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Achieving ~40% power conversion efficiency increase of single-junction GaAs solar cells via temperature regulation

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Abstract

Enhancing the power conversion efficiency (PCE) of solar cells is a constant and essential endeavor to advance the utilization of renewable electricity, especially for space and planetary exploration. The challenge of significantly enhancing the PCE of solar cells is considerable. This report examines the impact of temperature on the PCE of monocrystalline single-junction GaAs solar cells under 450/520/635 nm lasers and achieves ~40% increase over the PCE at room temperature when the temperature is reduced from 300 K to 160 K. The notable enhancement in PCE can be attributed to suppressing the lattice atoms' thermal oscillations and mitigating thermal loss. Below 160 K, however, the radiative recombination produces many low-energy photons, which cannot overcome the GaAs bandgap, resulting in energy loss and a sharp PCE decrease. In addition, the onset of carrier freeze-out effects restricts further increase in PCE. Our study elucidates the optimal operating temperature of GaAs solar cells, paving the way for designing an ultra-high PCE energy supply for planet probes such as the Moon and Mars, where the temperature exceeds 160 K.

Keywords: GaAs solar cells, power conversion efficiency, nonradiative recombination, radiative recombination, temperature regulation



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INTRODUCTION

Solar cells play a significant role in renewable energy because they convert solar energy directly into electricity^[1]. The most critical metric for assessing the efficacy of solar cells is the power conversion efficiency (PCE), which is proportional to the utilization of light energy in solar cells. However, the PCE of single-junction solar cells is theoretically limited by the Shockley-Queisser (S-Q) limit, which indicates that the maximum efficiency achieved by a single-junction solar cell under the standard solar spectrum is about 33.7%^[2], resulting in over 50% of energy losses in thermalization and in-band transparency^[3].

Recent studies have shown that, by inhibiting the lattice atoms' thermal oscillations to suppress thermal loss, the PCE of a single-junction Si solar cell grows to ~51% at 30 K, representing roughly 2.7 times the PCE achieved at 300 K or about two times the record efficiency of 27.3%^[4-6]. This strategy can significantly increase PCE without changing Si-based solar cell structures. Exploring whether the ultra-high PCE achieved by thermal loss inhibition can be applied to other solar cell systems, particularly those with direct bandgap semiconductors, will be interesting.

III-V photovoltaic cells have become popular in solar cells because of their higher PCE than photovoltaic cells made of other photovoltaic materials^[7]. Compared with the traditional photovoltaic material Si, GaAs has a larger bandgap (1.42 eV at 300 K)^[8], higher light absorption coefficient^[9], and better resistance to high temperature and radiation^[10,11], making it particularly suitable for space applications such as artificial satellites and exoplanet exploration equipment^[12-14]. In fact, GaAs space solar cells were first applied to the NTS-2 satellite in 1977^[15]. Although the state-of-the-art efficiency of single-junction GaAs solar cells has reached 29.1% at room temperature^[5], it is unclear what the optimal PCE could be for GaAs solar cells, considering the significant temperature differences in space, especially at low temperatures. Ataser^[16] investigated the temperature dependence of GaAs/c-InN solar cells, revealing a linear enhancement in PCE under AM1.5G illumination across the 400-200 K range, with a remarkable efficiency improvement of 40.3%. This research inspired us to study the properties of GaAs solar cells over a wide temperature range of 10-300 K in order to better serve the extreme temperature environments of outer space. With exploration and base building on the Moon and Mars^[17,18], designing solar cells with the best PCE for different planets where the temperature environment is different is highly desirable for space and planetary exploration but also a considerable challenge.

Although intensive studies^[19,20] have demonstrated similar temperature-dependent trends in various GaAs-based solar cells, the physical mechanism of the temperature-dependent PCE is still unclear. This study investigates the temperature-dependent PCE of n-type single-junction GaAs solar cells irradiated with 450 nm, 520 nm, and 635 nm lasers under non-standard test conditions (see Experimental Section for details) with temperatures from 300-10 K. The monochromatic laser emits photons with fixed energy, thereby eliminating the impact of the uneven energy distribution of visible light on the PCE of solar cells, which is more conducive to investigating the underlying mechanisms. The PCE increases by ~35%-45% from 300 K to 160 K under all monochromatic lasers by inhibiting the lattice atoms' thermal oscillations through temperature regulations. Below 160 K, the photon energy released by radiative recombination is significantly lower than the bandgap energy, preventing photon recovery. Through detailed energy conversion analyses, we successfully elucidated and experimentally validated the dominant loss mechanisms governing PCE degradation. This achievement provides a robust foundation and empirical support for advancing GaAs photovoltaic applications in specialized operational environments, particularly in space-related scenarios where extreme temperature variations are critical performance determinants.

Additionally, the carrier freeze-out effect leads to a significant reduction in carrier concentration. The combination of radiative recombination dominance and carrier freeze-out effects causes a decrease in PCE^[21]. Understanding this phenomenon will dramatically facilitate the energy supply for planets probing within the inner solar system, such as Mars, which has a global average temperature (excluding polar regions) of 170 K^[22].

EXPERIMENTAL

Materials

Single-junction GaAs solar cells with a size of $1 \times 1 \text{ cm}^2$ were purchased from Xiayi New Energy Technology (Xiamen) Corporation. Here, the dopant concentrations of the p-type and n-type doped layers are $1.0 \times 10^{18} \text{ cm}^{-3}$ and $1.5 \times 10^{17} \text{ cm}^{-3}$, respectively. The thicknesses of the p-type doped layer and n-type doped layer are $\sim 500 \text{ nm}$ and $\sim 3 \text{ }\mu\text{m}$, respectively. The 450/520/635 nm diode lasers (LR-MFJ-450/80 mW, LR-MFJ520/80 mW, and LR-MFJ-635/80mW) with a power range from 0 mW to 80 mW were purchased from Changchun Laser Technology Co.

Characterization of photoelectric properties

The test environment for the optoelectronic properties was conducted with a Physical Properties Measurement System (PPMS-9, Quantum Design Co.), which can provide variable temperatures from 1.9-400 K and a helium atmosphere of 10 Torr. The 450/520/635 nm lasers were connected to the PPMS by an optical fiber that can pass light at 300-1400 nm wavelengths. The input power of the laser can be manually adjusted. Light at different wavelengths undergoes attenuation when transmitted through optical fibers. A photometer quantifies the attenuation level by measuring the light intensity at both input (P_{in}) and output (P_{out}) ports. The simple setup diagram is shown in [Supplementary Figure 1](#). Furthermore, the distance between the output port and the cell surface within the PPMS vacuum chamber was precisely adjusted to ensure complete illumination coverage over the entire cell surface. The optical power density incident on the surface was subsequently determined by calculating the ratio of the measured optical power to the cell's effective surface area.

The J-V curves were measured by an external system source meter (Keithley 2612B) with scanning speeds and dwell times of 0.1 mV/step and 0.1 s, respectively. The optical absorption spectra in the 200-1200 nm range were recorded at room temperature by a Hitachi U-4100 ultraviolet-visible-near infrared (UV-Vis-NIR) spectrophotometer. PCE of the AM 1.5G standard solar spectrum was measured at room temperature by a sunlight simulator (SS-X50, Enlitech).

Characterization and fitting of photoluminescence/time-resolved photoluminescence

Photoluminescence (PL)/time-resolved PL (TRPL) data were measured using an FLS980 Spectrometer (Edinburgh Instruments Ltd.) with liquid nitrogen for cooling. Here, the excitation wavelength of light for both characterizations is 532 nm. Variable-temperature carrier lifetime obtained by decomposing fluorescence efficiency. The normalized fluorescence efficiency is numerically equivalent to the radiative recombination efficiency (*RRE*), representing the photon radiation process as a percentage of all energy loss processes. For semiconductors, the energy loss process is related to recombination, which is determined by radiative (τ_{rad}) and nonradiative (τ_{nrad}) recombination. In addition, the photoluminescence lifetime τ_{PL} denotes the total lifetime, including the dynamic changes of τ_{rad} and τ_{nrad} . So *RRE* and τ_{PL} can be expressed by^[23,24]

$$RRE = \frac{\tau_{\text{rad}}^{-1}}{\tau_{\text{rad}}^{-1} + \tau_{\text{nrad}}^{-1}} \quad (1)$$

$$\tau_{PL}^{-1} = \tau_{rad}^{-1} + \tau_{nrad}^{-1} \quad (2)$$

Furthermore, τ_{nrad} is related to the thermal velocity of excitons, which is proportional to $\sqrt{T}$. Taking into account the localization due to temperature variations, τ_{nrad} can be expressed as^[25]

$$\tau_{nrad}^{-1} = C\sqrt{T} \exp\left(\frac{T_0}{T}\right) \quad (3)$$

where T_0 is the degree of localization in temperature. Combined equations (1), (2), (3), the measured fluorescence lifetimes can be decomposed into τ_{rad} and τ_{nrad} , and their temperature dependence can be fitted to the curve.

RESULTS AND DISCUSSION

N-type single-junction GaAs solar cells with a size of 1 cm² have an average thickness of 3.5 μ m for the p-n layer, as shown in [Figure 1A](#). The light absorption pattern is shown in [Supplementary Figure 2A](#). Different monochromatic lasers, i.e., 450 nm, 520 nm, and 635 nm, corresponding to the photon energies 2.76 eV, 2.38 eV, and 1.95 eV, respectively, were used to assess the temperature-dependent photovoltaic performance of the GaAs solar cells.

This paper primarily focuses on the impact of temperature on the PCE of GaAs cells and explores a novel approach to enhancing PCE by suppressing thermal vibrations of lattice atoms. Monochromatic light enables a more precise analysis due to its uniform photon energy. Since solar radiation energy is mainly concentrated in the visible range (400-750 nm), the three selected monochromatic wavelengths-450 nm, 520 nm, and 635 nm-provide a uniform distribution within this region. Given that the bandgap of GaAs is 1.42 eV, corresponding to an absorption wavelength of 873 nm, most light with wavelengths above 873 nm is scarcely absorbed by single-junction GaAs cells. Therefore, the temperature effect on PCE under monochromatic illumination can, to some extent, represent its behavior under the full-spectrum AM 1.5. In this paper, the discussion will primarily be based on the photoelectric properties of the 635 nm laser, serving as a notable illustration of high-energy photon effects.

The current density-voltage (J-V) and power density-voltage (P-V) curves at temperatures of 300 K and 160 K (the temperature close to the maximum PCE) under a 635 nm wavelength laser with a power density of 20 mW cm⁻² are displayed in [Figure 1B](#). The PCE increased significantly from 24.2% $\pm$ 1.2% at 300 K to 34.2% $\pm$ 1.7% at 160 K (average of 3 samples), a roughly 41.3% increase. Forward/reverse scanning overlapping at 300 K and 160 K J-V curves [[Figure 1C](#)] shows no significant difference in the photovoltaic performance of the cell under forward and reverse bias. Steady-state photocurrents/PCE and dark current curves [[Supplementary Figure 2B and C](#)] indicate the stability of the test samples and the reliability of the data.

The temperature-dependent open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF), and PCE are shown in [Figure 2](#) (J-V/P-V curves are shown in [Supplementary Figure 3](#)), and the J-V curve measured under standard test conditions serves as the reference data [[Supplementary Figure 4](#)]. The PCE of AM 1.5 matches that of monochromatic light very well, suggesting that the experimental data for monochromatic lasers are consistent with those recorded for AM 1.5. The V_{oc} monotonically increases with a decrease in temperature, reaching 1.43 V at 10 K [[Figure 2A](#)]. This marks an improvement of approximately 48% compared to room temperature, with a temperature coefficient of -1.66 mV/K, aligning well with the reported data for single junction GaAs solar cells^[26]. The temperature-dependent V_{oc} is expressed as follows^[27]

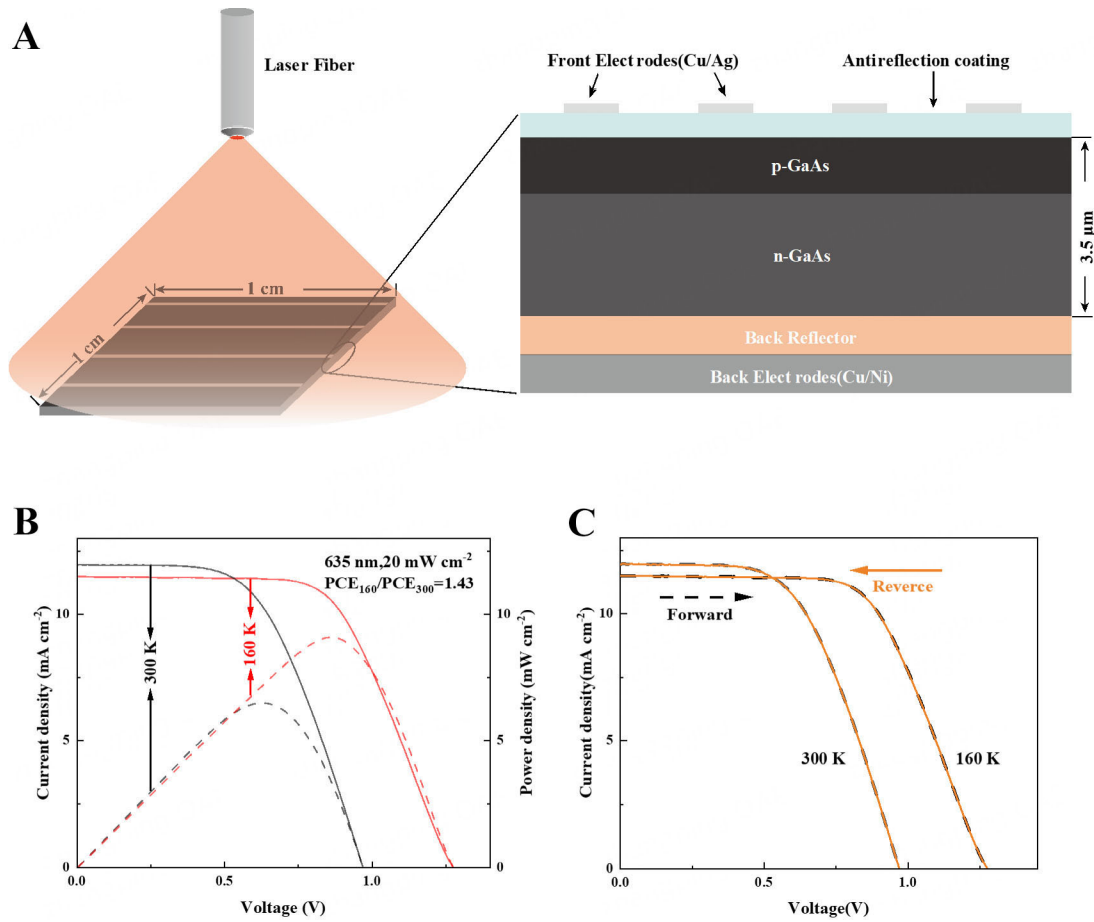


Figure 1. The schematic diagram of the experimental setup and photovoltaic performance of n-type single-junction GaAs solar cells under monochromatic light irradiation of 635 nm with a power density of 20 mW cm^{-2} . (A) Schematic diagram of the experimental setup for photovoltaic performance measurement; (B) J-V/P-V solid/dash curves at 300/160 K. Here, PCE_{300} and PCE_{160} denote the PCE of the cell at 300 K and 160 K, respectively; (C) The forward-reverse J-V curves at 300/160 K. PCE: Power conversion efficiency; J-V: current density-voltage; P-V: power density-voltage.

$$V_{OC} \approx \frac{nkT}{e} \ln \left(\frac{J_{SC}}{J_0} \right) \quad (4)$$

Here, n is the ideality factor, k is Boltzmann's constant, e is the elementary charge, and J_0 is the saturation current density. J_0 depends on the concentration of intrinsic carriers, which decreases exponentially with decreasing temperature^[28] and results in a linear increase of V_{OC} with temperature. In addition, a reduction in temperature will weaken the lattice's thermal vibrations, leading to an increase in carrier mobility^[29,30]. Theoretically, higher carrier mobility will lead to a shorter transport time (cooling time) of hot carriers (including both electrons and holes) and result in a higher V_{OC} ^[3].

From 300 K to 100 K, J_{SC} decreases monotonically with the temperature decreasing at a rate of $\sim 0.04\%/K$ (relative to the J_{SC} measured at 300 K, Figure 2A), close to the reported rate of $0.033\%/K$ ^[31]. The decrease in J_{SC} with decreasing temperature is attributed to the shift of the energy gap and reduction in the diffusion length of the minority carriers^[32]. Below 100 K, J_{SC} decreases rapidly at a rate of $\sim 0.75\%/K$ (relative to J_{SC} measured at 100 K). The previous interpretation no longer applies, implying that a carrier-related effect is responsible for this phenomenon.

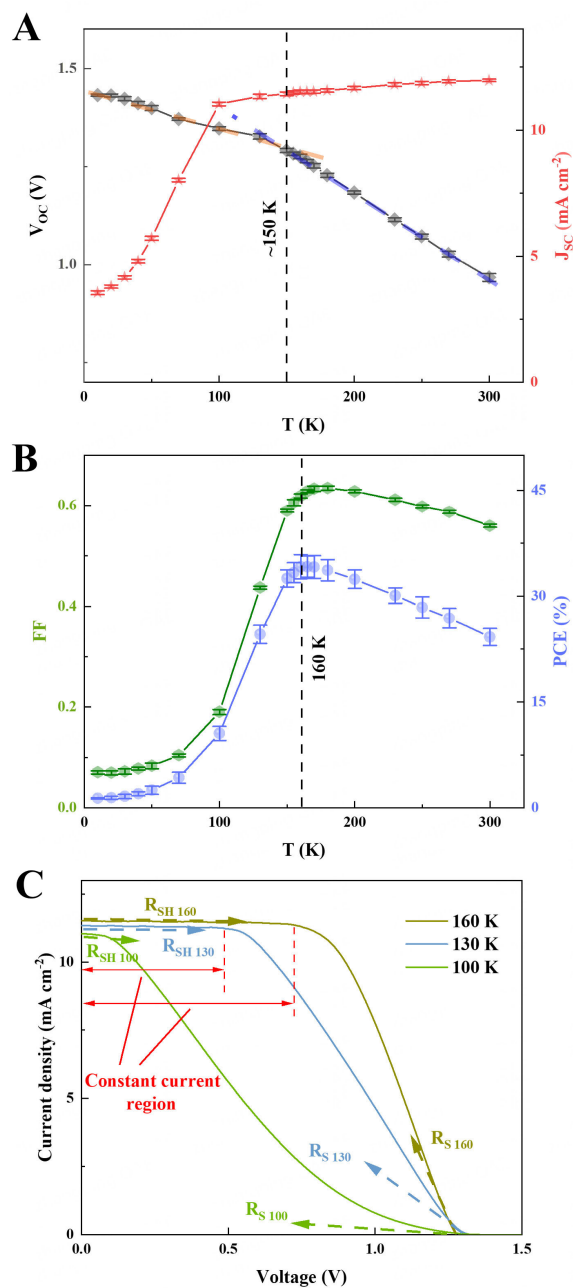


Figure 2. The variable temperature photovoltaic performance of the single-junction GaAs solar cells. (A) V_{OC} and J_{SC} ; (B) FF and PCE; (C) R_S/R_{SH} at different temperatures. The laser is 635 nm with a power density of 20 mW cm^{-2} . PCE: Power conversion efficiency; V_{OC} : open circuit voltage; J_{SC} : short-circuit current density; FF: fill factor.

The changes in PCE and FF [Figure 2B] are more complex but show a similar trend. PCE increases monotonically with decreasing temperature between 300 K and 160 K and reaches the maximum at 160 K, increasing by 41.3% (relative to the PCE at 300 K). The rate of change in PCE follows a rate of $-0.34\%/K$ from 160–300 K, which is slightly higher than the reported rate of $-0.31\%/K$ for GaAs solar cells^[33]. The observed increase in PCE can be attributed to the increase in V_{OC} .

Unexpectedly, PCE decreases dramatically at temperatures below 160 K, with a rate of 0.64%/K. This behavior cannot be explained either from the V_{OC} or the J_{SC} variational temperature profile, suggesting that it must be related to factors affecting FF. FF increases from 0.56 (300 K) to 0.63 (160 K) and then decreases rapidly with decreasing temperature and approaches zero below 50 K, with a value of 0.07 at 10 K.

Indeed, FF represents a significant parameter influencing PCE. **Figure 2B** demonstrates a highly consistent correlation between FF and PCE with temperature. FF is associated with shunt resistance (R_{SH}) and series resistance (R_S). R_{SH} and R_S are related to the slopes of the J-V curves under short-circuit and open-circuit conditions, respectively^[34,35], as illustrated in **Figure 2C**. The constant current region of R_{SH} and the slope of R_S in **Figure 2C** are strongly dependent on the temperature, resulting in the FF decreasing with the temperature. These changes in R_{SH}/R_S should be associated with the conductivity of GaAs cells [Supplementary Figure 5], which reduces significantly when the temperature falls below 160 K, indicating an increase in resistance due to the carrier freeze-out effect at low temperatures^[36,37].

Furthermore, it is noteworthy that the photovoltaic performance (both J-V and P-V curves) of GaAs solar cells under 450/520 nm laser irradiation exhibits similar temperature-dependent trends as observed with the 635 nm laser [Supplementary Figures 6 and 7]. The temperature points corresponding to the highest PCEs are all around 160 K, suggesting that photons with energies higher than the bandgap energy of GaAs should all have similar photovoltaic performance.

GaAs is a direct bandgap semiconductor exhibiting radiative and nonradiative recombination mechanisms^[38,39]. Temperature-dependent PL spectra of the GaAs solar cells under conditions of emission at 532 nm and 1 mW cm⁻² (excitation spectrum shown in Supplementary Figure 8) depict the trend of radiative recombination changes from room temperature to low temperatures [Figure 3A]. Peak A arises from band-to-band transitions, while the generation of peak B is attributed to transitions involving electron-ionized acceptors^[40,41]. Peak A is much higher than peak B, indicating that the former dominates the radiative recombination. The disappearance of peak B above 160 K is due to the release of holes from ionized acceptor centers with increasing temperature^[42]. From the two-dimensional contour map, the rapid rise in PL intensity from 175 K to 145 K suggests a massive production of photons. The bandgap-temperature line fitted by the references^[43,44] shows that both peaks A and B are above the bandgap line [Figure 3A], indicating that the photons released from radiative recombination are hard to absorb by GaAs. This energy loss process leads to a decrease in PCE. The temperature-dependent external quantum efficiency (EQE) derived from J_{SC} , combined with reflection/transmission-corrected internal quantum efficiency (IQE), collectively confirms the predominant contribution of radiative recombination to energy loss near 160 K [Supplementary Figure 9].

Figure 3B illustrates the relationship between the natural logarithm of the PL efficiency and the reciprocal of temperature and fitting curve using the Arrhenius equation, where the PL efficiency is normalized peak PL intensity. The slopes of two different curves correspond to two thermal activation nonradiative recombination mechanisms, denoted as A and B. The relationship between efficiency and temperature is expressed as follows^[45]

$$\eta = \left[1 + {}^A C \exp\left(\frac{-E_A}{kT}\right) + {}^B C \exp\left(\frac{-E_B}{kT}\right) \right]^{-1} \quad (5)$$

where ${}^A C$ and ${}^B C$ represent the ratio of nonradiative to radiative recombination probabilities under mechanisms A and B, respectively. E_A and E_B denote the thermal activation energies, numerically equal to the ionization energies of the corresponding defects^[46]. According to the fitting curve, $E_A = 0.76$ eV, $E_B =$

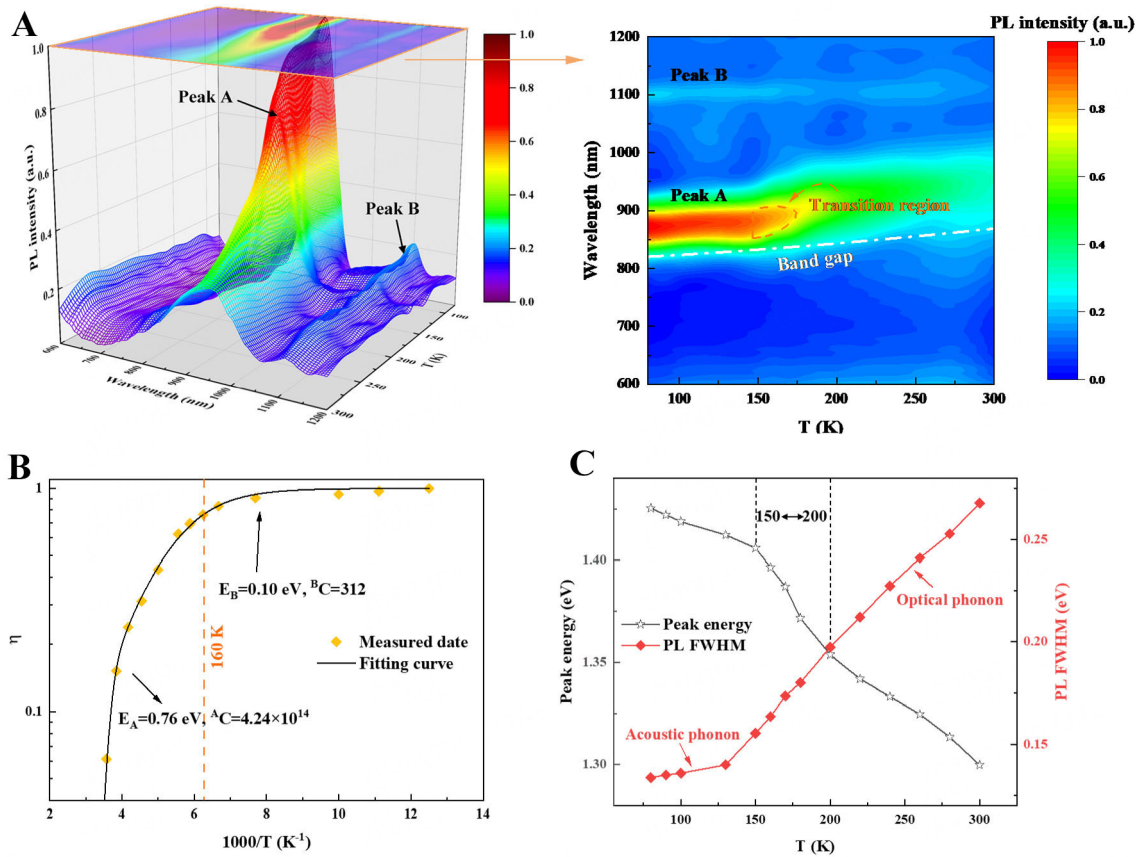


Figure 3. Temperature dependence of photoluminescence of n-GaAs solar cells. (A) Variation of photo-luminescence intensity with temperature in a certain wavelength range; (B) Photoluminescence efficiency as a function of inverse temperature; (C) Peak Energy/PL FWHM vs. Temperature. PL: Photoluminescence; FWHM: full width at half maximum.

0.10 eV, ${}^A C = 4.24 \times 10^{14}$, and ${}^B C = 312$. E_A is the deep impurity energy level, and E_B is the shallow impurity energy level at low temperatures (< 160 K). Such large values of ${}^A C/{}^B C$ indicate that the probability of nonradiative recombination at low temperatures is negligible relative to room temperature^[47,48].

The variation of the peak energy with temperature is shown in Figure 3C, and the slope changes significantly in the 150–200 K interval, indicating that the free carriers change from the bound localized state to the thermally activated state in this interval^[23,49]. Additionally, the full width at half maximum of PL exhibits two distinct temperature trends. At lower temperatures, the dominant influencing factor is acoustic phonons. Optical phonons with higher longitudinal energy become the primary factor when the temperature rises^[50].

Variable temperature TRPL data were measured and fitted with a mono-exponential decay function [Supplementary Figure 10]. The fluorescence lifetime τ_{PL} can be approximated as a minority carrier lifetime^[51,52]. Usually, τ_{PL} can be decomposed into τ_{rad} and τ_{nrad} (see Experimental Section), which vary with temperature as shown in Figure 4A. At 300 K, τ_{nrad} is significantly shorter than τ_{rad} , indicating that nonradiative recombination overwhelmingly dominates the carrier loss mechanism. As the temperature decreases, τ_{nrad} progressively approaches τ_{rad} , suggesting a gradual enhancement in the probability of radiative recombination. Below 200 K, τ_{rad} remains relatively stable, whereas τ_{nrad} exhibits a sharp increase, signifying a rapid suppression of nonradiative recombination and an eventual dominance reversal between these two

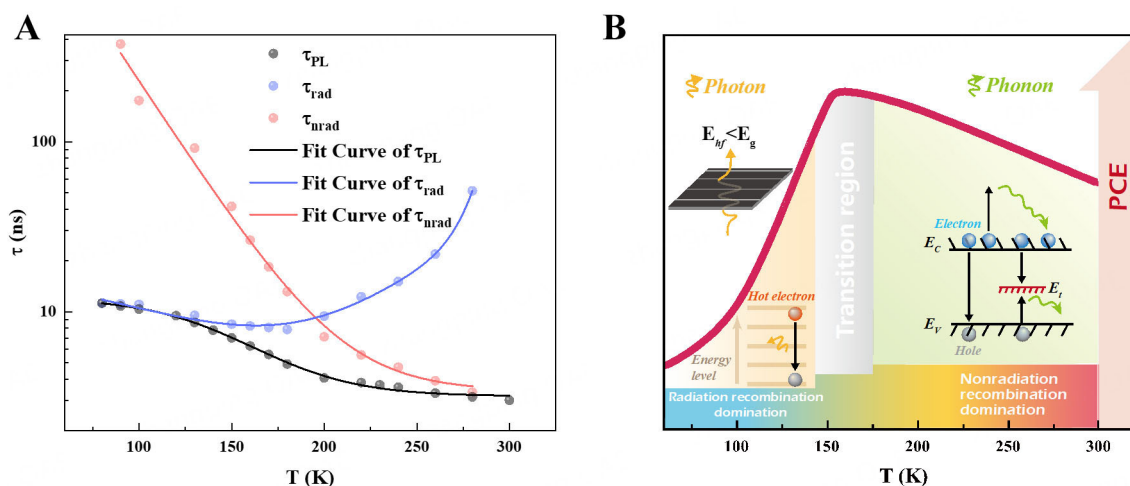


Figure 4. Fluorescence lifetimes of n-GaAs solar cells at variable temperatures and mechanism diagrams. (A) $\tau_{PL}/\tau_{rad}/\tau_{nr}$ variation with temperature data and fitted curves; (B) Mechanism plot of probability vs. temperature for different recombination types; τ_{rad} : radiative lifetime; τ_{nr} : nonradiative lifetime; τ_{PL} : photoluminescence lifetime.

recombination pathways. When the temperature is further reduced below 150 K, τ_{rad} approaches τ_{PL} , while τ_{nr} demonstrates an exponential increase, unambiguously demonstrating that radiative recombination becomes the primary contributor to energy loss processes under cryogenic conditions.

The relationship between J_{SC} and light intensity (I) extracted from J-V curves at different temperatures [Supplementary Figure 11] shows that Auger recombination and Shockley-Read-Hall (SRH) recombination together form an important part of the nonradiative recombination at 300–160 K^[53–56]. The slope of τ_{PL} in 150–200 K is significantly faster than that in other temperature ranges, indicating that the hole lifetimes are most sensitive to temperature within this temperature range. The low τ_{nr} at high temperatures (> 200 K) indicates high nonradiative recombination probability^[57].

Figure 4B illustrates the reasonable mechanism of PCE variation with temperature for GaAs solar cells from the recombination perspective. In the relatively high-temperature region, nonradiative recombination dominates (Includes Auger recombination and SRH recombination, E_t denotes the recombination center located in the forbidden band), and thermal dissipation is the primary cause of energy loss in solar cells, particularly notable for photons possessing energy significantly surpassing the solar cell's bandgap^[58]. The excess energy is released in the form of phonons, thus restricting the achievable PCE values^[59,60]. Phonons embody thermal oscillations of the lattice atoms within a crystal. Therefore, the PCE of monocrystalline single-junction GaAs solar cells can be improved by inhibiting the thermal oscillations of lattice atoms to suppress thermal loss. However, the radiative recombination probability increases rapidly when the temperature is below 160 K. It dominates the transport process [Figure 3A and Figure 4B], in which a large number of photons will be generated, which energy, however, is less than the bandgap and thus difficult to be absorbed by the solar cells, resulting in energy loss in-band transparency. It is important to note that this transformation is not instantaneous but requires a process.

The PCE of monocrystalline single-junction solar cells can be significantly enhanced by inhibiting the thermal oscillations of lattice atoms to suppress thermal loss. However, the maximum PCE temperature for disparate solar cells varies considerably, such as Si^[4] (30–50 K) and GaAs (~160 K), which is attributed to the different mechanisms underlying their respective photovoltaic processes. The causes of such differences

may include distinct transition mechanisms, different lattice vibration scattering patterns, and varying mobility temperature coefficients. Through temperature regulations, an optimal PCE can be achieved for different solar cells.

CONCLUSION

In summary, using temperature regulation, the PCE of monocrystalline single-junction GaAs solar cells can be tuned with high-energy photon lights, i.e., the 450/520/635 nm lasers. The notable enhancement in PCE of ~40% is achieved by reducing the temperature from 300 K to 160 K, which can be attributed to suppressing the thermal oscillations of lattice atoms, thus mitigating thermal loss. At temperatures below 160 K, the carriers shift in recombination dominance from a nonradiative recombination state to a radiative recombination state. The radiative recombination produces many low-energy photons smaller than the bandgap, which are difficult to absorb by solar cells and result in a decrease in energy utilization of incident light. Additionally, the carrier freeze-out effect at low temperatures similarly limits the PCE. The outcomes of this research provide guidance and pave the way for the design of ultra-high PCE for the energy supply of space probes such as the Moon and Mars, where the temperature is above 160 K.

DECLARATIONS

Authors' contributions

Designed the experiments: Li, Z.; Wei, B.

Performed synthesis experiments and photoelectric characteristics with different temperatures: Wang, S.; Tian, B.; Zhao, S.; Li J.

Performed the conductivity characterization with different temperatures: Sun, J.; Zhong, L.

Performed the fitting of fluorescence lifetimes: Wang, S.; Guo, R.

Performed data analysis: Wang, S.; Liu, X.; Li, Z.

Primarily wrote the paper, with all authors contributing: Wang, S.; Li, Z.; Wei, B.

Availability of data and materials

The data supporting this work are provided in the [Supplementary Materials](#). Additional raw data will be available by the corresponding authors upon reasonable request.

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Conflicts of interest

Wei, B. is an Editorial Board Member of the journal *Energy Materials*. Wei, B. was not involved in any steps of editorial processing, notably including reviewer selection, manuscript handling, or decision-making. The other authors declare that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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