

Is Auger recombination the ultimate performance limiter in concentrator solar cells?

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In principle, Auger recombination should constitute the ultimate limiting mechanism for concentrator photovoltaic performance as optical concentration, and hence current densities, are raised to progressively higher values. In reality, however, the effect will be rate-limiting only in indirect-band-gap solar cells—a point well established for silicon but not yet explored for germanium which comprises the lowest-energy junction in today's ultraefficient commercial multijunction concentrator solar cells. Detailed calculations of when Auger recombination should play a substantial role are presented, and reinforced by existing data. © 2010 American Institute of Physics. [doi:10.1063/1.3510474]

Auger recombination refers to a three-particle process in which an electron (e) in the conduction band (from photon absorption generating an electron-hole pair) transfers its energy either to a hole (h) in the valence band (ehh process), or to another electron in the conduction band (eeh process). The excess energy transferred to the second particle is released as heat in the lattice (Fig. 1).

The Auger recombination rate R_{Auger} can be expressed as¹

$$R_{\text{Auger}} = C_n(n^2p - n_o^2p_o) + C_p(np^2 - n_op_o^2), \quad (1)$$

where C_n and C_p are the Auger coefficients for eeh and ehh processes, and n and p , respectively, denote electron and hole concentrations under illumination, with the subscript o indicating values under dark (equilibrium) conditions. Because R_{Auger} increases as the cube of carrier concentration, it should become performance-limiting at high carrier injection rates, e.g., in solid-state lasers, high current density light-emitting diodes, and solar cells under high irradiance. The latter should be more pronounced for indirect band gap semiconductors where radiative recombination plays a far smaller role, so even relatively low excess carrier concentrations n_{ex} ("excess" meaning relative to dark conditions) may result in discernible Auger losses. Indeed, earlier studies confirm Auger-limited behavior in silicon concentrator cells (at irradiance values not exceeding the order of 10^2 suns,²⁻⁴ where 1 sun = 1 mW/mm²), reflected primarily in limiting open-circuit voltage V_{oc} .

Present ultraefficient, high-irradiance photovoltaics (PVs) comprise multijunction III-V alloy cells, where the role of Auger recombination has appeared to remain unresolved, including the flux densities at which it becomes significant. This study is prompted in part by improved cells and optics evolving to progressively higher optical concentration (for both economic and efficiency reasons), and the interest in being able to predict at what levels Auger processes are not insubstantial. We focus on the cur-

rent commercial three-junction concentrator solar cell InGaP/InGaAs/Ge—specifically on the Ge subcell because it is an indirect and low band gap material which hence should be primarily responsible for Auger-limiting processes.

The effective lifetime τ_{eff} of a charge carrier derives from three recombination processes that depend mainly on (a) the nature and quality of the semiconductor (direct versus indirect band gap), (b) the doping level, and (c) cell irradiance, and can be expressed as¹

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{SRH}}} + \frac{1}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{Auger}}}, \quad (2)$$

where $\tau_{\text{Auger}} = 1/R_{\text{Auger}}$ [Eq. (1)], and τ_{SRH} and τ_{rad} are the carrier lifetimes associated with Shockley-Read-Hall (SRH) processes (recombination through traps in the forbidden gap) and radiative recombination, respectively (detailed in Ref. 5).

Due to the apparent absence from the published record of information on the doping levels (and even layer thicknesses) of the Ge subcell (ostensibly due to its proprietary nature), base doping levels covering three orders of magnitude are considered toward covering all likely scenarios. (The selected Ge layer thickness of 150 μm is based on both the inspection of commercial three-junction cells and the insensitivity of Auger losses to layer thickness.)

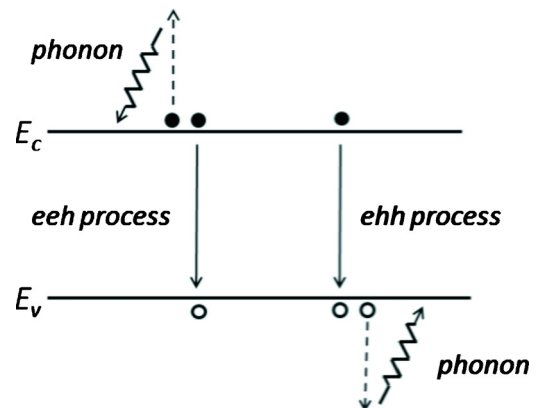


FIG. 1. (Color online) eeh and ehh Auger recombination. E_c and E_v denote the conduction and valence band edges, respectively.

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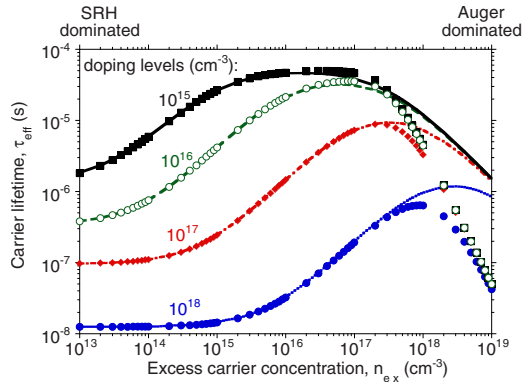


FIG. 2. (Color online) Effective carrier lifetime of a Ge subcell as a function of excess carrier concentration at base doping levels from 10^{15} to 10^{18} cm^{-3} . For each doping level, the symbols indicate results *with* Auger recombination, and the curves correspond to results *without* Auger recombination.

With $C_n = 2.2 \times 10^{-30}$ cm^{-6}/s , $C_p = 5.4 \times 10^{-31}$ cm^{-6}/s [Eq. (1)] and material parameters from Refs. 6–8, τ_{eff} was calculated for the Ge subcell at base doping levels from 10^{15} to 10^{18} cm^{-3} —plotted as a function of n_{ex} in Fig. 2.

τ_{eff} in the low-injection regime are SRH-controlled and depend strongly on the doping-dependent impurity concentration in the forbidden gap. The trap-filling effect (i.e., the decrease in the effectiveness of trap capture due to the smaller number of traps available for electron-hole recombination) leads to a progressive increase in τ_{eff} as n_{ex} increases. The effect of Auger recombination in lowering τ_{eff} grows noticeable when n_{ex} reaches 10^{17} – 10^{18} cm^{-3} (depending on the base doping level), and dominates at higher n_{ex} —a point sharpened by also plotting τ_{eff} in the absence of Auger effects in Fig. 2. These estimates will now be translated into the impact of Auger recombination on photovoltaic performance parameters as a function of flux concentration.

Figure 3 quantifies the effects of Auger recombination on V_{oc} and short-circuit current I_{sc} for a 1.0 mm^2 Ge cell with a p-type doping level of 10^{15} cm^{-3} and a 10^{19} cm^{-3} n-doped emitter, as calculated using PC1D software (a solar cell simulator that solves the coupled nonlinear equations for the transport of electrons and holes).⁹ (Millimeter-scale cells comprise a recent trend in ultraefficient commercial concentrator PVs, and have been shown to suffice with passive heat rejection even at 10 000 suns.^{10,11})

The effects of Auger recombination become perceptible only above ~ 1000 suns for V_{oc} , and even then are modest. And that relates solely to the Ge subcell, which in turn contributes only $\sim 10\%$ of the total V_{oc} of the three-junction device. For I_{sc} , the Auger effect is negligible even at 10 000 suns, at which solar cell operation may already appear impractical. The simplification of excluding cell series resistance was made because it does not affect carrier lifetimes, and the aim here was to isolate the relative contribution of Auger recombination. Because series resistance can only worsen cell performance, its inclusion would render the role of Auger recombination as slightly smaller than deduced here, which only reinforces the conclusion of Auger effects being essentially negligible for ultraefficient multijunction PVs.

Auger recombination should limit the performance of concentrator solar cells at sufficiently high irradiance. The question is how high an irradiance, and whether those values are relevant for concentrator PV. The fact that even the

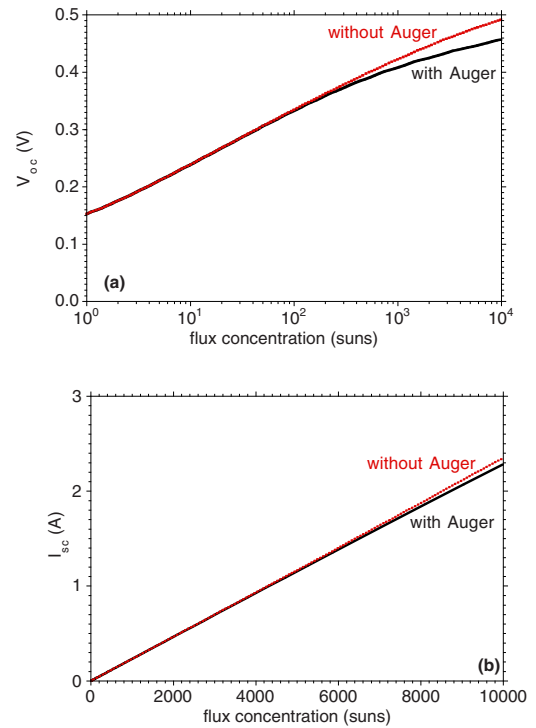


FIG. 3. (Color online) Calculated (a) V_{oc} (semilog plot) and (b) I_{sc} (linear plot), with and without Auger recombination, for a 1.0 mm^2 Ge concentrator cell, as a function of flux concentration.

highest-quality crystalline silicon PVs are Auger-limited at irradiance values well below those implemented in today's III–V PV concentrator systems prompted a closer inspection of the ultraefficient three-junction cells at the heart of many current commercial concentrator photovoltaic systems.

Most commonly, the lowest-energy junction comprises the indirect band gap semiconductor Ge, for which the role of Auger losses at high irradiance has been equivocal. (In fact, only recently has the contribution of Auger recombination in common GaAs–AlGaAs light emitting diodes been evaluated at current densities comparable to those generated in concentrator PVs.¹²)

Analytic and simulation modeling of the effects of Auger recombination on Ge solar cell performance were conducted for a wide range of doping levels, and up to ultrahigh optical concentration. Degradation of cell performance was found to be insignificant up to irradiance levels of thousands of suns.

A prediction of the imperceptibility of a fundamental physical effect prompts revisiting published results for three-junction Ge-based PVs. No evidence of discernible Auger effects in high-efficiency III–V solar cells appears to have been noted, including experiments at irradiance levels of thousands of suns (even up to 12 000 suns).^{10,13–16} Namely, the model predictions here are not inconsistent with the available data, so it would appear that Auger recombination should not represent a detectable limitation for high- and even ultrahigh concentration PVs.

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