In addition to direct solar illumination to the photovoltaic cell, the albedo effect provides a unique opportunity to enhance energy harvesting. However, conventional solar cells are inefficient albedo energy harvesters because the rear side of the cell is usually blocked by a thick substrate or metal contact. In this study, structurally thin active layers of GaAs thin-film solar cells covered with transparent Ag nanowires that enable bifacial solar cell operations are fabricated. The GaAs bifacial thin-film solar cell is fabricated by bonding the active regions of the solar cell on colorless polyimide sheets with highly transparent epoxy adhesives. The fabricated bifacial solar cells without any anti-reflection coatings demonstrated power conversion efficiencies of 8.54 and 6.78% at the front and rear sides, respectively, under AM 1.5 G irradiance conditions. The increase in energy harvesting by the GaAs bifacial thin-film solar cells was estimated, which showed approximately a 72% increase in short-circuit current density ($J_{SC}$) when the solar cells operated on a high-reflection-coated ground. Positioning the solar cells on snow or sand (deserts and beaches) increased $J_{SC}$ by $\sim$44 and 31%, respectively, compared to monofacial solar cells.

1. Introduction

Compound semiconductors such as GaAs and InP provide superior optoelectrical properties over Si, such as high carrier mobility and large absorption coefficients. Among the various compound semiconducting materials, GaAs has the most favorable bandgap for a single-junction solar cell according to the Shockley–Queisser limit. However, high material costs hinder the widespread use of GaAs in photovoltaic applications. Recently, a nondestructive substrate removal process called epitaxial lift-off (ELO) has been investigated for substrate reuse, and an extremely high power conversion efficiency (PCE) of 29.1% for GaAs thin-film solar cells has been achieved via the photon recycling effect. The reduced material cost and higher power conversion efficiency enable GaAs thin-film solar cells to be employed in niche applications where high-efficiency and lightweight photovoltaic (PV) is required, such as mobile applications, electrical vehicles, and drones. GaAs thin-film solar cells can produce more energy within a limited space compared to Si solar cells with minimal weight; therefore, the balance between system costs can be dramatically reduced by minimizing the cost of the installation. Furthermore, cost can be further reduced via wafer reuse techniques such as epitaxial lift-off (ELO) and nondestructive ELO (ND-ELO), compared to conventional substrate-based GaAs solar cells. The ultra lightweight and mechanical flexibility of thin-film solar cells permit their use in diverse weight-sensitive and/or conformal-shaped applications such as building-integrated photovoltaic systems (BIPV), unmanned aerial vehicles (UAV), and satellites.

The most advantageous benefit of using GaAs thin-film solar cells is the possibility of implementing a bifacial platform owing to the active layer that is only a few microns thin, which is
comparable to the carrier diffusion length without the parent substrate, achievable through epitaxial lift-off technology. Bifacial solar cells are capable of generating electricity by receiving light from both the front and back sides of the cell surface. Thus, the power output can be increased by 50% compared to the monofacial solar cell structures. Furthermore, bifacial solar cells have the advantage of being able to operate in snowy conditions. Even if the solar cells are covered with snow, they not only generate power from the light reflected from the snow surface but also allow the snow on the top of the cell to melt faster. Therefore, bifacial solar cells can potentially maximize the energy harvesting efficiency and lower the cost of electricity generated by photovoltaic power plants compared to monofacial solar cells; however, this concept has been implemented only in Si-based photovoltaics with a long carrier diffusion length.

In this study, we fabricate GaAs bifacial thin-film solar cells by bonding the active regions on colorless polyimide (CPI) sheets with highly transparent epoxy adhesives via the epitaxial lift-off process. The Ag nanowires (NWs) are employed as top-ohmic contacts on p-GaAs for carrier extraction and bending stability. The fabricated bifacial solar cells without antireflection coating (ARC) demonstrated power conversion efficiencies (PCE) of 8.54 and 6.78% under simulated illumination conditions of air mass 1.5 global (AM 1.5 G) on the front and rear sides, respectively. For comparison, a monofacial GaAs thin-film solar cell with a back metal reflector and identical heterostructure showed a PCE of 10.94% under AM 1.5 G. The short-circuit currents ($J_{SC}$) of the bifacial solar cell were 13.50 mA cm$^{-2}$ and 10.96 mA cm$^{-2}$ for front- and rear-side illumination, respectively, and 15.67 mA cm$^{-2}$ for the monofacial solar cell. The fabricated solar cell demonstrated a lower PCE because the active layer thickness is significantly thinner than the conventional GaAs solar cell (≈60% thinner). Furthermore, the bifacial solar cell demonstrated a slightly lower PCE than the monofacial solar cell due to the absence of the light trapping and photon recycling effect. However, the bifacial solar cell generated more electricity in the presence of albedo light. We simulated the short-circuit current of the bifacial solar cell with various ground conditions underneath the cell, such as concrete, waterproof green paint, sand, snow, soil, grass, and high-reflection coating. The $J_{SC}$ was boosted up to a maximum of 23.17 mA cm$^{-2}$ when a commercially available high-reflection coating was applied to the ground. Even on natural surfaces such as snow and sand, the $J_{SC}$ of the bifacial solar cell reached 22.52 mA cm$^{-2}$ and 20.54 mA cm$^{-2}$, respectively. These values are 44 and 31% higher than that of the monofacial solar cell, respectively. Thus, the GaAs bifacial thin-film solar cell on a properly reflective surface can boost current generation as well as the PCE by absorbing additional light from the rear side.

2. Experimental Results and Discussion

Figure 1a presents a schematic of the GaAs bifacial thin-film solar cell. The active layer is sandwiched between two electrodes. The front n-electrode consists of AuBe/Pt/Au and the rear p-electrode was formed by bus bars and randomly dispersed Ag NWs. Due to the nature of the imbalanced diffusion lengths of electrons and holes, an asymmetric p-n junction is preferred for overall higher efficiency. Here, the n-type emitter on the

![Figure 1. a) Schematic of the GaAs bifacial thin-film solar cell. Randomly dispersed Ag nanowires and metal bus bar form the p-electrode on the backside. A regular grid pattern is used for the front electrode. b) Detailed heterostructure grown by metal–organic chemical vapor deposition (MOCVD). The asymmetric p-n junction with n-GaAs emitter and p-GaAs base was designed and the inverted structure was grown considering that the structure is flipped over after the transfer to the colorless polyimide sheet.](image-url)
p-type base structure is designed to take advantage of a longer electron diffusion length in the base, and we defined the n-type emitter side as the front side. As shown in Figure 1b, the inverted structure was grown considering that the structure is flipped over after being transferred onto the CPI sheet. An identical heterostructure was also used to fabricate a monofacial solar cell, details can be found in previous work.\cite{10}

Prior to dispersing Ag NWs as a rear side contact on p-GaAs, the proper density and optimal processing conditions were studied. As shown in Figure 2a, the as-spin-casted Ag NWs on p-GaAs after the evaporation of residual solvent exhibited nonlinear current–voltage (I–V) characteristics. Therefore, thermal annealing was performed at 200 °C for 15 min to form an ohmic contact between the Ag NWs and p-GaAs. Figure 2b shows a scanning electron microscopy (SEM) image of the annealed Ag NWs. It can be observed that the intersections of the randomly dispersed Ag NWs are fused together. The Schottky junction behavior before annealing is possibly due to the native oxide around the Ag NWs, which is desorbed away during thermal annealing. The contact resistance of the Ag NWs on p-GaAs was characterized by using the transmission line method (TLM) patterns with spacing distances of 10, 20, 30, 40, and 50 μm. As shown in Figure 2c, the current increases linearly with respect to the applied voltage for all distances, and the conductivity becomes lower as the channel distance is increased. From a linear fit of the extracted resistance with respect to the spacing distance, it was found that the contact resistivity between the Ag NW and p-GaAs is \( \approx 7.76 \times 10^{-2} \, \Omega \text{ cm}^2 \).

The Ag NW density-dependent optical and electrical properties were also characterized. The Ag NW-dispersed solution with different Ag NW densities of 0.5 mg ml\(^{-1}\), 1 mg ml\(^{-1}\), 2 mg ml\(^{-1}\), 3 mg ml\(^{-1}\), and 4 mg ml\(^{-1}\) were prepared and spin-casted on a quartz substrate. Figure 2d shows the transmission spectra when various densities of the Ag NW-dispersed solution are spin-casted. The transmission spectrum of a bare quartz substrate was calibrated to 100%. The increased Ag NW density resulted in a lower transmittance throughout the entire visible range. We also characterized the sheet resistance by using the four-point probe method. Figure 2e shows the transmission at \( \lambda = 550 \, \text{nm} \) and the sheet resistance for the various Ag NW densities. It can be observed that there is a trade-off between the transmittance and conductivity when the density of the dispersed Ag NWs changes. It is noted that the sheet resistance exponentially increases as the Ag NW density decreases, reaching an

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**Figure 2.** a) Current–voltage (I–V) characteristics of the spin-casted Ag nanowires (NWs) on p-GaAs before and after thermal annealing at 200 °C for 15 min. b) Scanning electron microscope image of the thermally annealed Ag NWs. The fusions of the NWs at the intersections can be clearly observed. c) I–V characteristics between the Ag NW ohmic contacts on p-GaAs with various spacing distances of 10 μm, 20 μm, 30 μm, 40 μm, and 50 μm. d) Transmission spectra of the Ag NW-dispersed solutions with various densities of 0.1 mg ml\(^{-1}\), 1 mg ml\(^{-1}\), 2 mg ml\(^{-1}\), 3 mg ml\(^{-1}\), and 4 mg ml\(^{-1}\) spin-casted on a quartz substrate. e) The transmittance at a wavelength of 550 nm and the sheet resistance measured by the four-point probe method for various spin-casted Ag NW-dispersed solutions.
order of $10^8 \ \Omega/$sq when 0.5 mg ml$^{-1}$ of Ag NW solution is used. When the Ag NW-dispersed solution with a density below 1 mg ml$^{-1}$ is used, the Ag NW most likely does not form a nanowire mesh as a quasi-continuous contact layer to spread the current. Here, we employed 3 mg ml$^{-1}$ of the Ag NW-dispersed solution for the fabrication of the GaAs bifacial thin-film solar cell to obtain over 80% solar spectrum transmission and achieve good current spreading.

**Figure 3a** shows a photograph of the fabricated GaAs bifacial thin-film solar cells on a CPI sheet. The rear side of the solar cell is also observable through the mirror. The size of one cell is 0.20 cm$^2$. Figure 3b shows the measured external quantum efficiency (EQE) of the fabricated GaAs bifacial thin-film solar cell when the front or rear side is illuminated. For both the front and rear sides, the spectral response of the EQE ranges up to 880 nm corresponding to the bandgap energy of GaAs. The EQE of the front side was higher than that of the rear side in the absorption wavelength range. This can be attributed to two reasons. First, light entering from the rear is only partially transmitted as it travels through the sapphire substrate, CPI sheet, and epoxy layer. The individual transmittance of each layer is more than 90% but the cumulative loss is significant. Second, most of the photo-generated electrons are generated near the back surface field (BSF) layer and must diffuse over longer distances to reach the junction. This results in the loss of more carriers and, thus, a lower EQE in comparison to the case of front illumination.

**Figure 3c** represents the measured current density–voltage ($J$–$V$) characteristics under AM 1.5 G sunlight. The $J_{SC}$ for the front and rear sides of the GaAs bifacial thin-film solar cells are 13.50 mA cm$^{-2}$ and 10.96 mA cm$^{-2}$, respectively. As previously mentioned, a larger $J_{SC}$ at the front side contributes to enhanced light absorption and efficient carrier extraction compared to the rear side. The open-circuit voltages ($V_{OC}$) of the front and rear sides were nearly identical: 0.906 V and 0.902 V, respectively. The fill factors (FF) were 69.82 and 70.31% for the front and rear sides, respectively. A slightly lower value compared to the FF of 76.45% for the monofacial solar cell is due to the higher series resistance across the Ag NWs. The estimated PCE was 8.54% for the front side and 6.78% for the rear side. Additionally, we further investigated the PCE when using thick metals of AuBe and AuGe for the top and back contacts, respectively. The same bifacial GaAs solar cell structure achieved a PCE value of up to 12.72% (front side) and 8.79% (rear side) (see Table S1, Supporting Information). The $J_{SC}$ of the GaAs bifacial solar cell with thick metal contacts was increased to 17.19 mA cm$^{-2}$ (front side) and 20.03 mA cm$^{-2}$ (rear side). The $V_{OC}$ also reached to 1.03 V (front side) and 1.01 V (rear side). A FF of 71.84 and 43.55% was achieved for the front and back sides, respectively.

**Figure 3.** a) Photograph of the fabricated GaAs bifacial thin-film solar cell on a CPI sheet. The rear side of the solar cell is shown through the mirror. b) Spectral external quantum efficiencies for the front and rear sides of the fabricated GaAs bifacial thin-film solar cell. c) Current density versus voltage characteristics for the front and rear sides in the GaAs bifacial thin-film solar cell. The performance of the monofacial GaAs thin-film solar cell is also shown for comparison.
The corresponding I–V curve is given in Figure S1, Supporting Information. The front side FF was enhanced by introducing thick metal contacts instead of Ag NWs, whereas the back side FF was reduced. These results indicate that optimizing the metallization process for the GaAs bifacial solar cell can further improve the performance of the solar cell. Although the bifacial solar cell with the Ag NWs presents a lower PCE here, the fabrication compatibility of Ag NWs on a flexible substrate is higher than conventional metallization processes. As we demonstrated that the annealing process can enhance the ohmic contact between Ag NWs and GaAs, further investigation of annealing effects on Ag NWs may potentially increase the PCE of the GaAs bifacial solar cell. The efficiency ratio of the front and rear sides, also called the bifaciality, is defined as $\eta_{\text{front}}/\eta_{\text{rear}}$, where $\eta_{\text{front}}$ and $\eta_{\text{rear}}$ are the PCEs of the front side and rear side, respectively.[26] The bifaciality of the device is 126% due to the asymmetric p–n junction structure. A monofacial solar cell fabricated with an identical epitaxial wafer exhibited a $J_{\text{SC}}$ of 15.67 mA cm$^{-2}$ and $V_{\text{OC}}$ of 0.913 V, indicating that the overall performance of the GaAs bifacial thin-film solar cell is not as efficient as the monofacial solar cell because the light trapping and photon recycling effect by the back reflector were absent.[27] However, in the presence of albedo light, the bifacial solar cell simultaneously absorbs light via the front and rear sides, potentially outperforming the monofacial cell in field applications.

We calculated the total $J_{\text{SC}}$ of the fabricated GaAs bifacial thin-film solar cell assuming that the solar cell is sufficiently distant from the ground such that the reflected light enters the backside of the solar cell, as shown in Figure 4a. The inset figure represents the AM 1.5 G solar spectrum that is used for the $J_{\text{SC}}$ calculation. We chose seven types of ground conditions on which the solar cell can be potentially installed. In addition to natural surfaces such as grass, soil, sand, and snow, concrete and waterproof green paint that are easily found on parking lots or rooftops of buildings were also considered. Figure 4b shows the spectral reflectance of the seven types of surface materials.[28] A commercially available high-reflection coating demonstrates a reflection of over 90% through the entire wavelength range, and snow has excellent reflection across the solar spectrum. It is worth mentioning that sand also reflects 50% of the incident light for wavelengths greater than 600 nm. Figure 4c shows the estimated $J_{\text{SC}}$ of the fabricated GaAs bifacial thin-film solar cell on various ground conditions. The $J_{\text{SC}}$ of the monofacial solar cell is also shown as a dotted red line for comparison. With a high-reflection coating on the ground surface, the largest $J_{\text{SC}}$ value of 23.17 mA cm$^{-2}$ was theoretically attained. The $J_{\text{SC}}$ on snow was estimated to be 22.52 mA cm$^{-2}$, corresponding to 1.44 times that of the monofacial solar cell. Thus, in regions with frequent or continuous snow, a GaAs bifacial thin-film solar cell would be more efficient than a monofacial solar cell. The bifacial solar cell

Figure 4. a) Schematic representation of the GaAs bifacial thin-film solar cell simulation in the presence of albedo light. The inset shows the spectral irradiance under AM 1.5 G conditions. b) Spectral reflections of various surface materials (concrete, green paint, sand, snow, soil, grass, and Surfa paint). c) Calculated total short-circuit current densities ($J_{\text{SC}}$) for various surface conditions. The $J_{\text{SC}}$ (15.72 mA cm$^{-2}$) of the monofacial thin-film solar cell is denoted by the dotted red line for comparison.
on sand also shows a $J_{SC}$ of 17.07 mA cm$^{-2}$, which surpasses that of the monofacial solar cell. Owing to the considerable light reflection by sand, we expect an improved performance of the GaAs bifacial thin-film solar cell in deserts and beaches compared to monofacial cells. For other surfaces, the bifacial solar cell was comparable to the monofacial solar cell in terms of the total $J_{SC}$. Taking advantage of light absorption from the front and rear surfaces of the solar cell, bifacial thin-film solar cells boast higher efficiencies in most practical solar cell installation environments. In this study, the ARCs were not employed in all the solar cells. A properly designed ARC that considers the refractive indices of the epoxy and CPI sheet on the rear side will further improve the performance of the GaAs bifacial thin-film solar cells.

3. Conclusions

In this study, we investigated GaAs bifacial thin-film solar cells by bonding the active regions on CPI sheets with highly transparent epoxy adhesives. The fabricated bifacial solar cells without ARC demonstrated PCE of 8.54 and 6.78% for front and rear side illumination, respectively, under AM 1.5 G conditions. A larger current generation for the bifacial solar cell was achieved with various ground conditions such as concrete, waterproof green paint, sand, snow, soil, grass, and high-reflection coating compared to conventional monofacial solar cells. It was found that the $J_{SC}$ was increased to 23.17 mA cm$^{-2}$ when a high-reflection coating was applied to the ground surface. Furthermore, by simply positioning the bifacial solar cell on snow or sand, $J_{SC}$ values that were 44% or 31% larger than those of the monofacial solar cell, respectively, were achieved. We confirmed that the GaAs bifacial thin-film solar cells on a properly reflective surface can boost current generation and the PCE by absorbing more light from the rear side. By adding a properly designed ARC, the bifacial solar cell can be further improved, and this will potentially boost the widespread implementation of GaAs thin-film solar cells for niche applications.

4. Experimental Section

**Heterostructure Growth:** Heterostructures were epitaxially grown by metal–organic chemical vapor deposition (MOCVD). Veeco LDMD/180, on 2-inch n-type GaAs wafers with (100) 2° off toward [111]. InGaP etch-stop and AlAs sacrificial layers were grown prior to the growth of GaAs single-junction solar cells. The InGaP layer protects the n-GaAs surface of the active region while removing the substrate.

**Characterizations of the Ag NW Contacts:** The optimal Ag NW density as a contact to GaAs was found by characterizing the transmittance and contact resistance for the various NW densities. The Ag NWs dispersed in isopropanol (IPA) with 1.0 wt% was purchased from Nanopixys (South Korea), and the solution was further diluted to obtain various densities of 0.5, 1, 2, 3, and 4 mg ml$^{-1}$. The Ag NW-dispersed solutions were spin-coated on a quartz substrate and baked at 100°C for 3 min to evaporate the solvent. Then, the sample was annealed at 200°C for 15 min to enhance the conductivity of the Ag NW network by fusing the cross-points of the NWs. The transmittance was characterized in the visible range by using a fiber-coupled white light source (HL-2000, Ocean optics, USA) and a spectrometer (USB-2000, Ocean optics, USA). The sheet resistance $Rs$ [$\Omega$/$sq$] was measured using the four-point probe method.

The identical fabrication method was also applied to form the Ag NW electrode on the p-GaAs substrate to characterize the contact resistance. For an accurate estimation of the contact resistance between the Ag NW and p-GaAs, a TLM pattern was made using a parylene shadow mask. After the deposition of the 100 nm thick SiO$_2$ layer on p-GaAs using plasma-enhanced chemical vapor deposition (PECVD), a parylene-C coating was applied. Standard photolithography and the consecutive dry etchings of parylene and SiO$_2$ exposed the GaAs surface. The Ag NW-dispersed solution was spin-cast and the parylene was mechanically peeled off, leaving the Ag NW TLM pattern. The distances between the pads in the TLM patterns were varied from 10 μm to 50 μm in intervals of 10 μm.

**Fabrication:** The fabrication of the GaAs bifacial thin-film solar cell began with the formation of the Ag NW ohmic contacts. The Ag NWs were spin-casted on a p-GaAs ohmic layer as optimized. The p-GaAs ohmic layer was reduced to 10 nm prior to the Ag NW coating, and the region uncovered by the NWs was further etched away. For fine etching, an aqueous citric acid was used, and the etch rate was characterized to be $\approx$7 nm min$^{-1}$. By preserving the p-GaAs under the NWs, a good ohmic contact was achieved, and optical loss was simultaneously minimized. The p-electrode and metal bus bar connecting the Ag NWs were deposited along the rim of the device to reduce series resistance. Next, the solar cell active layer with the Ag NWs was transferred to the CPI sheet by bonding it with optical epoxy (302-3M, Epoxy Technology, USA) followed by substrate removal in the wet etchant. The epoxy and curing agents were mixed, and the bubbles were removed in a vacuum oven. The mixture was applied by spin coating and a slow thermal curing was conducted at 50°C for 10 h to minimize the strain. The InGaP layer was selectively etched using a dilute hydrochloric (HCl) solution. The front n-electrode and a grid pattern of the n-ohmic contact were formed on n-GaAs by a lift-off process of AuBe/Pt/Au. Finally, the mesa was defined by etching all the layers down using a phosphoric-acid-based etchant (H$_3$PO$_4$+H$_2$O$_2$+H$_2$O:Dl = 2:1:5), resulting in the exposure of the p-electrode.

**Measurements:** Due to the flexible nature of the CPI sheet on which the bifacial solar cells were fabricated, the sample was fixed to a rigid sapphire substrate for easy handling. For reliable bifacial characterization, the flip-pinning stage with small manipulators (TFI-F10, PV Measurements, Inc, USA) was used. Because the sample can be flipped over during probing, the front and rear sides of the bifacial solar cells were independently and carefully illuminated by light sources (e.g., solar irradiation). The EQE was characterized by illuminating a monochromatic light on either the front or rear side of the device and by measuring the short-circuit current. The monochromatic light was obtained by filtering the light from a xenon lamp with a 150 mm focal length monochromator. The wavelength was swept from 400 to 920 nm in a 10 nm interval. The illumination light power was measured using an optical power meter at each wavelength. The EQE was calculated using the equation $\text{EQE} = (I_p\lambda/h\nu) / P_{0\lambda}$), where $I_p\lambda$ is the short-circuit current, $e$ is the electric charge, $P_{0\lambda}$ is the illuminated optical power, and $h\nu$ is the photon energy. The performances of the solar cells (e.g., I–V characteristics and power conversion efficiency) were measured using a class A solar simulator with a xenon lamp under AM 1.5 G illumination. The irradiance of the simulator was calibrated using a reference solar cell to verify the AM 1.5 G illumination before measuring the fabricated devices.

**Simulations:** The total short-circuit currents of the GaAs bifacial thin-film solar cell were calculated on various ground conditions using the measured spectral EQE data. The considered ground types are concrete, waterproof green paint, sand, snow, soil, grass, and high-reflection coating (SurfaPaint ThermoDry, NanoPhos A.E., Greece). The short-circuit current when the ground-reflected light enters the rear side of the bifacial solar cell ($J_{SC,\text{rear}}$) was estimated by considering the measured EQE of the rear side, spectral reflectance of the ground (R), and AM 1.5 G solar spectrum (F), as shown in the following equation $J_{SC,\text{rear}} = \int (F(\lambda) \times R(\lambda)) \times \text{EQE}(\lambda) \times \frac{dh\nu}{dh\nu} d\lambda$, where $h\nu$ is Planck’s constant and $c$ is the velocity of light. The total $J_{SC}$ was obtained by summing the $J_{SC,\text{rear}}$ and the measured short-circuit current ($J_{SC,\text{front}}$): $J_{SC} = J_{SC,\text{rear}} + J_{SC,\text{front}}$. 

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Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
albedo, bifacial solar cells, GaAs, photovoltaics, thin-film

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