Optimizing performance parameters of graphene–silicon and thin transparent graphite–silicon heterojunction solar cells

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ABSTRACT
We investigated heterojunctions of Si with large-area high-quality monolayer and multi-layer graphene, as well as thin transparent graphite. We show that by controlling the transmittance and sheet resistance of large-area graphitic electrodes, it is possible to obtain solar cells with power conversion efficiency (PCE) exceeding 3% without any doping requirements. Our calculations indicate that such junctions can form extremely robust interfaces with near-100% internal quantum efficiency. Under optimized doping conditions, power conversion efficiencies increase almost universally by a factor of 2.5. Optimized conditions for reproducibly obtaining cells with PCE > 5% are presented, with the best PCE obtained ~7.5% with short-circuit current density exceeding 24 mA/cm².

1. Introduction
Graphene, one-atom-thick planar sheet of sp2-bonded carbon in a two-dimensional honeycomb structure [1,2], is an extremely promising material for many technological fields such as high-performance nanoelectronics [3], optoelectronics [4], sensors [5,6], energy storage [7–9], and smart composites [10]. In recent times, owing to its unique optical response [11–16], graphene is also rapidly becoming an attractive material for photodetection [17–20], and photovoltaic devices [21–23], especially as a large-area [24] front-end electrode for planar Si-based solar cell structures [25–27].

Li et al. [25] reported one of the earliest efforts towards developing graphene-based solar cells, whereby thin transparent graphite (tens of nanometers thick) transferred onto bare Si surfaces, produced solar cells with power conversion efficiencies (PCE) of 1.5%. It was pointed out that these structures were “un-optimized”, and could potentially be optimized by carefully controlling the sheet resistance vis-a-vis the optical transmittance of the graphite electrode, since both these quantities play important roles in determining high PCE values. Subsequently, other efforts have significantly improved the PCE in graphene–Si based solar cells, with high PCE obtained primarily by doping approaches, for example, PCE ~6.1% using HNO₃-treated graphene woven fabrics [26], and PCE ~8.6% using bis(trifluoromethanesulfonyl)amide[(CF₃SO₂)₂NH] (TFSA) doped graphene [27]. While doping is an attractive method for improving the PCE, its impact is limited by the PCE of the parent junction. As a result, it is imperative that the most ideal junction configuration (without doping) is first established. Although there has been some effort in quantifying the relationship between the sheet resistance and optical transmittance in solution-processed graphene sheets [28], to our knowledge, there has been no systematic study to understand the impact of these two parameters on the resultant PCE in graphene-based solar cells.

Recently, we have shown that large-area, high-quality graphene can be easily fabricated on Pd substrates [29]. Monolayer graphene flakes obtained on Pd substrates form domains exceeding tens of microns, with absence of any defect-induced Raman peak, implying their high quality.
Further, by controlling the CVD growth conditions, it is also possible to obtain a variety of graphene morphologies on Pd substrates, including monolayer and multilayer graphene, along with thin transparent graphite (TTG) with well-controlled optical transmittance. Our detailed investigation with these TTG sheets reveal Raman spectra are as good as those obtained from highly oriented pyrolytic graphite. Hence, using a combination of CVD growth of graphene on both Cu and Pd substrates gives us the opportunity to systematically investigate the PCE of solar cells formed by heterojunctions of Si with thickness-controllable high-quality transparent graphitic electrodes, and obtain the sheet resistance and transmittance of optimized electrodes for the best solar cell performance.

In this work, we show how, by controlling the effective thickness of graphene and TTG layers, the critical photovoltaic parameters such as short-circuit current density, open circuit voltage, fill-factor, and the overall power conversion efficiency are affected by the sheet resistance/transmittance of the electrodes. Moreover, as a proof-of-concept, we doped the graphitic electrodes of the same devices via a simple solution-phase doping approach. Past reports have shown an irregular effect of doping, i.e., the PCE enhancement factor obtained (by doping the electrodes) varies quite randomly \cite{27}. This uncertainty is an issue for reproducible manufacturing of solar cells. In contrast, our simple doping approach produces solar cells with PCE increases by about 2.5 times across the entire range of electrodes investigated (eight devices with electrodes that were near-transparent to near-opaque, see later), representing a remarkable reproducibility of the doping approach. As a result of these optimization processes, we can exactly quantify the electrode properties for reproducibly obtaining PCE values higher than 5%, with the maximum value obtained, PCE = 7.5%.

2. Experimental

2.1. Synthesis of graphene and thin transparent graphite (TTG) films

Large-area graphene (mostly monolayer, 1LG) was grown on commercially purchased Cu foils in a low-pressure chemical vapor deposition (CVD) system as reported by Li and co-workers \cite{24}. The copper foils were annealed in a flow of 7 sccm H2 for 30 min under 1015 °C to increase the grain size of copper and to clean the copper surface of any unwanted oxide or physisorbed species before growth. After that, CH4 was introduced (flow-rate of 25 sccm) into the system to grow graphene for t = 30 min. The chamber was then cooled down to room temperature with flowing H2 in the system.

Thin transparent graphite (TTG) samples were synthesized on Pd foils, using a very similar low pressure CVD method that we have recently demonstrated for the growth of large-area high-quality graphene on Pd wire \cite{29}. The palladium foils were annealed in gas mixture of 7 sccm H2 and 50 sccm Ar for 30 min to clean the Pd surface before growth. To obtain large-area very thin transparent graphite (sample TTGa and TTGc), we chose a higher growth temperature, shorter growth duration and a very low flow rate for CH4. Sample TTGa and TTGc were grown under 1015 °C. CH4 (with a flow rate of 2 sccm) was introduced in the low pressure CVD system for 3 and 5 min respectively. Since the growth rate of graphene on Pd foil under high temperature is very high, it is very hard to grow thicker transparent graphite under 1015 °C in controllable way. To grow samples TTG1, TTG2, TTG4, and TTG5, the Pd foils were annealed under 840 °C in gas mixture of 7 sccm H2 and 50 sccm Ar for 30 min, and then 20 sccm CH4 was introduced into low pressure CVD system for 3, 5, 15, 25 min, respectively. The Table 1 summarizes the growth condition for each sample. Each prepared sample was cut into smaller pieces, and these pieces were used for characterizations as well as device fabrication as discussed below.

The obtained graphene and thin transparent graphite samples are characterized and analyzed by scanning electron microscopy (Zeiss Surra 25) and Raman Spectrometer (Jobin Yvon LabRam HR800). The optical Transmittance (200 nm < i < 1100 nm) of the samples was measured in a UV–Vis–NIR spectrophotometer (Perkin-Elmer Lambda 35). Two-probe sheet resistance was measured using a Keithley model 2400 Sourcemeter. The average thickness of monolayer graphene samples was found to be about 1 nm (AFM step-height measurement). The thickness of the thin transparent graphite samples were measured using a Dektak profilometer model 3ST.

2.2. Device fabrication and measurement

The graphene–Si and TTG–Si heterojunction devices are fabricated on commercially purchased lightly n-doped (resistivity of 1-10 Ω-cm) Si wafers with 400 nm SiO2 layer. These wafers were diced into square pieces of 2 cm edges for device preparation. First, the front surface of SiO2/Si wafers were patterned by photolithography and wet-etching of the SiO2 layer (buffered oxide etchant) to prepare square windows (5 mm × 5 mm) where the n-doped silicon was exposed. The back surface oxide was also etched out during this process. Next, an e-beam deposition technique was used to deposit rectangular Ti/Au (5 nm/100 nm) film contact pads along the periphery of the Si window on the front as well as on the back surface of Si squares, leaving the front windows exposed. To transfer graphene and TTG films onto this window or other substrates, the as-grown graphene and TTG films (on metal foils) were spin-coated with PMMA, and the metal foils were dissolved in a dilute FeCl3 solution. The PMMA-coated graphene and TTG films were then transferred onto the top of the exposed square window of Si, ensuring that they covered the window and extended onto the Au part of the top contact. After that, the devices were thoroughly rinsed with acetone and isopropanol to remove the PMMA, and dried. The Measurements of solar power efficiency were performed in a solar simulator calibrated to operate at 1 Sun (AM 1.5 G). The forward bias was defined as positive voltage applied to the graphene films.

2.3. Responsivity and IPCE measurement as a function of wavelength

To study the relationship between photocurrent responsivity and wavelength, we modified a commercially purchased...
UV–vis–NIR spectrophotometer (Perkin–Elmer Lambda 35) to use it as a variable wavelength (190–1100 nm) monochromatic light source to illuminate the graphene–Si samples. The incident power at each wavelength was independently measured using the previously mentioned photometer, which varied between 0.3 and 1 μW over the entire range of wavelengths. A mount was fabricated to insert the devices (attached to electrical leads) inside the dark optical chamber of the spectrophotometer, and to align them for normal incidence to the monochromatic light. At each wavelength, a complete IV was measured using a Keithley 2400 SourceMeter. As before, the forward bias was defined as positive voltage applied to the graphene films.

3. Results and discussion

Fig. 1a and b shows typical SEM images of large-area graphene grown on Cu and multilayer graphene/thin transparent graphite samples grown on Pd substrates, respectively. Graphene grown on Cu foils are mostly uniform monolayer (Fig. 1a), as confirmed by obtained Raman spectra at several random locations on the samples. In contrast, samples grown on the Pd foil surface (Fig. 1b) were covered with a mixture of thin graphite (darker regions) and multilayer graphene (lighter regions). By changing the growth conditions, samples with varying relative coverage of the thicker and thinner transparent graphitic areas could be obtained. Fig. 1c shows a Raman spectrum of a typical monolayer graphene sample grown on Cu. It reveals the spectral features of a G peak at ~1580 cm⁻¹ and a single-Lorentzian G' peak around 2706 cm⁻¹, with the relative intensity of the G’ peak with respect to that of the G peak >3, which are all signature characteristics of monolayer graphene. A defect-induced D band at ~1350 cm⁻¹ was either negligible or completely absent in these samples, indicating the high quality of graphene. When measured randomly at various regions of a sample, more than 80% of the spectra showed such a monolayer nature. In contrast, depending on the growth condition, the thin transparent graphite samples grown on Pd were found to have varying amounts of monolayer, Bernal multilayer, and...
turbostratic multilayer graphene regions within the same sample [29]. Fig. 1d shows a typical example of a Raman spectrum from a monolayer graphene region on Pd. In order to cover the complete range of transmittance values for the graphene or TTG sheets, we prepared graphene and TTG layers with mean thickness between 1 and 300 nm, and selected the ones with optical transmittance (at = 550 nm) values covering 5% < T < 98%, having sheet resistances (R_h) ranging between 20 Ω □^−1 < R_h < 3 kΩ □^−1. Table 2 summarizes the transmittance at = 550 nm, the sheet resistance values, and the mean thickness of the graphene and various TTG samples that were used to prepare solar cells. Fig. 1e and f shows a schematic and a digital photograph of typical solar cells obtained by forming heterojunctions of graphene or TTG with Silicon.

Fig. 2a schematically describes the photoexcitation process at a graphene–Si heterojunction. The relative positions of the Fermi levels of graphene (E_f(Gr) in darkness) and lightly n-doped Si (E_f(Si)) under a forward bias V = V_bias is as shown (the forward bias was defined as positive voltage applied to the graphene films). Under illumination, photoexcited carriers (holes) from Si get injected into graphene, lowering the

<table>
<thead>
<tr>
<th>Table 2 – Optical and electrical properties of graphene and TTG films of different thicknesses.</th>
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<tr>
<td>Graphene and TTG samples</td>
</tr>
<tr>
<td>Transmittance (i = 550) (%)</td>
</tr>
<tr>
<td>Sheet resistance (Ω □^−1)</td>
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<td>Mean thickness (nm)</td>
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Fig. 2 – (a) Energy-level diagram of a graphene-Si (lightly n-doped) junction showing the Fermi and quasi-Fermi levels in dark and illuminated conditions, respectively. (b) IV curves measured in junctions with increased layer-thickness values. (c) Variation of short-circuit current density, open-circuit voltage and fill factor as a function of the transmittance (at i = 550 nm) of their electrodes. (d) Variation of the overall power conversion efficiency as a function of sheet resistance and optical transmittance of the electrodes.

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quasi-Fermi level of graphene ($E_F$) will align with the quasi-Fermi level for holes in Si. Unlike bulk metals, atomically thin graphene has a limited number of accessible states for the holes to inject into, and hence the photocurrent generated is restricted by the number of accessible states between these two levels (shown as the colored surface of the Dirac cone between $E_F$ and $E_f$) under high power illuminations. In monolayer graphene, this limits the photocurrent and hence to overall PCE, and can be overcome by layer thickening. Layer thickening provides increased number of states for the photoexcited carriers to inject into. Further, as the graphene or TTG sheets increase, they become better carrier collectors, and hence initially, the 1-Sun IV curves begin to improve their overall shapes approaching those expected for conventional Schottky-junctions. This is accompanied by a significant initial increase of the 1-Sun short-circuit current ($I_{SC}$) and other cell parameters.

The open circuit voltage ($V_{OC}$), and the fill-factor ($FF = P_{max}/(I_{SC} \times V_{OC})$, where $P_{max} = [I \times V]_{max}$) also improve as the graphitic layer is thickened further beyond a monolayer. Beyond a certain point, however, the thicker layers (with more transmittances) prevent a large fraction of light from reaching the junction, resulting in a decrease in the cell performance. Fig. 2c shows the variation of the current density $J_{SC}$, $V_{OC}$ and $FF$ as a function of the transmittance $T$ (at $\lambda = 550$ nm) of the graphene and TTG layers of the device. $J_{SC}$ peaks at $\sim 21.5$ mA/cm$^2$ for $T_{550}$ nm = 56%, while $V_{OC}$ peaks at $\sim 425$ mV between 35% < $T_{550}$ nm < 55%. Within the same range of transmittance values, the fill factor $FF$ varies between 25% and 35%. Fig. 2d summarizes the overall PCE of every device tested, as a function of sheet resistance and transmittance at 550 nm. The maximum power conversion efficiency ($PCE = P_{max}/P_{in}$ = $J_{SC} \times V_{OC} \times FF$)/(1000 W/m$^2$) $\sim 3.16\%$ was obtained in device TTGc–Si simply by layer thickening, which is much better than most past reports on undoped junctions [25–27], and as discussed later, could be significantly improved via doping methods.

A reasonable measure of the interface quality can be obtained by ascertaining the internal quantum efficiency (i.e., the ratio of carriers produced per absorbed photon) of the cells. Unfortunately, since our setup was not equipped to measure the reflectance, $R(\lambda)$, we were unable to directly obtain the internal quantum efficiency, IQE($\lambda$) = IPCE($\lambda$)/[(1 - $R(\lambda)$) x $\tau(\lambda)$]) for each incident wavelength, $\lambda$ (where, IPCE = incident photon conversion efficiency, $I_{SC}(\lambda)/P(\lambda)$). Instead, we obtained the absorption corrected quantum efficiency, ACQE($\lambda$) = IPCE($\lambda$)/$\tau(\lambda)$, and since IPCE < ACQE < IQE, the ACQE sets a lower limit for the IQE. Fig. 3a shows the IPCE and ACQE of device TTG2–Si, as function of $\lambda$. Between 600 nm and 800 nm, the ACQE $\geq$ 90%, implying that the $R(\lambda)$ < 10% for this wavelength range. While polished Si surfaces have a reflectance $>30\%$ in this wavelength range, texturing the surface can bring it down below 10% [30–34]. This indicates that the TTG electrodes are also possibly working as a texturing layer that reduces the effective reflectance of the devices. Fig. 3b shows the variation of the (IPCE) and (ACQE) (averaged over $\lambda = 400$–900 nm) of all the tested devices, as a function of $T_{550}$ nm. We see that as the (IPCE) decreases with decreasing transmittance, the (ACQE) reaches values exceeding 90% in several devices, implying that the IQE values reach near-100% over a broad range of solar-spectrum useful wavelengths, indicating the robust nature of the interface formed by these junctions. Here we note that the IPCE measurement is performed in commercially purchased UV–vis–NIR spectrophotometer (Perkin–Elmer Lambda 35). The details about measurement can be seen in experimental information. The incident power at each wavelength varied between 0.3 and 1 $\mu$W over the entire range of wavelengths. It could render 1LG–Si and 3LG–Si devices higher IPCE value than under 1-Sun illumination, because the limited number of accessible states in graphene restrict generated photocurrent and further decrease IPCE value under high power illumination.

![Fig. 3](image-url)

Fig. 3 – (a) Spectral dependence of the IPCE and the ACQE (see text) of device TTG2-Si with electrode transmittance $\approx 30\%$. (b) Variation of the mean IPCE and ACQE (averaged between 400 and 900 nms) as a function of electrode transmittance. Devices with the thickest layers (smallest transmittances) have ACQE exceeding 90% over this broad range of photovoltaics-friendly wavelengths.

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To further improve the efficiencies of the devices, the graphene and TTG sheets were p-doped using two different agents, 1-pyrenecarboxylic acid (PCA), and AuCl3. Since p-doping lowers the Fermi level of graphene with respect to its Dirac point, one expects a larger Schottky barrier height [35–38], and hence increased values of \( V_{OC} \). Doping is also expected to reduce the sheet resistance of the graphene and TTG layers, and hence increase \( I_{D} \). The organic PCA dopant was dissolved in methanol (15 mM), while the AuCl3 powder was dissolved in Nitromethane (2.5 mM). Gate modulated transport can directly show how the PCA and AuCl3 doping on graphene can change their electronic properties. To do this, a back-gated, 3-terminal monolayer graphene device was fabricated on a SiO2/Si substrate (gate thickness = 400 nm of SiO2) (the Si wafer was used as the back-gate). Fig. 4 shows the \( I_{D} - V_{G} \) curves of pristine and doped devices. It can be seen that graphene was originally p-doped during the process of growth and transferring steps, possibly due to residual impurities and/or substrate effects. The charge-neutrality point for pure graphene was at \( V^{\text{min}}_{G} = 121.5 \text{ V} \). After dropping 25 \( \mu \text{L} \) PCA solution on top of graphene film, \( V^{\text{min}}_{G} \) shifted to 148.5 V. With further doping with 20 \( \mu \text{L} \) AuCl3 on graphene, \( V^{\text{min}}_{G} \) goes above 180 V (the gate oxide becomes unstable beyond this voltage). The shifting of \( V^{\text{min}}_{G} \) to higher positive values implies increased p-type doping of graphene associated with the addition of PCA and AuCl3. To estimate the doping level and effect of doping on the mobility, we note that in the 3-terminal device, the drain current \( I_{D} \) can be written in terms of the gate voltage \( V_{G} \) as \( I_{D}/V_{SD} = G = \mu C_{ox} \times (V_{G} - V^{\text{min}}_{G}) + G_{res} \). Here, \( G \) and \( G_{res} \) are the 2D conductance and residual conductance (when \( V_{G} = V^{\text{min}}_{G} \), respectively, and \( \mu \) is the mobility. \( V_{SD} \) is the applied bias across the graphene sheet, while the gate capacitance per unit area, \( C_{gate} = \varepsilon_{0} \varepsilon_{r} / t \), where the relative permittivity \( \varepsilon_{r} \), and thickness \( t = 400 \text{ nm} \), respectively, for SiO2. From this, we obtained the mobility, \( \mu = dI_{D}/dV_{G} \times [V_{SD}C_{gate}]^{-1} \), and carrier density, \( n = (1-I_{D}/V_{SD}C_{ox}) \). The mobility of the pristine device was 273 cm²/V-s, which dropped to 138 cm²/V-s, and further to 125 cm²/V-s after the PCA and the AuCl3 doping steps, respectively. This drop in mobility is not unexpected, as the attached molecules of PCA and/or AuCl3 also act as scattering sites for the charge carriers. At the same time, the intrinsic carrier density, which was \( 9.9 \times 10^{12} \text{ holes/cm}^{2} \), increased to \( 1.2 \times 10^{13} \text{ holes/cm}^{2} \) and further to \( 1.5 \times 10^{13} \text{ holes/cm}^{2} \) upon PCA and AuCl3 doping, respectively. We note that these numbers are just indicative of the doping behavior in the monolayer sheet, which could be quantitatively different in the TTG sheets. More importantly, while the enhanced carrier concentration will be distributed uniformly over the entire TTG electrodes, the dopant molecules remain on the surface, reducing their impact (as scattering sites) on the mobility of the thicker TTG devices.

Each device was doped with a combination of PCA and AuCl3, and the photovoltaic properties were measured after drying the devices completely. Initially, the photovoltaic properties were found to improve significantly with doping steps, followed by a saturation or degradation. For example, 4 drops (=25 \( \mu \text{L} \)) of PCA solution was administered onto the top of the TTGc-Si device, followed by about 3 drops (=20 \( \mu \text{L} \)) of AuCl3 solution, and then by an additional 3 drops of AuCl3 solution (this sequence was always found to be the optimal approach). Fig. 5a shows the effect of doping on the 1-Sun IV characteristics of device TTGc-Si (which possessed the highest PCE, both undoped and after doping). As the doping level increases, the IV curves improve their shape, with increased values of \( J_{SC}, V_{OC} \) and FF as tabulated in Table 3. Doping beyond this resulted in either a saturation or degradation of the overall PCE.

Fig. 5b summarizes the PCE of all the devices under optimally doped conditions, as a function of the sheet resistance and transmittance of the pristine graphene or TTG layers. Three of the devices exceed 5% power conversion efficiency, with the best device operating at 7.5% PCE. These values exceed most of the best reported ones for organic/polymer photovoltaic devices [39,40], and approach those of much more complex and expensive solar cells [41,42], while the current density \( J_{SC} \approx 24 \text{ mA/cm}^{2} \) begins to rival those of expensive commercial Si-based solar cells. These values are encouraging improvements over previously reported ones for other carbon-based solar cell devices. For instance, dye-sensitized solar cells using composite clusters of porphyrin-peptide oligomers and C60 have been reported with a PCE of 1.6% and current density of 0.36 mA/cm² [43]. Solution-processable reduced graphene oxide based polymer solar cell demonstrated a PCE of 3.63% and a current density of

![Fig. 4 - Channel current as a function of gate voltage in pristine and doped graphene FETs. (a) pristine, (b) PCA doped, and (c) PCA + AuCl3 doped. The shifting of the charge-neutrality point \( V^{\text{min}}_{G} \) to higher positive values indicates increased p-type doping of graphene.](image-url)
9.33 mA/cm²[44]. Multiwall carbon nanotube based dye-sensitized solar cells have been reported with a PCE of 2.37% and current density of 14.4 mA/cm² although the PCE could be further improved to 7.66% by annealing[45]. The PCE of our best device agrees quite well with a very recent report[27], where a different dopant was used that resulted in one device with PCE/C24 8.6%. More importantly (as seen in Fig. 5c), our systematic optimization approach results in a highly predictable trend between the transmittance of the TTG electrodes and their resultant PCE values in cell-configuration, for both undoped and doped electrodes. The dashed lines are separate linear trends for the low- and high-transmittance regions, corresponding to the un-doped (black) and doped (red) electrodes. A strikingly universal enhancement factor of ~2.5 is seen (ratio of the slopes of the linear trend-lines shown) for the entire range of electrodes used. (d) IPCE and Responsivity of the best solar cell obtained, TTGc-Si, before and after doping with PCA, showing the enhanced performance across nearly the entire solar-friendly wavelengths.

<table>
<thead>
<tr>
<th>Solar cells with</th>
<th>IPCE (%)</th>
<th>Responsivity (A/W)</th>
</tr>
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<tbody>
<tr>
<td>Pristine Electrodes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doped Electrodes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTGc-Si</td>
<td>2.5xPCE(undoped)</td>
<td></td>
</tr>
<tr>
<td>TTGc-Si + 4PCA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTGc-Si + 4PCA + 3AuCl₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTGc-Si + 4PCA + 6AuCl₃</td>
<td></td>
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</table>

Fig. 5 – (a) Evolution of the 1-Sun IV curves in device TTGc-Si before and after each doping step up to the most optimally doped condition. (b) Power conversion efficiency after optimal doping of each device, as a function of their pristine transmittance and sheet resistance values. (c) PCE before and after optimal doping of each device. A universal enhancement factor of ~2.5 is seen (ratio of the slopes of the linear trend-lines shown) for the entire range of electrodes used. (d) IPCE and Responsivity of the best solar cell obtained, TTGc-Si, before and after doping with PCA, showing the enhanced performance across nearly the entire solar-friendly wavelengths.

Table 3 – Photovoltaic parameters of TTGc-Si with different degrees and types of doping.

<table>
<thead>
<tr>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF (%)</th>
</tr>
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<tbody>
<tr>
<td>TTGc-Si</td>
<td>21.52</td>
<td>0.41</td>
</tr>
<tr>
<td>TTGc-Si + 4PCA</td>
<td>23.8</td>
<td>0.47</td>
</tr>
<tr>
<td>TTGc-Si + 4PCA + 3AuCl₃</td>
<td>23.92</td>
<td>0.49</td>
</tr>
<tr>
<td>TTGc-Si + 4PCA + 6AuCl₃</td>
<td>24.28</td>
<td>0.51</td>
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4. Summary

We have optimized the performance parameters of solar cells made from heterojunctions of graphene and TTG electrodes with Si, which led to predictable device structures with high

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power conversion efficiencies. In these structures, it appears that sheets with $T_{550nm} = 35$–60% transmittance have the optimal sheet resistance values that can reproducibly result in solar cells with PCE values exceeding 5% after doping, with the maximum PCE obtained at $T_{550nm} \approx 56\%$. Evidence of near-100% internal quantum efficiency has been observed in many of these devices, along with a possible surface texturing effect due to the nature of the TGT electrodes. An indirect indication of the level of optimization was seen from the universal doping-induced enhancement factor of about 2.5 for these devices. Built using such simple, low-cost, and scalable methods, further improvements in the PCE can be potentially obtained by optimizing the CVD conditions that gives graphene-based electrodes with higher transmittances at lower sheet resistance, as well as other doping agents that may further improve the sheet resistances without decreasing transmittance, potentially leading to a significant progress in next-generation low-cost solar cells.

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References


