

# What is the efficiency limit of a single-junction silicon solar cell?

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## ABSTRACT

Silicon solar cells have an indirect bandgap, and so radiative recombination is an inefficient process. As such, their maximum power conversion efficiency is assumed to be less than the Shockley–Queisser limit, which has historically been associated with the radiative recombination process that results in luminescence radiation. Instead, the Auger–Meitner recombination process that ultimately results in thermal radiation is thought to prevent silicon solar cells from reaching the Shockley–Queisser limit. However, the Shockley–Queisser formalism is fundamentally based on a balance between the absorbed radiation and externally emitted recombination radiation, regardless if this is luminescence radiation or thermal radiation. Therefore, the limiting efficiency of a 1.12 eV bandgap silicon solar cell is 33.4% when the cell is irradiated by the standard AM1.5G solar spectrum and the temperature of the cell is 298.15 K. This revised efficiency limit is larger than the reported efficiency limit of 29.4% for the same solar spectrum and cell temperature. In general, while Auger–Meitner recombination is a loss in light-emitting diodes, it is not necessarily a loss in solar cells. In order to achieve peak power conversion efficiency, luminescence radiation and thermal radiation should be emitted externally out of the cell. Additionally, thinning the cells without sacrificing current density will result in reduced entropy per photogenerated electron, and this will help in the quest to maximize the voltage.

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It is widely assumed that the power conversion efficiency of an indirect bandgap silicon (Si) solar cell is limited by the Auger–Meitner recombination process that results in thermal radiation<sup>1,2</sup> instead of by the radiative recombination process that results in luminescence, which is non-thermal radiation. Since the Shockley–Queisser limit<sup>3</sup> is also referred to as the radiative luminescence limit, it is natural to infer that a thermal emission process such as Auger–Meitner recombination would be considered a loss, leading to reduced power conversion efficiency. Auger–Meitner recombination and Shockley–Read–Hall (SRH) recombination are referred to as nonradiative recombination processes.

Although it will be challenging in reality to completely eliminate all bulk and surface SRH recombination, for the purpose of computing the idealized limiting efficiency of solar cells, it is assumed that there is no SRH recombination. When a solar cell is operated at the open circuit condition, the only available sink for the photogenerated electrons—in the absence of SRH recombination—is through both radiative and Auger–Meitner recombination processes. These are fundamentally intrinsic processes that cannot be eliminated.

So far, it is thought that real Si solar cells are limited by impurity-induced SRH recombination in the bulk of the wafers.<sup>4</sup> In contrast, if it

is assumed that SRH recombination can be eliminated or at least mitigated, then it has been reported that Auger–Meitner recombination serves to limit the efficiency of Si solar cells to a value of 29.4% (AM1.5G solar spectrum, 298.15 K cell temperature).<sup>5</sup>

In the standard Auger–Meitner recombination process,<sup>6</sup> an electron and hole recombine and are annihilated, but instead of this resulting in luminescence, the energy is either transferred to an electron or to a hole. This temporarily excited electron or hole relaxes through dissipative carrier-phonon scattering, a process that results in heating of the solar cell. The heated cell emits thermal radiation. So, in the Auger–Meitner process, electron-hole recombination ultimately creates thermal radiation instead of luminescence radiation. Either way, radiative recombination and Auger–Meitner recombination result in the annihilation of electrons and holes.

We can think of a solar cell as a “bank” and the charge carriers as “currency.” The absorption, and subsequent annihilation, of a photon creates an electron and hole. These charge carriers get “deposited” in the bank, and thus the carrier concentration in the bank increases incrementally. When a photogenerated electron recombines with a hole, they are annihilated and thus “withdrawn” from the bank, incrementally decreasing the carrier concentration. Whether carrier recombination is due to

radiative recombination (resulting in luminescence radiation) or due to Auger–Meitner recombination (resulting in thermal radiation), charge carriers are "withdrawn" from the bank.

In the Shockley–Queisser analysis, the limiting (i.e., maximum) efficiency of the cell is computed from a balance between the absorbed radiation and externally emitted recombination radiation. The externally emitted radiation may be luminescence radiation or thermal radiation. Likewise, different types of radiation sources may irradiate the solar cell. The source could be a polychromatic thermal emitter such as the Sun or an incandescent light bulb, a nearly monochromatic incoherent luminescence emitter such as a light-emitting diode (LED), or a monochromatic coherent luminescence emitter such as a laser diode.

Overall, the radiation absorbed in the cell that generates charge carriers should balance the radiation emitted externally out of the cell due to recombination of those charge carriers. Considering a balance between incoming and outgoing radiation, the externally emitted recombination current density must balance the absorbed current density at open circuit as given by

$$J_{absorb} = J_{emit}. \quad (1)$$

Before continuing, the core assumptions and idealizations that are being made in the Shockley–Queisser detailed balance limit formalism are outlined here: (i) there is no Shockley–Read–Hall recombination, (ii) only photons with energy greater than the bandgap energy are absorbed, (iii) the quasi-Fermi level separation is constant, and (iv) there is no parasitic loss due to series resistance. Additionally, the Shockley–Queisser formalism does not depend on specific details such as cell thickness, dopant concentration, cell polarity (e.g.,  $n$ -on- $p$  or  $p$ -on- $n$  configuration), or contact metal electrode work function.

Now, the recombination current density emitted externally from an irradiated solar cell is given by

$$J_{emit} = \exp\left(\frac{\Delta\mu}{kT}\right) \left[ e \frac{2\pi\gamma E_g^2 k T}{h^3 c^2} \exp\left(\frac{-E_g}{kT}\right) \right], \quad (2)$$

where  $\Delta\mu$  is the quasi-Fermi level separation,<sup>7</sup>  $k$  is the Boltzmann constant,  $T$  is the cell temperature,  $e$  is the elementary charge,  $E_g$  is the bandgap energy,  $h$  is the Planck constant,  $c$  is the speed of light in vacuum, and  $\gamma$  represents the optical media surrounding the cell. If the cell has an ideal backside reflector, then  $\gamma = 1$ ; radiation is only emitted out of the front of the cell into air with refractive index  $n = 1$ . For a bifacial cell,  $\gamma = 2$ ; radiation is emitted out of the front and rear of the cell into air. For a cell constructed on an absorbing substrate,  $\gamma = 1 + n^2$ , where  $n$  is the refractive index of the substrate.

The portion of Eq. (2) in square brackets is the thermal current density when the cell is in the dark ( $\Delta\mu = 0$ ). When the cell is irradiated by an external radiation source, the thermal current density is scaled by the term  $\exp(\Delta\mu/kT)$ . Thus, the Shockley–Queisser formalism describing emission from an irradiated solar cell is actually the thermal current density in the dark scaled by the quasi-Fermi level separation ( $\Delta\mu > 0$ ) that is created when the cell is irradiated and thus no longer in the dark.

For a solar cell in the dark ( $\Delta\mu = 0$ ), absorption and emission of thermal radiation occur at the same rate according to detailed balance and Kirchhoff's law of thermal radiation. Thus, it follows that the thermal radiation emitted as a result of Auger–Meitner recombination

should be included along with the luminescence radiation when computing the detailed balance-limiting (Shockley–Queisser-limiting) open circuit voltage and power conversion efficiency of a solar cell when it is irradiated. Like radiative recombination, Auger–Meitner recombination is intrinsic and is not able to be eliminated. It must be considered as a fundamental process when determining the limiting voltage and efficiency of a Si solar cell.

Recognizing that  $\Delta\mu = eV_{oc}$  where  $V_{oc}$  is the open circuit voltage, Eq. (2) may be substituted into Eq. (1), yielding

$$J_{absorb} = \exp\left(\frac{eV_{oc}}{kT}\right) \left[ e \frac{2\pi\gamma E_g^2 k T}{h^3 c^2} \exp\left(\frac{-E_g}{kT}\right) \right]. \quad (3)$$

Rewriting Eq. (3), the limiting open circuit voltage for a conventional<sup>8</sup> solar cell is expressed as

$$V_{oc} = \frac{E_g}{e} - \frac{kT}{e} \ln\left(\frac{2\pi\gamma e E_g^2 k T}{h^3 c^2 J_{absorb}}\right). \quad (4)$$

For a given bandgap  $E_g$ , and also assuming the cell has been designed with an ideal backside reflector ( $\gamma = 1$ ),  $V_{oc}$  may be made larger by increasing  $J_{absorb}$  with the use of optics to concentrate the incident sunlight and/or by reducing  $T$ .

Solar cells produce power at the maximum power point. The maximum power point voltage is given by

$$V_m \approx V_{oc} - \frac{kT}{e} \ln\left(1 + \frac{eV_{oc}}{kT}\right). \quad (5)$$

Recognizing that  $J_{absorb}$  is approximately equivalent to the short circuit current density  $J_{sc}$ , the maximum power point current density is given by

$$J_m = \frac{J_{sc}}{1 + (kT/eV_m)}. \quad (6)$$

Finally, the power conversion efficiency, shown in Fig. 1, is given by

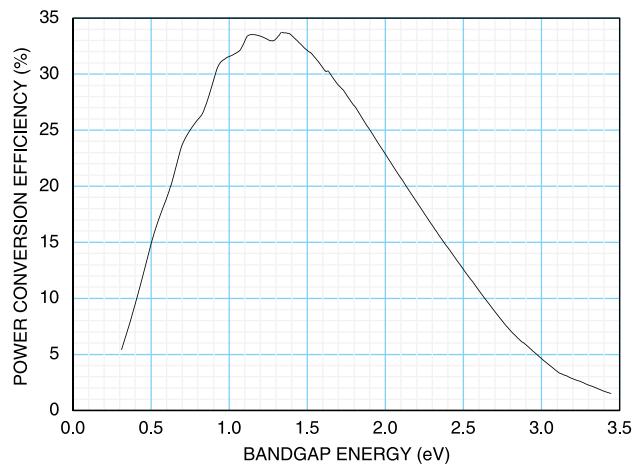


FIG. 1. Limiting power conversion efficiency of single-junction solar cells as a function of bandgap energy (AM1.5G solar spectrum,  $T_{cell} = 298.15$  K, cells have an ideal backside reflector). The limiting efficiency of Si ( $E_g = 1.12$  eV) is 33.4%.

$$\eta = \frac{P_{out}}{P_{in}}, \quad (7)$$

where  $P_{out} = J_m V_m$  and  $P_{in}$  is the irradiance (e.g.,  $0.1 \text{ W cm}^{-2}$  for the AM1.5G solar spectrum).

Although this may seem counterintuitive, we suggest that Auger–Meitner recombination, resulting in the creation of thermal radiation, is not a fundamental loss in a solar cell. Since Auger–Meitner recombination is an intrinsic process, it does not “rob” the cell of charge carriers any more than radiative recombination does. Note, however, that in an LED or laser diode, Auger–Meitner recombination is considered a loss because the purpose of these devices is to successfully convert injected charge carriers into externally emitted luminescence radiation rather than thermal radiation. This point underscores that care is needed when applying reciprocity arguments in an attempt to compare solar cells and LEDs.<sup>9</sup>

At the maximum power point where solar cells actually generate power, the goal is to extract the photogenerated charge carriers. At open circuit, however, the photogenerated electrons cannot remain perpetually in an excited state, so they must recombine. Since Auger–Meitner recombination is an intrinsic recombination process, we suggest that the standard Shockley–Queisser formalism can still be used to compute the limiting efficiency of a Si solar cell.<sup>10</sup> To achieve peak efficiency, both the luminescence radiation resulting from radiative recombination and the thermal radiation resulting from Auger–Meitner recombination should be emitted externally. For solar cells with a backside reflector, the reflector should have high reflectance for luminescence radiation and thermal radiation in order to avoid parasitic absorption in the reflector.

With continued improvements in cell design, cell fabrication, and material purity, it is expected that the AM1.5G power conversion efficiency of Si solar cells will increase beyond the world record efficiency of 27.8% as of September 2025.<sup>11</sup> As the cells are thinned, the voltage should increase as long as the bulk and surface electronic quality are maintained and as long as nearly the same  $J_{sc}$  is realized through advanced light trapping techniques. Note, however, that any increase in  $V_{oc}$  will not exceed the limiting  $V_{oo}$  which is calculated independent of cell thickness. For context, the limiting  $V_{oc}$  for a 1.12 eV bandgap (Si) backside reflector solar cell is 0.879 V (AM1.5G solar spectrum, 298.15 K cell temperature). The previously mentioned world record Si solar cell has a  $V_{oc}$  of 0.745 V for the same solar spectrum and cell temperature.<sup>11</sup>

One of the typical assumptions for the correlation between increased  $V_{oc}$  and reduced cell thickness is that the volume recombination is reduced as the cell is thinned. An intuitive way of thinking about this was previously pointed out by Brendel and Queisser.<sup>12</sup> As long as there is not an appreciable reduction in  $J_{sc}$ , the photogenerated carrier concentration increases for a thinner cell compared to a cell that has the same area but is thicker. As a result, the entropy per photogenerated carrier is reduced in a thinner cell. This is expressed (for an ideal nondegenerate Fermi gas) as

$$s_{carrier} \propto k \left[ \frac{5}{2} - \ln \left( \frac{n_{ph}}{N_C} \right) \right], \quad (8)$$

where  $n_{ph}$  is the photogenerated electron concentration and  $N_C$  is the effective conduction band density of states.

Voltage is related to entropy. Since an increase in  $n_{ph}$  results in a reduction in  $s_{carrier}$ , a thinner cell will have a larger open circuit voltage as shown in the expression given by

$$V_{oc} \propto \frac{kT}{e} \ln \left( \frac{n_{ph} p_{ph}}{n_i^2} \right), \quad (9)$$

where  $p_{ph}$  is the photogenerated hole concentration and  $n_i$  is the intrinsic carrier concentration.

As a point of conjecture, as Si cells are thinned (without sacrificing  $J_{sc}$ ), and as the bulk and surface electronic quality continues to improve (resulting in reduction of SRH recombination), the next generation of Si single-junction solar cells may reach the previously assumed power conversion efficiency limit of ~29.4% and possibly get closer to the Shockley–Queisser limit of 33.4%. Even if an efficiency of “only” 29.1% is achieved in a Si solar cell, this alone will equal the efficiency of the world record direct bandgap GaAs single-junction solar cell as of September 2025.<sup>13</sup>

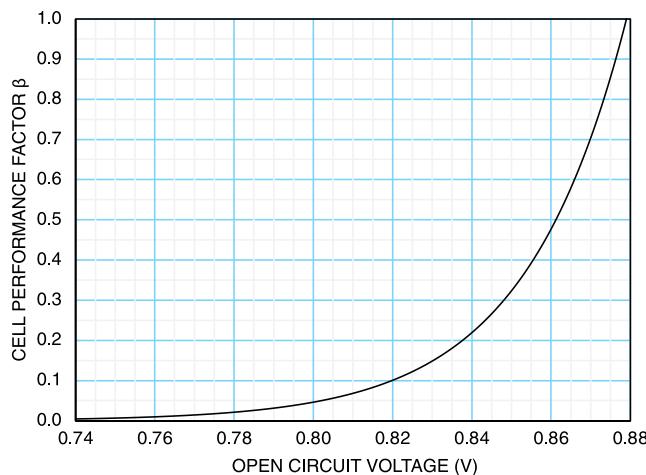
Green and Zhou suggest that Si cells with a thickness  $\leq 60 \mu\text{m}$ , when fabricated with a cross-groove light trapping architecture and located on a single-axis sunlight tracker, can achieve 30.1% efficiency (AM1.5G solar spectrum).<sup>1</sup> Bhattacharya and John suggest that 15  $\mu\text{m}$  thick Si cells with an advanced inverted micro-pyramid photonic crystal light trapping architecture can achieve 31% efficiency (AM1.5G solar spectrum).<sup>14</sup> For clarity, note that Green and Zhou have called into question<sup>15</sup> some of the simulation work by Bhattacharya and John on thinned Si solar cells.<sup>16</sup> A concern is that temporarily trapped radiation may have inadvertently been treated as absorbed radiation, resulting in overestimated external quantum efficiency (EQE).

One way to gauge the progress of Si solar cells is through the  $V_{oc}$ . This may be accomplished with a “cell performance factor”  $\beta$ , expressed as

$$V_{oc\_actual} = V_{oc\_max} - \frac{kT}{e} \ln \left( \frac{1}{\beta} \right), \quad (10)$$

where  $0 < \beta \leq 1$ . When  $\beta = 1$ , the actual  $V_{oc}$  of the cell has reached its maximum (i.e., limiting)  $V_{oc}$ . A plot of the cell performance factor is shown in Fig. 2.

To conclude, Auger–Meitner recombination does not have to be considered as a parasitic loss process in solar cells even though it is a loss process in light-emitting diodes. In the absence of Shockley–Read–Hall recombination, the only remaining sink for the photogenerated electrons at open circuit is via radiative recombination and Auger–Meitner recombination. Thus, in order to achieve an actual balance between absorption and emission of radiation at open circuit, both radiative recombination and Auger–Meitner recombination must be considered, the former creating luminescence radiation and the latter creating thermal radiation. In order to achieve peak power conversion efficiency, the luminescence radiation due to radiative recombination and the thermal radiation due to Auger–Meitner recombination need to be emitted externally from the cell. In other words, extracting thermal radiation from the cell is as important as extracting luminescence radiation. Along with this, parasitic absorption (e.g., as might occur in a suboptimal backside reflector) should be minimized. Also, carefully thinning solar cells—without sacrificing the short circuit current density—will allow the open circuit voltage to get closer to the Shockley–Queisser limit due to the reduction in entropy per photogenerated carrier.



**FIG. 2.** Silicon solar cell performance factor ( $T_{cell} = 298.15\text{ K}$ ). The world record Si cell as of September 2025 had a  $V_{oc}$  of 0.745 V. The limiting  $V_{oc}$  is 0.879 V for 1.12 eV Si (AM1.5G solar spectrum).

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## AUTHOR DECLARATIONS

### Conflict of Interest

The author has no conflicts to disclose.

### Author Contributions

**Alexander P. Kirk:** Conceptualization (lead); Formal analysis (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead).

### DATA AVAILABILITY

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

### REFERENCES

- <sup>1</sup>M. A. Green and Z. Zhou, “Improved silicon solar cells by tuning angular response to solar trajectory,” *Nat. Commun.* **16**, 251 (2025).
- <sup>2</sup>What is referred to as Auger–Meitner recombination in this Letter has historically been referred to solely as Auger recombination. In order to recognize Lise Meitner’s discovery of what is known as the Auger effect before Pierre Auger’s independent observation, it has been proposed that Meitner’s name be added. A discussion of this proposal may be found in: D. Matsakis, A. Coster, B. Laster, and R. Sime, “A renaming proposal: ‘The Auger–Meitner effect’,” *Phys. Today* **72**(9), 10–11 (2019).
- <sup>3</sup>W. Shockley and H. J. Queisser, “Detailed balance limit of efficiency of *p-n* junction solar cells,” *J. Appl. Phys.* **32**, 510–519 (1961).
- <sup>4</sup>B. Steinhauser, T. Niewelt, A. Richter, R. Eberle, and M. C. Schubert, “Extraordinarily high minority charge carrier lifetime observed in crystalline silicon,” *Sol. RRL* **5**, 2100605 (2021).
- <sup>5</sup>T. Niewelt, B. Steinhauser, A. Richter, B. Veith-Wolf, A. Fell, B. Hammann, N. E. Grant, L. Black, J. Tan, A. Youssef, J. D. Murphy, J. Schmidt, M. C. Schubert, and S. W. Glunz, “Reassessment of the intrinsic bulk recombination in crystalline silicon,” *Sol. Energy Mater. Sol. Cells* **235**, 111467 (2022).
- <sup>6</sup>Besides the standard Auger–Meitner process, there is also the trap-assisted Auger–Meitner process. The various trap-assisted mechanisms are outlined in: P. T. Landsberg, C. Rhys-Roberts, and P. Lal, “Auger recombination and impact ionization involving traps in semiconductors,” *Proc. Phys. Soc.* **84**, 915–931 (1964); A discussion of trap-assisted Auger–Meitner recombination in the context of solar cells may be found in: F. Staub, U. Rau, and T. Kirchartz, “Statistics of the Auger recombination of electrons and holes via defect levels in the band gap—Application to lead-halide perovskites,” *ACS Omega* **3**, 8009–8016 (2018).
- <sup>7</sup>The quasi-Fermi level separation  $\Delta\mu$  is created when the solar cell is perturbed by an external radiation source, e.g., the Sun or a solar simulator lamp in a laboratory. The absorption of photons from this external radiation source creates a concentration of photogenerated charge carriers that determines the separation of the quasi-Fermi levels in the irradiated solar cell. Note that photon recycling—in which recombination annihilates electrons and holes and creates either luminescence photons or thermal photons that fail to escape externally out of the cell and instead are trapped internally and eventually absorbed and annihilated—does not result in an increase in carrier concentration.
- <sup>8</sup>The term “conventional” means a standard solar cell that does not rely on hot carrier extraction, intermediate bands, multiple exciton generation, photon up- or downconversion, or any enhancement due to quantum coherence.
- <sup>9</sup>It has been stated that “a great solar cell also needs to be a great light-emitting diode” in O. D. Miller, E. Yablonovitch, and S. R. Kurtz, “Strong internal and external luminescence as solar cells approach the Shockley–Queisser limit,” *IEEE, J. Photovoltaics* **2**, 303–311 (2012). Note that the best Si solar cells as of 2025 are “great” solar cells but “poor” LEDs, underscoring that solar cells and LEDs are not exactly reciprocal devices.
- <sup>10</sup>Based on the online Recombination Calculator from PV Lighthouse (<https://www.pvlighthouse.com.au>), single-crystal Si with  $1 \times 10^{15}\text{ cm}^{-3}$  *n*-type phosphorous doping at 300 K is dominated by Shockley–Read–Hall (SRH) recombination for excess carrier concentration ( $\Delta n = \Delta p$ ) of  $1 \times 10^{12}\text{ cm}^{-3}$  to  $\sim 5 \times 10^{16}\text{ cm}^{-3}$ . Auger–Meitner recombination dominates for excess carrier concentration from  $5 \times 10^{16}\text{ cm}^{-3}$  to  $1 \times 10^{17}\text{ cm}^{-3}$ . If SRH recombination could be eliminated or greatly minimized, then Auger–Meitner recombination dominates radiative recombination for excess carrier concentration of  $\sim 5 \times 10^{14}\text{ cm}^{-3}$  to  $1 \times 10^{17}\text{ cm}^{-3}$ . This highlights that in the Shockley–Queisser formalism (i.e., no SRH recombination), Auger–Meitner recombination must be considered when balancing the absorption and external emission of recombination radiation.
- <sup>11</sup>M. A. Green, E. D. Dunlop, M. Yoshita, N. Kopidakis, K. Bothe, G. Siefer, X. Hao, and J. Y. Jiang, “Solar cell efficiency tables (Version 66),” *Prog. Photovoltaics* **33**, 795–810 (2025).
- <sup>12</sup>R. Brendel and H. J. Queisser, “On the thickness dependence of open circuit voltages of *p-n* junction solar cells,” *Sol. Energy Mater. Sol. Cells* **29**, 397–401 (1993).
- <sup>13</sup>The world record 27.8% efficient Si solar cell as of September 2025 had a designated illumination area of  $133.6\text{ cm}^2$  compared to the world record 29.1% efficient GaAs solar cell with an aperture area of  $0.998\text{ cm}^2$ .<sup>11</sup> Development of either  $\sim 1\text{ cm}^2$  Si solar cells or  $\sim 133\text{ cm}^2$  GaAs solar cells would allow comparison of the power conversion efficiency of state-of-the-art Si and GaAs solar cells on an equal area basis.
- <sup>14</sup>S. Bhattacharya and S. John, “Beyond 30% conversion efficiency in silicon solar cells: A numerical demonstration,” *Sci. Rep.* **9**, 12482 (2019).
- <sup>15</sup>M. A. Green and Z. Zhou, “Light-trapping by wave interference in intermediate-thickness silicon solar cells: Comment,” *Opt. Express* **33**, 37499–37502 (2025).
- <sup>16</sup>S. Bhattacharya and S. John, “Light-trapping by wave interference in intermediate-thickness silicon solar cells,” *Opt. Express* **32**, 29795–29816 (2024).