formation, built-in potential-induced band-bending at the junction, and the relationship between the performance of 2D *sp*^{2}-carbon-based heterojunction solar cells and the surface-junction characteristics. The typical current density versus applied voltage characteristics due to the thermionic-emission transport for a metal semiconductor Schottky junction diode can be expressed as[10]: $J = J_0\left[\exp\left(\frac{qV}{nk_BT}\right) - 1\right]$, where J is the current density across the graphene/semiconductor interface, J_0 is the reverse bias saturation current density, q is the charge of an electron (1.6×10^{-19} C), V is the voltage across the diode, k_BT is the thermal voltage (k_B is the Boltzmann constant (1.38×10^{-23} J K^{-1}), T is the temperature in Kelvin), and n is the ideality factor, which is a function of voltage for a graphene/Si photojunction[11] (n can be derived from the slope of ln$J$ versus V curve). Here J_0 can be determined by extrapolating the straight line of ln$J$ to intercept the axis at zero voltage and it is presented as[10]: $J_0 = A^{*}T^2\left[\exp\left(\frac{q\phi_{SBH}}{k_BT}\right)\right]$, where A^{*} is the Richardson constant (for p-Si: 32 A (cm^2 K^2)$^{-1}$; for n-Si: 112 A (cm^2 K^2)$^{-1}$). The Schottky barrier height (ϕ_{SBH}) for such devices is calculated via the formula[10]: $\phi_{SBH} = \frac{k_BT}{q}\left[\ln\left(\frac{A^{*}T^2}{J_0}\right)\right]$. Further, graphene becomes hole-doped (work function (ϕ_G) ~4.7 eV) due to the transfer of electrons from graphene to the exposed electron-accepting molecules[12,13]. The semimetallic graphene with hole-transport characteristics creates a rectifying Schottky junction, when interfaced with lightly doped semiconductors[14]. Figure 2 presents the energy-band alignment at both equilibrium and in forward bias for a heterojunction of graphene with n-type bulk Si. In such a 2D/3D heterostructure, a junction barrier, only one atom below the surface, is created due to the difference in the work function of the 2D layer and the electron affinity of the 3D bulk semiconductor. With light irradiation (air mass (AM) 1.5G) on the graphene/n-Si heterojunction, the excitons are generated due to the absorption of photons by both the graphene and the bulk Si underneath, followed by the built-in potential (V_0)-induced separation of electrons and holes. Electrons are then transported towards n-Si and holes are transported to graphene and finally collected by the back and front metal contact electrodes, respectively. Here the graphene film performs a dual role of (1) a transparent and current spreading sheet for light transmittance and electrical conduction and (2) a photoactive junction layer for the exciton dissociation and carrier transport. The J–V characteristics of a Schottky junction typically allow the estimation of the barrier height and its doping-dependent tunability. However, the direct measurement of the magnitude of the built-in voltage (V_0) and the distribution and dopant concentration (N_D) are generally estimated via the capacitance versus applied bias voltage (C–V) profile of the graphene-on-semiconductor heterojunction. Following from the Schottky–Mott rule, the inverse square of capacitance ($1/C^2$) is related to the reverse bias voltage (V_R) as: $\frac{1}{C^2} = 2\left(\frac{V_R + V_0}{qN_D\varepsilon_S\varepsilon_0}\right)$, to estimate the uniform distribution of ionized donors within the depletion width of the semiconductor[10]. Here ε_S and ε_0 are the relative permittivity of the semiconductor and vacuum, respectively.

Challenges in graphene-on-semiconductor solar cells

Graphene-on-bulk semiconductor 2D/3D heterojunction photovoltaic sensors are emerging candidates for large-scale integration[15] and for relatively high-efficiency and robust solar technologies. However, the performance efficiency of graphene-on-semiconductor (for example, graphene/n-Si) single-junction cells is less than that of Si-wafer-based p–n-junction photovoltaic cells. This can be ascribed to three fundamental reasons. First, low Schottky barrier height: the interfacial barrier height of graphene/n-Si heterojunction solar cells is typically found by subtracting the electron affinity of n-Si ($\chi_{n\text{-}Si}$) from the work function of graphene (ϕ_G) — $\phi_{SBH} = \phi_G - \chi_{n\text{-}Si}$, which is ~0.65 eV (less than the Si energy bandgap (1.1 eV at 300 K)). Further, the open-circuit maximum potential difference (V_{OC}) is a function of ϕ_{SBH}, and therefore, the V_{OC} obtained for the graphene-coated n-Si heterojunction cells is typically less than the p-Si/n-Si homojunction solar cells. Second, transfer-based solar cell design: the graphene-on-semiconductor solar cell architectures are developed by transferring graphene onto the semiconductor substrates via a polymer-film-based chemical-transfer process. This is because these graphene films are typically synthesized on metal catalytic surfaces via a chemical vapour deposition (CVD) process. The transfer-associated contaminants, such as metallic particles (underneath graphene) and residual polymers (atop graphene), get incorporated into the photovoltaic device. These defects act as defect centres to multiply the interfacial carrier recombination, thus reducing the overall photovoltaic performances. Third, large lateral resistivity of graphene: the mobility of carriers in CVD-produced graphene is extremely high (over 10,000 cm^2 V^{-1} s^{-1}). However, a single layer of graphene film exhibits higher sheet resistance (100–1,000 $\Omega\ \square^{-1}$)[16] than solar-grade doped Si (50–100 $\Omega\ \square^{-1}$) in p–n-junction solar cells[13]. Such a large lateral resistivity of the graphene films will cause parasitic losses, including an increase in series resistance (R_S) and a decrease in fill factor for graphene-on-semiconductor heterojunction photovoltaic cells. Several routes to overcome the challenges in graphene/Si photovoltaic devices have been discussed[15]. The following section highlights the approaches to tune the interface by using the appropriate interlayers and to modulate the graphene functionality for achieving highly efficient and robust graphene/semiconductor heterojunction photovoltaic cells.

Enhancing solar cell performance

A graphene-on-semiconductor heterojunction has an exposed graphene surface and a functional junction only one atom apart. A 2010 report first demonstrated that the integration of a CVD-produced graphene layer on planar Si creates a Schottky junction photovoltaic sensor with a light energy to electricity conversion efficiency of 1.5% at AM 1.5G irradiation[17]. Since then, this graphene-on-Si functional heterojunction has been thoroughly investigated to understand the charge-transport mechanism and to produce a toolkit for achieving high efficiency and robustness in these photovoltaic devices. Current developments in surface science and interfacial engineering principles to enhance efficiency can be principally classified into two categories: surface science (tuning the graphene's work function, enhancing the light absorption via plasmonics and employing an ARC) and interfacial engineering

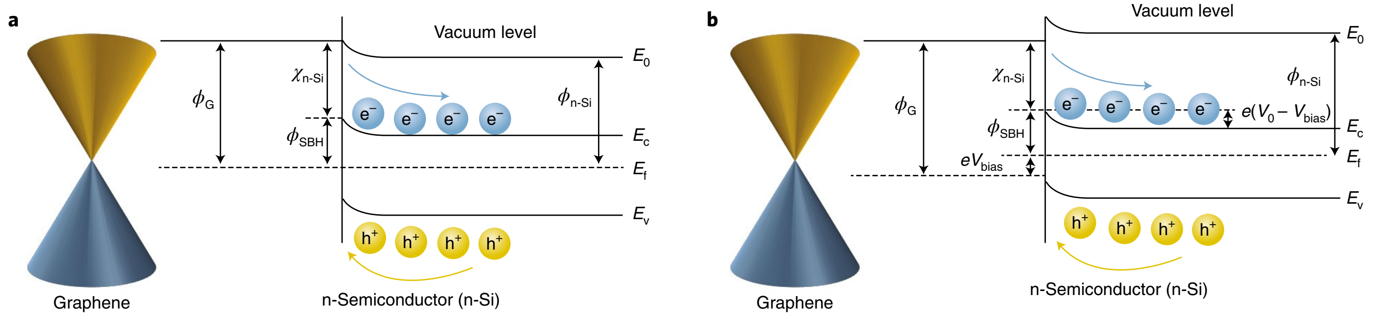

Fig. 2 | Graphene-on-semiconductor (n-Si) energy-band structure. a,**b**, Band-alignment diagram at equilibrium (**a**) and in forward bias (**b**). Here ϕ_G and $\phi_{\text{n-Si}}$ are the work functions of graphene and n-Si, respectively. $\chi_{\text{n-Si}}$ is the electron affinity of n-Si, ϕ_{SBH} is the Schottky barrier height, V_0 is the built-in potential and V_{bias} is the applied potential across the graphene/n-Si heterojunction. E_0 is the vacuum energy level, E_f the Fermi energy, e the electronic charge, and E_c and E_v the conduction and valence band energy, respectively.

(adding an electron-blocking or hole-transporting interlayer and interfacing graphene with other semiconductor nanostructures (nanowires) or wide-bandgap semiconductors). Below is a list of strategies for controlled development in the performance of graphene-on-semiconductor heterojunction cells.

Chemical functionalization of the graphene layer. The chemical functionalization or modification of graphene's electronic structure via surface doping is the most common and effective approach to control graphene's chemical potential to tune its work function and sheet resistance. Several surface doping chemistries, including nitric acid (HNO_3), thionyl chloride ($SOCl_2$), gold(III) chloride ($AuCl_3$) and bis(trifluoromethanesulfonyl)amide (TFSA), have been employed to modify graphene's chemical potential (change in Fermi level). In a 2013 report[18], researchers exposed the surface of the graphene/Si heterojunction with HNO_3 vapour to increase the graphene's work function, thus increasing the Schottky barrier height (Fig. 3a). This Schottky junction solar cell exhibited an enhanced efficiency of about 9%. However, the surface functionalization approach is challenging, because it distorts the graphene's sp^2 triangular lattice planarity and reduces its optical transmittance. The disruption in the lattice structure also reduces the charge-carrier mobility. Further, the stability of the covalent functionalization of graphene is important, as over time, any deterioration of functionalization by the ambient air could lead to a reduction of photovoltaic efficiency by more than 50%[19]. A functionalization chemistry that retains the structural integrity and charge-carrier mobility in the interfaced graphene is critically required to overcome the challenges associated with this emerging photovoltaics research.

Plasmonic enhancement via nanoparticles. Application of plasmonics to amplify the light absorption by integration of low-dimensional metal nanostructures (nanoparticles and/or nanowires) is a direct route to enhance the efficiency of graphene-interfaced-semiconductor heterojunction photovoltaic sensors. Particularly, the plasmonic enhancement of illumination intensity increases the maximum current (J_{SC}) that can be extracted from the solar cells. In a 2014 report[20], researchers introduced gold nanoparticles (AuNPs) of varying thickness on monolayer and few-layer graphene as a hole-conducting dopant. The nanoparticle-embellished graphene exhibited an enhancement in the work function and the electrical conductivity due to the charge transfer between graphene and the AuNPs. A threefold plasmonic enhancement in power conversion efficiency (from 2% to 7.34%) of AuNPs/few-layer graphene/Si solar cells was observed by adjusting the initial thickness of the plasmonic Au films. In another contribution, researchers employed metal carbonyls (chromium tricarbonyl ($Cr(CO)_3$)) to functionalize graphene via η^6 chemistry and then anchored silver nanoparticles (AgNPs)[21].

The AgNPs p-doped the functionalized graphene and enabled an increase in the work function of graphene and thus the Schottky barrier height and the built-in potential (Fig. 3b). An approximately 11-fold plasmonic enhancement (from 0.11% to 1.24%) in the efficiency was found in the AgNPs/functionalized graphene/n-Si photovoltaic cell. This η^6 chemistry on the graphene surface not only anchors the AgNPs, but also maintains the sp^2 lattice planarity as the transition metal carbonyl moiety grafts with all the six carbon atoms in the molecular building unit of graphene via σ-bonding.

Colloidal antireflection coating. For efficient light management in photovoltaic cells, an ARC layer is widely employed to reduce the loss of photons due to their surface reflection. For a 2D/3D architecture, the junction being close to the surface would imply enhanced performance than for devices with buried heterojunctions. The advantage of the graphene-on-semiconductor planar junction system is that it is compatible with thin-film processing technologies such as coating with an ARC layer. A colloidal TiO_2 coating on a graphene/Si structure via spin-coating was employed to lower the visible light (500–800 nm) reflectance by about 10% (Fig. 3c)[22]. Further, with HNO_3 doping, the efficiency of the graphene-coated Si solar cell reached a record high of 14.5%[22]. Further, a poly(methyl methacrylate) layer as an ARC has been used to improve the performance of graphene/Si solar cells with buried silver nanowires and a monolayer graphene film as a transparent current electrode[23]. In another report, researchers showed that coating graphene oxide on graphene/Si Schottky junction solar cells improved the efficiency to 10.6% compared with 3.6% for a bare/uncoated graphene/Si heterojunction cell[24]. The dramatic enhancement in efficiency in this case is due to two reasons: the hole doping of graphene by the graphene oxide and the role of graphene oxide as an ARC layer.

Electron-blocking or hole-transporting interlayer. Another avenue to minimize the carrier recombination and to enhance the efficiency of graphene/Si heterojunction solar cells is to introduce an interlayer, such as hexagonal boron nitride (h-BN)[25], poly(3-hexylthiophene-2,5-diyl) (P3HT)[26], silicon dioxide (SiO_2)[27] or molybdenum disulfide (MoS_2)[28,29]. These interlayers essentially function as an effective electron-blocking or hole-transporting medium, which ultimately reduce the electron–hole charge-carrier recombination. Researchers have employed h-BN, an atomically thin 2D insulator, to suppress the interface recombination, and as a result, there was an increase of 62 mV in the V_{OC} (Fig. 3d)[25]. This is because, with the decrease in interfacial recombination, the light-generated current increases and therefore, the V_{OC} increases according to the equation: $V_{OC} = \frac{nkT}{q}\ln(\frac{I_L}{I_0}+1)$. Here I_L is the light-generated current and I_0 is the dark saturation current. The atomically thin h-BN crystal is introduced due to its dangling bond-free, ultra-smooth sp^2

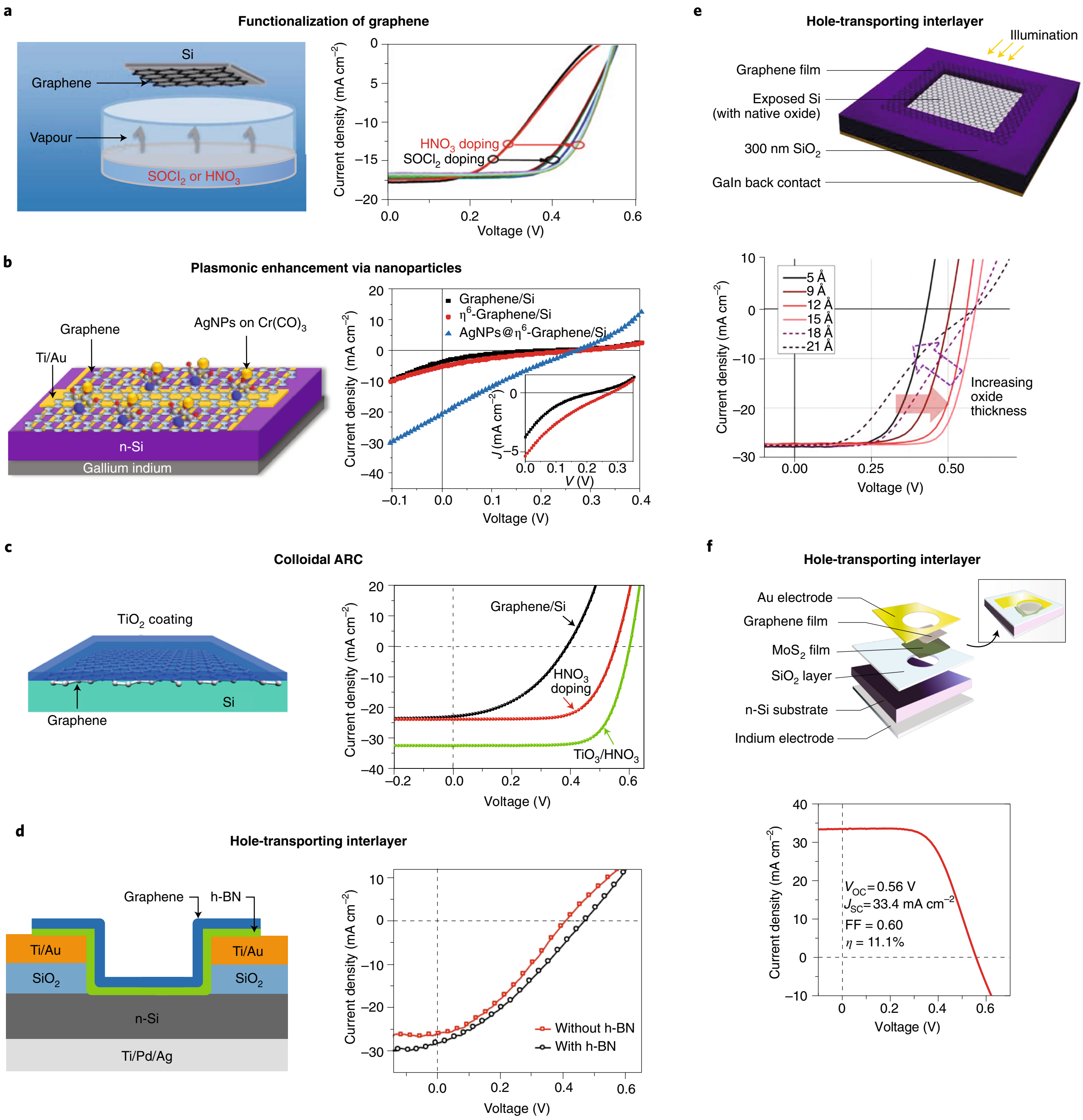

Fig. 3 | Graphene/Si heterojunction photovoltaics. Schematics and photovoltaic characterization of innovative approaches to achieve efficient graphene/Si heterojunction solar cells. **a**, Chemical doping of graphene. The green and blue curves show the effects of doping on V_{OC} and J_{SC}. **b**, Incorporating metallic nanoparticles for plasmonic enhancement. **c**, Colloidal ARC on the graphene surface. **d**–**f**, Introducing a hole-transporting interlayer between graphene and Si, such as h-BN (**d**), native silicon oxide (**e**), or MoS_2 thin film (**f**). FF, fill factor. Figure reproduced from: **a**, ref. [18], RSC; **b**, ref. [21], American Chemical Society; **c**, ref. [22], American Chemical Society; **d**, ref. [25], Elsevier; **e**, ref. [27], American Chemical Society; **f**, ref. [29], RSC.

lattice structure and its characteristic role as a tunnelling layer. The defects and contaminations were likely to be reduced by (1) creating directly grown graphene/h-BN heterostructures following transfer onto semiconductor (n-type Si) substrates, or (2) directly synthesizing h-BN on semiconductors following transferring or directly nucleating graphene on h-BN/semiconductor substrates. In another report, researchers employed an optimal thickness of SiO_x layer to passivate the dangling bonds on the Si surface before placing the CVD-grown graphene (Fig. 3e)[27]. Furthermore, along with an optimal oxide thickness of 15 Å, chemical doping and application of an ARC (TiO_2), they showed a new efficiency record of 15.6%. The J–V profile of these heterojunction solar cells matched well with the metal–insulator–semiconductor model. Introducing h-BN and SiO_x layers modifies the interface of graphene/Si solar cells, creating a metal–insulator–semiconductor-type structure. The presence of a thin insulating layer between graphene and n-Si is advantageous

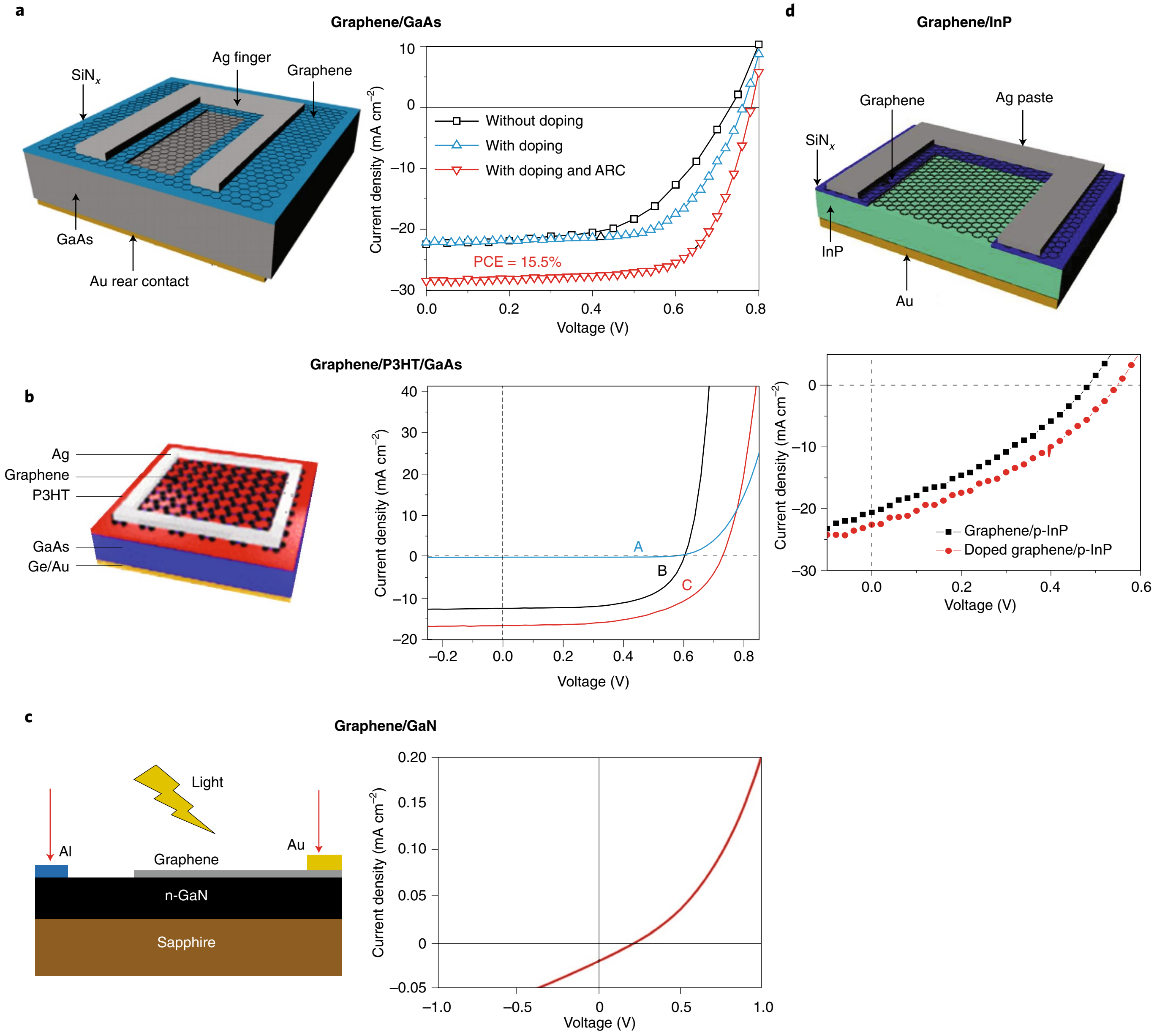

Fig. 4 | Graphene/III–V semiconductor heterojunction photovoltaics. a–d, Interfacing graphene with III–V semiconductors such as in a graphene/SiN$_x$/GaAs solar cell (**a**), graphene/P3HT/GaAs solar cell (**b**), graphene/n-GaN solar cell (**c**) and graphene/SiN$_x$/InP solar cell (**d**). In **b**, curve A corresponds to a P3HT/GaAs solar cell device, curve B to a graphene/GaAs solar cell device without a P3HT layer, and curve C to a graphene/GaAs solar cell device with a P3HT layer. PCE, power conversion efficiency. Figure reproduced from: **a**, ref. [30], Elsevier; **b**, ref. [31], Elsevier; **c**, ref. [32], AIP; **d**, ref. [33], Elsevier.

as it chemically passivates the surface of Si and impedes the interfacial recombination of charges. The charge carriers transport across the ultrathin insulating layer via a tunnelling mechanism and improves the performance of the graphene/Si photovoltaic devices. In another set of studies, semiconducting MoS$_2$ was employed as an electron-blocking/hole-transporting layer to reduce the charge-carrier recombination[28,29]. According to ref. [29], the photovoltaic properties of the graphene/Si heterojunction solar cells are enhanced with an increasing number of graphene layers and decreasing thickness of the MoS$_2$ layer. The optimized trilayer-graphene/n-Si heterojunction with a MoS$_2$ insertion layer exhibited an efficiency of 11.1% (Fig. 3f).

Interfacing graphene with III–V semiconductors. To leverage new interfacial science and in the quest for realizing high-efficiency and stable graphene-based photovoltaic cells, graphene films are not only interfaced with Si, but can also be combined with other inorganic semiconductors, including III–V direct-bandgap compound semiconductors such as gallium arsenide (GaAs), gallium nitride (GaN) and indium phosphide (InP) (Fig. 4). Owing to the large direct bandgap of III–V semiconductors, their heterojunction with graphene could exhibit a higher built-in potential. Researchers have employed GaAs as an active junction layer in graphene-based heterojunction solar cells (Fig. 4a)[30]. They have achieved an efficiency of 18.5% with TFSA doping and with a silicon nitride (SiN$_x$) ARC layer. In another report, 13.7% efficient graphene-on-GaAs heterojunction solar cells with P3HT as a hole-transport and electron-blocking film have been shown (Fig. 4b)[31]. And researchers have employed n-GaN as an n-type semiconductor to combine with graphene to build heterojunction photovoltaic cells and examined the effect of temperature on the V_{OC} and J_{SC} (Fig. 4c)[32]. A decrease in the V_{OC} with temperature may be attributed to the increase in the saturation current and carrier recombination. Further, enhancement of the J_{SC} with temperature is due to the increase in the photogenerated carriers in the heterojunction interface at elevated temperatures. In another report, researchers employed InP (bandgap of 1.34 eV) to interface with graphene and the efficiency improved to 3.3% even without chemical doping, which may be due to the large interfacial built-in electric potential (Fig. 4d)[33].

Outlook

Unlike conventional photovoltaic devices where the heterojunction is buried within the cell, the ultrathin graphene-on-3D semiconductor heterostructure has a photoresponsive junction one atom under the 2DN (graphene) surface. Thus, by engineering the exposed surface of the 2DN, its doping density/polarity, chemical potential (Fermi level) and optical absorption can be controlled for improved photovoltaic efficiency, while leveraging their efficient charge transfer properties. With a large number of possible combinations of 2DNs, 3D semiconductors (inorganic, organic and hybrid inorganic–organic perovskites), chemical interfaces for 2DN doping and plasmonic nanoparticles, several 2D/3D heterojunction photovoltaic systems are poised to emerge, starting a new research direction. Further, the advancement in the chemical growth of 2DN layers, interfacial chemistries and design strategies for 2D/3D heterojunctions will lead to evolved 2D optoelectronics, photovoltaics, photonics and nanoelectronics.

From an industrial context, the graphene-on-3D bulk semiconductor heterostructure systems are promising. The graphene-on-Si photovoltaic systems show an efficiency of 15–17%[9], which is in the vicinity of that for metal halide perovskite photovoltaic cells with a maximum efficiency of 20–22%[34]. Moreover, there is a tremendous scope for improvement in the performance of the 2D layers-on-bulk semiconductors photovoltaic systems by: (1) interfacing appropriate 2D active layers such as graphene and transition metal dichalcogenides; (2) chemical doping or surface functionalization of 2D layers; (3) anchoring metallic nanoparticles on the surface of 2D active layers; (4) integration of 2D insulating crystals (for example, h-BN) and making 2D semimetal or semiconductor/2D insulator/3D semiconductor architectures (for example, graphene/h-BN/Si); and (5) using an ARC layer for efficient light management. The 2D layers-on-bulk semiconductors (graphene-on-Si) photovoltaic system is relatively more stable, whereas there is a major challenge of materials and device robustness for the hybrid perovskite solar cells[35]. The perovskite-based photovoltaic cells are environmentally unstable because the crystal structure of hybrid organic–inorganic perovskite layers hydrolyses on exposure to the environment[36]. Furthermore, high-energy radiation (ultraviolet) and thermal stress also degrade the stability of perovskite-based photovoltaic cells. Therefore, with further understanding to control the chemical and electronic structure of the surface junctions and the architecture of the 2D layers-on-bulk semiconductors photovoltaic systems, they are becoming a serious candidate for commercialized photovoltaic cells. Several research efforts are required to further stabilize such hybrid 2D-on-3D heterojunction photovoltaic cells for long-term durability and technological importance.

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Competing interests

The authors declare no competing interests.

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