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Thermophotovoltaic and Photovoltaic Conversion at High-Flux Densities

Timothy J. Coutts and James S. Ward

Abstract—We first discuss the similarities between generation of electricity using thermophotovoltaic (TPV) and high-optical-concentration solar photovoltaic (PV) devices. Following this, we consider power losses due to above- and below-bandgap photons, and we estimate the ideal bandgap by minimizing the sum of these, for a 6000 K black-body spectrum. The ideal bandgap, based on this approach, is less than that previously predicted, which could have a significant influence on the performance of devices and systems. To reduce the losses, we show that the low-energy photons may be removed from both types of cells and consider the specific case of a back-surface reflector. This approach to the management of waste heat may offer a useful additional tool with which to facilitate the design of high-photon-flux solar cells. In the case of the high-energy photons and the associated problem of thermalization of hot electrons, however, the heat must be removed by other means, and we consider the applicability of microchannel cooling systems. These appear to have the potential to handle thermal loads at least several times those generated by 1000 times concentrators, or by black-body TPV radiators at a temperature of far greater than 1500 K. We go on to consider the management of the very high currents generated in both concentrator TPV and PV systems and discuss the concept of the monolithically integrated minimodule.

I. INTRODUCTION

THE ATTRACTIONS of using solar cells under optically concentrated sunlight are already well understood; both economic and performance advantages may result. Concentrator systems use expensive single-crystal material and the economic advantage comes from the replacement of a large area of expensive semiconductor with much lower-cost optical components such as mirrors or lenses. On the other hand, the additional costs of optical tracking and the ratio of the direct normal to global irradiance, also need to be accounted for before such a claim can be verified. The performance advantage comes from the fact that the short-circuit current density (J_{sc}) increases, approximately in proportion to the flux density, and this causes both the open-circuit voltage (V_{oc}) and the fill-factor (FF) to increase in logarithmic proportion. Hence, the efficiency and power-density output of the cell both increase. The performance of individual cells, under optical concentration, is now approaching or has already exceeded 30% [1]–[3], measured under both the simulated direct and AM0 spectra [4], [5]. All these devices are based on III–V semiconductors, the maturity of which has been an enabling

technology for high-efficiency devices. Rapid progress has been made with both flat-plate and concentrator cells, and at least two U.S. companies are making large volumes of GaAs/Ge single-junction cells [6], [7], resulting in a smaller number of silicon cells now being made for space power supplies. Tandem-cell technologies developed by Avery *et al.* [3], Wanlass *et al.* [1], and Bertness *et al.* [2] are, therefore, of growing interest for a variety of space-based missions. The GaInP/GaAs tandem device developed by NREL [2] is also being manufactured in the United States, and seems likely to take a major share of the space photovoltaic (PV) market in the future.

Despite this progress in device technology, and the interest of public utilities [8] in concentrator systems, the limiting factor now appears to be the optical concentration and tracking mechanisms. Progress has, however, been made by the solar-thermal community in developing cost-effective, reliable means of concentrating sunlight. Single and multiple faceted dishes have been made using lightweight, stretched-membrane facets. These are being used in conjunction with Stirling engine technology [9].

Although the technical benefits have been appreciated for many years, it has often been argued that concentrator solar cells are unlikely ever to be economically attractive. One of the main reasons for this sentiment is that there is a large flux of photons with energies too low to be usefully absorbed in direct transitions by the semiconductor. Unless properly managed, these sub-bandgap photons can heat the semiconductor by free-carrier absorption.

Furthermore, of the potentially useful photons, many have much more energy than the minimum required for optical absorption. This causes photogeneration of hot electrons that, as they thermalize, heat up the semiconductor. Both free-carrier absorption and hot carriers therefore lead to deleterious heating of the semiconductor. These issues are well-known and have been addressed in the development of tandem cells, and in the development of active and passive cooling systems. However, there has been no attempt to resolve the problem at the design stage by modifying the bandgap(s) of the cell(s) according to the losses of above- and below-bandgap photon power. In particular, the incorporation of a BSR can effectively eliminate the negative consequences of sub-bandgap photon power loss. Hence, there may be a good reason to increase the bandgaps of the component cells in the tandem stack to minimize the above-bandgap losses as well.

In some respects, a thermophotovoltaic (TPV) converter bears similarities to a concentrator solar cell. It is, however, placed relatively near ($\sim$2 cm) the radiant surface, which is

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expected to be held at a temperature in the range of about 1300–1800 K. The power-density incident on the TPV cells is therefore far greater than that incident on a flat-plate solar array, and the potential power density output is much larger, because the efficiency is comparable to that of a solar cell. A TPV converter operating in conjunction with a radiator at a temperature of about 1500 K could be expected to generate at least 1 W cm^{-2}, which would require optical concentrations on the order of 50 times or more using concentrator solar cells.[1] For the foreseeable future, TPV *system* efficiencies[2] seem unlikely to exceed 20%. However, this may not be too problematic, particularly in the recovery of "free" high-temperature industrial waste-heat or when the excess heat is to be used for cogeneration.

TPV generation of electricity has begun to reemerge after years of obscurity [10]–[14] and is now being widely investigated for a variety of applications, both military and nonmilitary. In the view of the authors, one of the main reasons for the renewal of interest in TPV is the availability of high-performance PV cells with more appropriate bandgaps for efficient conversion. Previously, when only silicon [15] or germanium [16] cells were available, the electrical power output was poor. Silicon has too large a bandgap to convert enough of the incident spectrum, even if the temperature of the radiator were as high as 2000 K. The performance of germanium cells was poor because of both fundamental and materials-related problems.

II. OPTICAL CONSIDERATIONS

Although a great deal of modeling has been performed to determine the optimum bandgap of a semiconductor p/n PV converter, we wish to take a slightly different approach by minimizing above and below-bandgap photon power losses.[3] The merit of this approach, in the present context, is that it directly addresses issues of losses of power and potential heating of the devices. All sub-bandgap photons are assumed to be nonconvertible, and the power associated with these is, initially, assumed to be lost. Free-charge absorption of sub-bandgap photons is not considered in this paper, even though we recognize its possible influence. Of the above-bandgap flux, there is an increasing power loss per incident photon with increasing photon energy. The actual power lost for a specific incident spectrum depends, of course, on the spectral distribution. The above- and below-bandgap losses must both

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[1] This is a conservative estimate that assumes parasitic thermal and electrical losses may reduce the maximum output power density by a factor of as much as ten. It does not have any fundamental basis.

[2] The system efficiency is simply the electrical energy output divided by the energy content of the input fuel. It includes losses due to all components in the system, rather than only that of the photovoltaic converter with or without sub-bandgap losses, depending on the use or not of a sub-bandgap photon reflector, and its efficiency.

[3] Although we consider photovoltaic conversion in this paper, and use the semiconductor bandgap as a parameter, the approach actually characterizes the source of radiation and it could equally well use a completely different energy parameter. Being specific to the source, it does not take into account the device-specific losses identified by Shockley *et al.* [17], extended by Henry [18], and applied to TPV devices by Cody [19]. In comparison with these, however, the approach is simpler and captures the essential losses inherent with PV conversion.

be accommodated in high-flux PV and TPV systems. First, we shall consider PV systems.

In principle, the maximum optical concentration of sunlight is about 4.6×10^4 times for imaging optics, although higher concentrations have been demonstrated with nonimaging optics. The concentration ratios generally considered to be practicable for use in PV systems are much lower than this, with 1000 times often being taken as the maximum feasible value. However, Diaz *et al.* [20] demonstrated concentration ratios of about three times this value, specifically for PV application. If we take 1000 times as the desired concentration ratio, then the incident power density is on the order of 100 W cm^{-2} (76 W cm^{-2} is more accurate for the direct normal spectrum). We do not wish to minimize the problems involved in designing and operating a system at such high fluxes, but we shall try to demonstrate that they are not insurmountable. Much higher fluxes than 1000 times could be accommodated with advanced cooling techniques that are currently available, as will be discussed later. The analysis makes many idealizing assumptions, but the necessary points still emerge. We shall first calculate the fraction of the incident power that is above the bandgap of a single-junction cell, i.e., the power that can only be dissipated by thermalization of hot electrons.

The total incident spectral power-density is given by Planck's equation

$$F[T_{\mathrm{emit}}, E]$$
$$= \left(2 \times 10^{-4}\pi\right)\left(e^4/h^3 c^2\right)E^3/[\mathrm{Exp}(E/kT_{\mathrm{emit}}) - 1] \quad (1)$$

where

e	electronic charge;
h	Planck's constant;
c	speed of light;
E	photon energy;
k	Boltzmann's constant;
T_{emit}	absolute temperature of the radiant surface.

The value of T_{emit} is taken as 6000 K, as an approximation to that of the sun's surface. In (1), the dimensions are W cm^{-2} eV^{-1}. The fractional available power lost in the thermalization of above-bandgap photons is therefore given by

$$\mathrm{FAPL}[T_{\mathrm{emit}}, E > E_g]$$
$$= \int_{Eg}^{\infty} E^2(E - E_g)/[\mathrm{Exp}(E/kT_{\mathrm{emit}}) - 1]\,dE$$
$$\div \int_0^{\infty} E^3/[\mathrm{Exp}(E/kT_{\mathrm{emit}}) - 1]\,dE \ \ \text{for } E \geq E_g. \quad (2)$$

The same procedure may be repeated for the fractional loss of sub-bandgap photons using a slightly modified form of (2), viz

$$\mathrm{FAPL}[T_{\mathrm{emit}}, E < E_g]$$
$$= \int_0^{Eg} E^3/[\mathrm{Exp}(E/kT_{\mathrm{emit}}) - 1]\,dE$$
$$\div \int_0^{\infty} E^3/[\mathrm{Exp}(E/kT_{\mathrm{emit}}) - 1]\,dE \ \ \text{for } E < E_g. \quad (3)$$
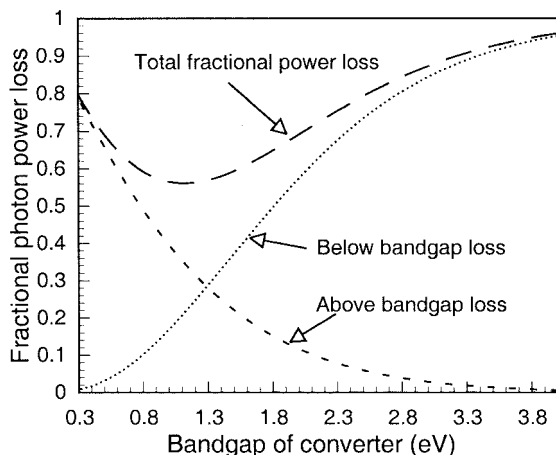
Fig. 1. Modeled total fractional photon power-density loss as a function of bandgap. The radiator temperature was taken as 6000 K. The minimum total loss is about 57.2% for a bandgap of approximately 1.13 eV.

Equations (2) and (3) are both dimensionless and their sum gives the total fractional power loss. This, together with the above- and below-bandgap fractional losses, is shown in Fig. 1. Notice that, at the minimum of the total loss curve, the bandgap is about 1.12 eV and the total fractional power loss is 57.2%. Therefore, for 1000 times concentration, and a one-sun spectrum normalized to 100 mW cm^{-2}, 57.2 W cm^{-2} must be extracted from the cell if it is to remain near room-temperature. Therefore, on the basis of the unavoidable photon power losses alone, only 42.8% of the incident power density can possibly be used by a single junction cell.

To some extent, the very-high concentration ratios considered here have already been demonstrated. A module was developed by Kuryla *et al.* of Varian Inc., that was operated at 1000 times, using a point-focus concentrator system [21]. The module had an efficiency of 22.3%, and it used small-area cells with lateral heat-spreading to minimize the increase in temperature. A single small-area (0.203 cm^2) cell was also made that had an efficiency of 28% [22]. Hence, about 28 W cm^{-2} of the potentially useful incident power density of 42.8 W cm^{-2}, calculated above, was extracted as electrical power. The remaining 14.8 W cm^{-2} deficiency, can be attributed to recombination losses above and beyond radiative recombination, parasitic losses in the grids, optical shadowing due to the grids, a less-than-100% effective antireflection coating and, possibly, other mechanisms. Note that the above power-densities must all be scaled down by 85%, to relate to the global spectrum, or by 76% for the direct normal spectrum.

A significant reduction in the total power loss may be achieved by using tandem cells with two or more junctions. If a converter with a bandgap greater than that of the initial converter is added, the effect is to reduce the energy lost in thermalization of hot electrons, with a small increase in the total sub-bandgap losses. If a converter of lower bandgap is placed beneath the initial cell, the effect is to reduce the sub-bandgap losses, with a small increase in the above-bandgap losses. To obtain Fig. 1, we used a black-body spectrum with a radiator temperature of 6000 K, as an approximation to the sun, rather than any of the standard reference spectra (AM0, direct normal, or global) in order to simplify the calculations.

The efficiency of PV cells, as limited only radiative recombination was originally modeled by Shockley *et al.* [17] with an extended version of this model being developed by Henry [18]. Henry included losses due to radiation of photons associated with recombination of excited charge, into three dimensions. Entropy is added to the system as well as energy being lost from it. De Vos [23], more recently, presented a fine tutorial on the thermodynamics of endoreversible heat-engines, including the solar cell. Two results were obtained for the device performance, one of which was identical to that of [17] the other being very similar and differing only in the vicinity of the open-circuit voltage. Cody [19] used the radiative recombination formulation in predictions of ultimate efficiency of p-n junction silicon solar cells and made the point that far higher efficiencies could probably be achieved in many types of solar cell, provided the work was supported by a long-term, consistently funded program of work. Gray *et al.* [24] used the de Vos formulation to calculate the power density output and efficiency of TPV cells for a variety of broadband and spectrally selective radiators. Cody [19] also made the critical point that the optimum bandgap of a TPV converter, based solely on radiative recombination, is much lower than that predicted using the semi-empirical approach of Wanlass *et al.* [25]. In addition, the predicted output levels were two to three times larger than that predicted by Wanlass *et al.* [25]. Given this situation, and anticipating later results, it was pointed out that the TPV community ought to be investigating lower bandgap semiconductors. Although these may have problems with Auger recombination, there are means of reducing this problem.

There are as many issues in the design and optimization of TPV systems as there are with PV systems. Here we consider only the cells, rather than other vital components in the system. First, it is interesting to normalize the x-axis above by dividing by the thermal energy of the radiator (kT_{emit}). For solar radiation (for which we have used $T_{\text{emit}} = 6000$ K), the thermal energy is equal to 0.517 eV, so the minimum loss occurs for $x = 2.17$ ($E_g = 1.12$ eV). For a TPV cell used with a radiator having a temperature of 1500K, the minimum loss occurs for a bandgap of about 0.283 eV, which, when divided by kT_{emit} (0.129 eV), also gives 2.17. These results are identical to those obtained from the Shockley and Queisser theory [17].

A black-body radiator at a temperature of 1500 K emits about 28 W cm^{-2}, which increases to 90 W cm^{-2} for $T_{\text{emit}} = 2000$ K. Hence, with a view-factor of unity, this is also the power density incident on the TPV converter. Therefore, a 2000 K radiator produces as high a flux-density on a TPV cell as would a 1000 times solar concentrator on a PV cell. As indicated above, the TPV converter must have a much lower bandgap than a well-designed PV converter to account for the large differences in spectral distributions. The output power densities for TPV, with very high-temperature radiators, would therefore be similar to those from PV cells used with 1000 times concentrated direct normal sunlight.

According to the photon power loss minimization model described above, the ideal bandgap of a p/n converter used with a radiator at a temperature of 1500K, should be about
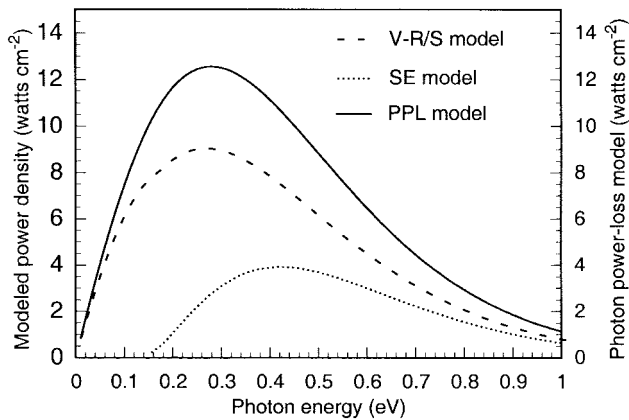
Fig. 2. Comparison of the modeled power-density outputs from a TPV converter with a radiator at 1500 K. The upper line (refer to the left-hand axis) shows the minimum useful power after deduction of sub-bandgap and above bandgap losses. The center curve represents the model of Shockley *et al.* [17] and the bottom curve represents the semi-empirical model [25].
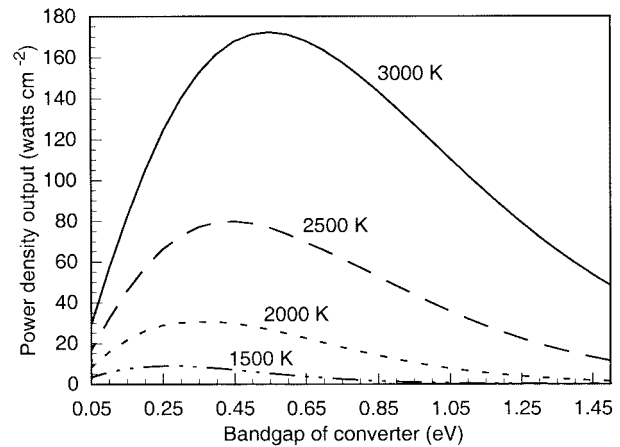

Fig. 3. Power-density output as a function of bandgap of the converter with the radiator temperature being treated parametrically. The theory of [17] was used to calculate the power-densities. The point is clear that the optimum bandgap increases significantly with radiator temperature.

0.28 eV, which would give a maximum useful incident power density of 12.6 W cm^{-2}. The device model of Shockley *et al.* [17], gives an identical bandgap for a maximum power density output of about 9.0 W cm^{-2}, corresponding to an efficiency of about 31.5%, without sub-bandgap photon recirculation. If the efficiency is calculated without including the sub-bandgap photons, then it increases to about 40%. On the other hand, the semi-empirical model of Wanlass *et al.* [25] indicates that the optimum bandgap is 0.422 eV which would give a resulting power density output of 3.9 W cm^{-2} and an efficiency of about 24.7%, for perfect sub-bandgap photon recirculation. These differences arise from the underlying assumptions in the models concerned. The photon power-loss minimization model, introduced here, is only a means of characterizing the radiative source and it makes no assumption about the nature of the conversion process, nor about recombination mechanisms. The model of [17] is based on radiative recombination as the limiting process in a p/n junction solar cell. Fig. 2 shows a comparison of the power density outputs for the three models, for a radiator temperature of 1500 K. Fig. 3 shows the effect of radiator temperature, using the radiative recombination model. This clearly shows that the optimum bandgap increases with increasing temperature, as is the case for the other models considered. This diagram was also shown by Gray *et al.* [24], as were several others, for a variety of spectral parameters.

Radiative recombination losses represent the minimum loss possible in the PV conversion process and they arise because of the principal of detailed balance between the rates of creation and recombination of photogenerated carriers. The photon power loss minimization model makes no such statement about recombination but simply enables us to calculate the maximum power output on the basis of above and below bandgap losses. It does not consider what happens to the excess energy, but simply estimates its magnitude. Finally, the semi-empirical model [25] implicitly assumes that it is unnecessary to specify the precise mode of recombination and simply draws on a large number of measured values of the reverse saturation current density for many devices of widely differing bandgaps. This approach enabled the reverse saturation current density to

be empirically related to the bandgap and the temperature. All three approaches assume a view-factor of unity in the modeling of TPV devices, and neglect the possibility of parasitic losses. While a view-factor of unity is not entirely unreasonable for a TPV device, it most certainly is for a PV device. The radiative recombination model neglects an effect that was introduced by Henry [18] that accounts for the increase in entropy of the semiconductor converter as it radiates photons created in the recombination of the photogenerated carriers. This further reduces the maximum efficiency. This theory was developed for solar cells but would be equally applicable to TPV converters.

As is well known, much of the incident infrared spectrum occurs for sub-bandgap wavelengths, and the consensus of the TPV community is that some form of mechanism for returning the sub-bandgap photons to the radiator is required. Obviously, this is not a realistic possibility for PV cells. However the possibility of using the sub-bandgap photons in some other conversion process, must not be totally neglected. The return of sub-bandgap photons may be achieved with front-surface and/or back-surface optical components, with varying degrees of success. In the next section we shall discuss the monolithic integrated mini-module (MIM), which uses back-surface reflection (BSR), in conjunction with a semi-insulating substrate. This has the distinct advantage that the sub-bandgap radiation is not absorbed by the substrate, thereby reducing the total photon power loss to only the above-bandgap thermalization component. It must also be remembered that use of a two-junction TPV cell could have a further advantage in reducing either the above-bandgap thermalization losses or the below-bandgap losses (depending on whether the second cell is placed above or below the initial cell) mentioned earlier. Although the reflected sub-bandgap radiation would not contribute to the cell efficiency, as is the case with TPV, its removal may be regarded as a means of thermal control, which is potentially very valuable for high concentration ratios. Indeed, if we assume that the sub-bandgap radiation can be largely removed from the PV cell, this may modify the choice of bandgaps in multijunction

stacks. The primary concern will remain, however, current-matching between all the cells in the stack.

It is also interesting to observe the direction that the TPV community has taken thus far, in relation to the predictions of the above models. Early work on TPV conversion used silicon [15] or germanium [26], simply because these were the only semiconductors available. However, silicon has too large a bandgap for a broadband spectrum, and the properties of germanium were inadequate. At present, the only commercially-available TPV system uses GaSb converters with a bandgap of about 0.73 eV [27]. According to all three models discussed above, this is still far too large to approach optimum performance and there has been a gradually increasing effort in recent years to develop converters with much lower bandgaps, 0.5 eV apparently being a realistic target [14] as will be discussed later. This direction has been guided by the empirical model of Wanlass *et al.* [25], rather than the more fundamentally-based models of Cody *et al.* [19], or the present paper. The major difference in these is the magnitude of the reduction needed to achieve optimum converters. This is caused by the neglect of a specific recombination mechanism in the semi-empirical model, whereas the theory of Shockley *et al.* [17] specifies radiative recombination. The principal attraction of GaSb is its manufacturability and relatively low cost. The two approaches presently being considered as a means of achieving a bandgap of about 0.5 eV, use either lattice-mismatched InGaAs, grown on an InP substrate [28], [29], or lattice-matched InGaAsSb, grown on a GaSb substrate [30], [31]. Excellent quality devices have been fabricated using both approaches and it is not yet clear which is the better choice, although recent indications seem to favor the latter [32]. However, the target of 0.5 eV is still significantly higher than suggested by the models and, so far as we are aware, no effort is yet being made to reduce the bandgap to even lower levels. Even though lower bandgaps would lead to even higher current densities, this could readily be mitigated using the MIM construction discussed in the next section. We therefore believe that there is a great opportunity for further progress by pursuing the development of these lower bandgap devices. So far as we are aware, there is no fundamental reason not to do this, even though one might speculate that additional recombination mechanisms (such as Auger recombination) may increase rapidly with decreasing bandgap.

The introduction of the optical component to return sub-bandgap photons to the radiator raises the interesting issue of how to define the term "efficiency." When one considers only the discrete device, the definition of efficiency is simple—electrical power out divided by total optical power in. With this definition, the semi-empirical model suggests a typical TPV device has a disappointingly low efficiency of less than 10%. However, when the sub-bandgap photon power is subtracted from the denominator of the above expression (under the assumption that these photons are all returned to and reabsorbed by the radiator), the modeled efficiency can increase to 30% or more, depending on radiator temperature. It is important to make this distinction clearly to those outside the TPV community. The efficiency of the complete system is much lower again than that of the device, because there are additional components, each of which has an efficiency less than unity. The reported efficiencies of several prototype systems are typically in the range up to about 6%. If thermal output is included in the numerator of the above expression, then the efficiency is greatly increased, but its definition is then less transparent and somewhat questionable. It is therefore important to define what is meant by "efficiency" in the context of TPV conversion. At the end of this section, it is important to stress that many assumptions are implicit in each of the models discussed here, and the reader must consult the original papers to learn more about these.

III. DESIGN AND FABRICATION OF MONOLITHIC INTEGRATED MINIMODULES (MIM's)

The issues in minimizing losses for high-flux PV power conversion devices are not limited to those of spectral utilization described in the last section. In addition to the power lost due to mismatch of the incident photons and the bandgap of the converter, there are the ubiquitous Joule losses associated with current flow both through the semiconductor and the metal grid structure of the device.

At high fluxes, high currents are generated, and the need to limit these currents to manageable levels defines both the dimensions of the grid structure (line width and separation) and the maximum size of the device. As an example, at a concentration ratio of 1000 times, and under the direct spectrum, a GaAs cell is expected to generate a current density of about 28 A cm^{-2}. The traditional method for dealing with this reality has been to use very small devices. However, even a small GaAs device of only 0.25 cm^2, will generate about 7 A. Currents of this magnitude typically require relatively large areas devoted to bus-bars and cell interconnects. Therefore, high-flux systems have typically used point-focus optical elements. In these systems, the high flux is focused on a relatively small active area; the bus-bars and interconnects are placed on the nonilluminated areas between the cells.

Monolithic integration provides an alternative method of dealing with high current densities, and it involves creating an array of small devices, connected in series during the fabrication process. This offers two potential advantages. First, the practical lower limit of the size of the component cells is drastically reduced, making it feasible to design large-area arrays that can be used with concentrating optics, that necessarily result in large illuminated areas, such as dishes and heliostats. Much larger concentration ratios may also be considered because the photocurrents may be reduced arbitrarily by reducing the area of the subcells. Second, fabricating these arrays on semi-insulating substrates allows the incorporation of a highly effective BSR. Free-carriers in a conductive substrate will absorb a portion of sub-bandgap flux (an aspect that was neglected in the previous section). In the TPV application, these sub-bandgap photons represent a large fraction of the incident flux and must be returned to the radiator to achieve high conversion efficiency for the system [33]. In the PV application, at very high fluxes, absorption of a significant fraction of the sub-bandgap flux will result in heating of the
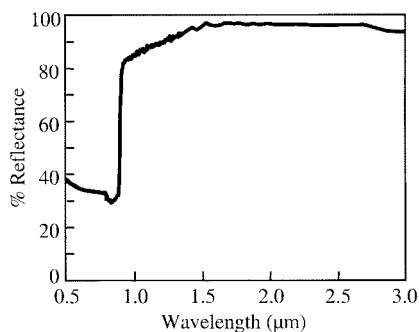
Fig. 4. Reflectance of a prototype back-surface reflector. This was a semi-insulating GaAs substrate that was coated with a film of gold on its back surface.
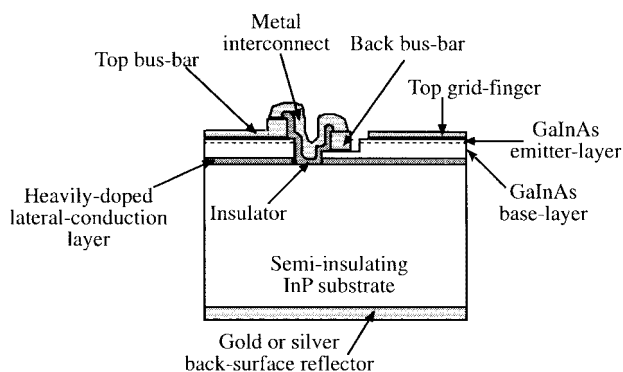

Fig. 5. Schematic of a conventional MIM. This makes the point that the electrical limitation is the lateral conduction layer, which must carry all the current from the top of one cell to the back of the adjacent cell.

devices, putting an additional load on the cooling system. Monolithic integration, with its potential for an effective, integral BSR, offers a strategy for dealing with both the Joule losses and the sub-bandgap optical losses associated with high-flux PV conversion. When used with multijunction cell design (which also reduces the generated current density), it offers the possibility of designing PV converters that could operate at very high flux densities, previously considered impractical. Fig. 4 shows the total reflectance from a semi-insulating GaAs substrate with a specular gold film on the back surface. This was not a device and did not have device layers but serves to make the point that the reflectance in the sub-bandgap region approaches 100%. The BSR approach would therefore be effective as either a thermal management tool in PV concentrator devices or as a photon recirculation tool in TPV devices.

One of the first descriptions of monolithic integration for III–V devices was given by Borden [34], and it concerned work done at Varian Associates, Inc. in the late 1970's. These GaAs devices were epitaxially-grown on semi-insulating, Cr-doped, GaAs substrates. It featured a top-contact metal-grid structure and a heavily-doped lateral conduction layer (LCL) located below the base layer of the device for current transport to the interconnect point. The interconnect itself was accomplished through a dedicated metallization structure. Effectively, a top-contact bus-bar from one cell was bridged to a back-contact bus-bar from the adjacent cell. This back-contact bus-bar was positioned within an etched trench, that penetrated the structure to the top of the LCL.

In the early 1990's, Wojtczuk *et al.* [35] reported an essentially identical approach using GaInAs lattice-matched to an InP substrate. The original intent was to use these devices as converters for laser-power beaming applications. Soon thereafter, researchers at NASA Lewis Research Center recognized the potential of the monolithic approach for TPV conversion [36]. It was only then that the significance of an integral BSR, and the ease with which it could be implemented in this device configuration, was first recognized. Fig. 5 shows a cross-sectional schematic diagram of this device developed for TPV, which used an InP substrate [37]. Most of the initial work on this device was done for relatively low radiator temperature (1000–1200 °C) applications. Depending on the bandgap used, current densities of between 1 and 6 A cm^{-2} are expected for this application. Even at these relatively low

current densities, current flow through the lateral-conduction layer is problematic, and the dedicated interconnect structure consumes a large fraction of the active area.

In response to these concerns, an interdigitated design was developed that used the grid fingers of the component cells as the interconnect structure [38], [39]. A simplified plan-view of this design, and an electron micrograph of an actual structure, are shown in Fig. 6. The advantages of this approach include an increased flexibility in the size of the component cells and, hence, the output parameters, as well as potentially higher current handling capacity. A potential drawback, however, is the possibility of light-trapping due to diffraction of incoming incident light by the etched features used for placement of the back-contact grid structure [40]. Trapped sub-bandgap light is problematic for the TPV application because it will eventually be absorbed by free carriers in the active layers of the device. Alternative designs may be required to overcome this important issue.

Through the use of processing techniques developed by the microelectronics industry, it is reasonable to expect that monolithically integrated designs will be developed that will be capable of dealing with extremely high current densities. When used with multijunction cell designs that reduce both current densities and the heat generated by above- and/or below-bandgap losses, it may be possible to design practical converters that can operate under extremely high flux densities (significantly greater than 1000 times) over relatively large areas.

IV. THERMAL MANAGEMENT

As discussed in the previous section, the BSR approach may be used to reduce, or eliminate, the below-bandgap power losses. At 1000 times, 23.5 W cm^{-2} of power is dissipated in thermalization of hot electrons and can only be removed by external cooling. We should also point out again, that we do not consider a concentration ratio of 1000 times to be an upper limit. Indeed, we feel that the real potential for concentrator technologies possibly lies in even higher fluxes, such as those experienced in solar furnaces, and nonimaging optical systems [41], [42]. The attraction of this approach is that much larger areas could be used than discussed earlier [22] because the solar radiation is not focused to a point.
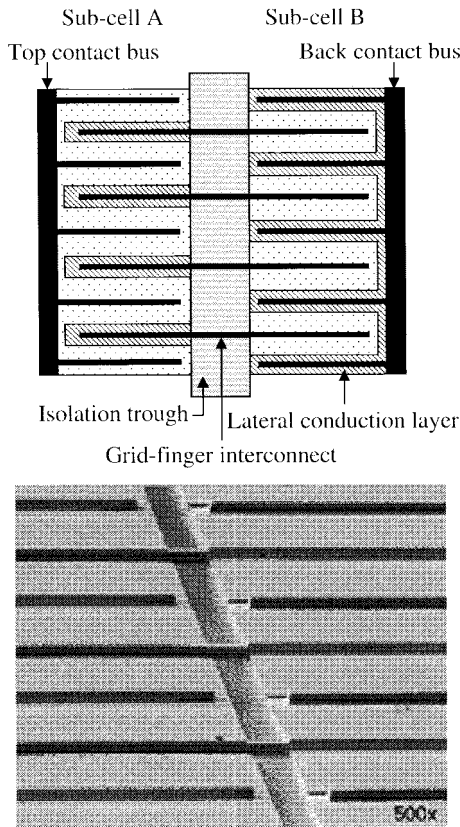
Fig. 6. Schematic and electron micrograph of a grid-finger interconnected MIM. In this case, the current being carried by the grid fingers must travel sideways by only half the width of a subcell, thus minimizing resistive losses.

Instead, very high fluxes may be maintained over relatively large areas. The optical components themselves consist of metalized plastic facets, that may be adjusted to provide the required flux-densities. Alternatively, a heliostat could be used with arbitrarily high flux-density. Naturally, this would require even larger heat-loads to be removed by external cooling. This apparent difficulty is not insurmountable and is, in reality, commonly encountered in the cooling of electronic, power, and laser devices [43]. It is also used in "...switches used in microwave antenna systems, thermal dumps for charged particle or photon beams, cryo-cooled UV light sources for laser lithography, and electron beam targets for high brightness X-ray sources" [44]. In these technologies, it is necessary to manage heat fluxes on the same order of magnitude, or even considerably greater, as those mentioned above. Future demands will necessitate cooling with incident flux levels of as much as several 1000 W cm^{-2}. We may quote from a book on the thermal modeling of electronic components [45]: "In fact, heat dissipation rates in excess of 1000 W cm^{-2} ... have been experimentally demonstrated while operating at room temperature." The approaches are generally based on microchannel heat sinks, with a coolant flowing through the channels. The fluid may be a phase-change material, which appears to impart significant benefits, or it may simply be flowing water. The indications are that heat fluxes far greater than those likely to be encountered by a solar cell, even with concentration ratios greater than 1000 times, are readily manageable, with existing technology, and ensure that the

device does not heat up to levels at which its performance and durability would be impaired.

A TPV system faces the same problems, but the incident heat fluxes seem likely to be less in the foreseeable future. A black-body at a temperature of 1500 K radiates about 28–29 W cm^{-2}. Assuming that the view-factor is not much less than unity, the above- and below-bandgap power densities are 3.3 and 16.4 W cm^{-2}, respectively, for a bandgap of 0.5 eV. The potential output could therefore be on the order of 10 W cm^{-2}, although recombination, parasitic, and system losses might reduce this to perhaps 2–3 W cm^{-2}.

It is worthwhile repeating the main point that the thermal loads encountered in both PV concentrator systems and TPV systems are already demonstrably manageable using well-established techniques used by the microelectronics and other communities.

V. SUMMARY

In this paper, we have discussed the similarities between PV and TPV converters, especially with regard to the flux densities under which they operate. Because of this, the optical, thermal, and electrical problems that these devices encounter are very similar, as are their solutions. We also discussed the heat fluxes of above- and below-bandgap photons and speculated that the removal of the latter may influence the choice of converter bandgap(s). Minimization of the sum of the two loss terms enabled the optimum bandgap for a single-junction device to be derived, although without regard to possibly important issues such as the loss of energy and increase in entropy associated with reradiated photons [18]. For a PV converter, the ideal bandgap, from a thermal point-of-view alone, is 1.12 eV, whereas that for a TPV converter receiving photons from a radiator at 1500 K, is about 0.28 eV, which is identical to the result obtained by applying the theory of radiative recombination of [17]. An empirical equation, (E_g[opt.] = $2.17kT_{\text{emit}}$), relating the optimum bandgap to the radiator temperature, was derived in this paper and stated explicitly for the first time, although it is implicit in the papers by Shockley *et al.* [17] and Cody [19]. An important conclusion of these two approaches is that both the radiative recombination and photon power loss minimization models predict a significantly lower bandgap than has been suggested using the semi-empirical model, or has been used by the TPV community so far. Other constraints, such as practical difficulties in fabricating the very low bandgaps suggested by the alternative, more idealistic models, may render these conclusions invalid. However, at present, there appears to be a pressing need to develop lower bandgap materials than appear to have been considered to date. In addition, recent data on TPV devices that took into account Auger recombination, suggested that the potential benefit of developing much higher quality material that is free of extrinsic processes, such as Shockley/Read/Hall recombination, would be considerable [32]. Ahrenkiel *et al.* [46] measured the Auger coefficient of In$_{0.53}$Ga$_{0.47}$As lattice-matched to InP but further work needs to be done on even lower bandgap materials to establish the point at which benefits from using these are outweighed by increased recombination

currents. We are unaware of any work on the application of some of the low bandgap candidate materials such as InAs, InSb, InAsSb, $Ga_xAs_{1-x}Sb$, Pb, and SnTe to TPV but Auger coefficients for some of these are undoubtedly available and ought to be included in expanded modeling.

Although it is not appropriate for discussion here, the simple thermal model may also be used to minimize the losses in a tandem stack of two or more converters connected in series. This is based on partitioning the incident photon flux spectrum into equal areas, the number of which is equal to the number of cells in the stack, to ensure current-matching in the tandem stack.

Having determined the photon power-density losses of the above- and below-bandgap components, we then considered the issue of reducing their heating of the cells. The back-surface reflector is an important component in TPV systems, because it acts as a means of returning the sub-bandgap photons to the radiator, thereby increasing system efficiency. In a PV concentrator system, however, it may be regarded as a means of thermal management. In this case, the sub-bandgap photons may simply be reflected out of the cell, to be dissipated elsewhere, or may be used for some other application, such as solar thermal heating.

Although heating of the cell by sub-bandgap photons may be reduced with the BSR, this is not the case with above-bandgap photons, which have more energy than necessary for photogeneration. The excess energy is simply dissipated in the cell by thermalization of excited charge, and the cell must be cooled by some other means. A PV cell operating at a concentration ratio of 1000 times has a heat load, due above-bandgap photons, of about 23.5 W cm^{-2} that must be removed if the cell is not to rise in temperature. This is readily achievable using microchannel cooling systems, such as those developed for several other technological sectors.

Electrical losses may be minimized using cells of small area and connecting these together in series. This was originally introduced for GaAs PV cells, but was used advantageously later for TPV devices. The original problem was that, at the high current-densities in TPV systems, the Joule losses were dictated by the lateral conduction layer (LCL) that enabled connection from the top of one cell to the back of the adjacent cell to be made. This problem was, however, alleviated by the introduction of the monolithically integrated interdigitated mini-module. This device is grown on a semi-insulating substrate. Current transfer between cells is achieved by the grid fingers, and the furthest that the current must travel in the LCL is the distance between the back-contact fingers. The only drawback is the possibility of trapping, and eventual absorption, of sub-bandgap photons in the structure. This is due to diffraction and, ultimately, absorption by free carriers in the device layers. This issue must be addressed so that new designs may be developed. Although the MIM concept has primarily been used for TPV cells in recent years, it appears to be equally applicable to PV devices. This is also true of the BSR, although this is also used in other PV devices. Hence, these two design developments are valuable to both technologies. Work is now underway to develop PV cells in the future with three or four junctions [47]. This will have

the benefit of reducing the current density, thereby further reducing the Joule losses and easing design constraints on the interconnecting grid lines between individual subcells. In addition, there will be a reduction in the losses of either below-bandgap or above-bandgap photons. In turn, these advantages would permit the use of much higher flux densities than have previously been considered feasible.

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