High Efficiency and High Concentration in Photovoltaics
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Abstract—In this paper, we present the state-of-the-art of multijunction solar cells and the future prospects of this technology. Their use in terrestrial applications will likely be for concentrators operating at very high concentrations. Some trends are also discussed and we present a cost calculation showing that highly efficient cells under very high concentration would be able to produce electricity at costs competitive with electricity generation costs for some utilities.

Index Terms—III–V semiconductor concentrators, photovoltaics, tandem cells.

I. INTRODUCTION

In a document prepared for the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992, it was stated [1] that if efficiencies of 45% were ever achieved, photovoltaic (PV) electricity using concentration could be produced at a cost of $0.031–0.039/kWh, given some favorable financial assumptions.

In this paper, we provide support for the performance implications of this conclusion by reviewing the achievement and trends in the production of high-efficiency solar cells as well as the prospects and problems of using concentrations high enough to make these cells cost effective.

An outline of the development of high-efficiency cells at one sun and in concentration is presented in Table I [2]–[13]. Although AlGaAs/GaAs two-junction cells, including tunnel junctions and metal interconnections, were developed in the early years, moderate efficiencies well below 20% were achieved [3]. This was due to difficulties in making high-performance and stable tunnel junctions, and of the defects related to the oxygen in the AlGaAs materials [14]. A double heterostructure (DH) tunnel junction was found to be useful for preventing diffusion from the tunnel junction and improving the tunnel junction performance by one of the authors [4] and coworkers. GaInP was proposed by NREL [7] as the material for the top cell. As result of performance improvements in tunnel junction and top cell efficiencies, over 30% has been achieved with GaInP/GaAs two-junction cells [12] at one sun. Such cells have recently drawn increased attention for space applications. In fact, the first commercial satellite with two-junction GaInP/GaAs-on-Ge solar arrays was launched in August 1997 [15]. Many more launches have followed and the majority of new satellites are powered by these arrays rather than crystalline silicon solar arrays.

II. EFFECTIVENESS OF MULTIJUNCTION CELLS

Fig. 1 shows several efficiency limits based on the Shockley–Queisser (SQ) [16] minimum entropy-rate model recalculated for the most ideal illumination case [17]. It also shows theoretical calculations [18]–[20] based on different device assumptions and realistically expected values [21] for single-junction and multijunction solar cells in comparison with experimentally achieved efficiencies [22]. Efficiencies of 25.1% have been attained at 0.1 W·cm$^{-2}$, (spectrum AM1.5 Global) with single-junction GaAs cells, this value being only 24% below the 32.9% SQ efficiency limit. It is worth noting...
that the GaAs is not the material with optimal bandgap so the best GaAs cell so far achieved is only 16% below the ideal SQ limit for this material.

The increase in the number of junctions allows for an increase in the efficiency that is very noticeable for ideal cells. In fact, this increase has already been achieved for two (monolithic) and three (stacked) junctions. However, the increased complexity suggests that approaching the ideal efficiencies will be more difficult. It is realistic to expect efficiencies of 33% for two-junction cells. Super-high efficiencies over 40% will eventually be achievable for four-junction cells.

Efficiencies have a natural tendency to increase under concentration but this advantage is partly lost due to the ohmic losses that become an important part of the cell losses. Therefore, the highest efficiency achieved for concentrator single-junction cells is 27.6% (with GaAs) at 255 suns (22.5 W-cm⁻² of irradiance) and this value is about 23% below its SQ limit for this concentration and material. The limit in Fig. 1 corresponds to full concentration, that is, to isotropic illumination with the brightness (irradiance) of the sun’s photosphere. This corresponds to a concentration of about 46 300 times.

Again under concentration, the increase in the number of junctions leads to important increases in the efficiency limits and smaller increases in the achieved efficiency. Very high efficiencies, of over 30% have already been achieved by several teams and super-high efficiencies over 40% will be achievable with three- and four-junction cells.

In the long term the achievement of efficiencies over 45% is not unthinkable. It should be remembered that the absolute upper limit of tandem cells, with infinite junctions, is of 86.4% for AM0 spectrum. But even this might not be the highest efficiency for an ideal solar converter, whose upper limit is 93.1% [23].

III. KEY ISSUES FOR REALIZING HIGH-EFFICIENCY MULTIJUNCTION CELLS

Selection of top cell materials is important for high-efficiency two-junction cells. When compared with AlGaAs for a top cell material lattice-matched to GaAs or Ge substrates, GaInP has some advantages such as lower interface recombination velocity, less problem with oxygen and the availability of a good window layer material.

The top cell characteristics depend on the minority carrier lifetime in the top cell layers. Fig. 2 shows changes in photoluminescence (PL) intensity of the top cell active layer as a function of the minority carrier lifetime of the p-InGaP base layer grown by MOCVD for different surface recombination velocities. The lowest surface recombination velocity was obtained by introducing an AlInP window layer and the highest minority carrier lifetime was obtained by introducing a buffer layer and optimizing the growth temperature. The best conversion efficiency of the GaInP single-junction cell was 18.5%.

Another important issue for realizing high-efficiency monolithic-cascade type multijunction cells is the achievement of a low-loss interconnection minimizing both, optical and electrical losses for two or more cells. A degenerately doped tunnel junction is attractive because it only involves one extra step in the growth process. To minimize optical absorption, the formation of a thin tunnel diode having a wide bandgap is necessary, as shown in Fig. 3. However, the formation of a wide-bandgap tunnel junction is difficult, because the tunnel current decreases exponentially with the increase in bandgap energy. A proper bandgap-energy choice of the tunnel junction materials is necessary to minimize optical and electrical losses.

In addition, impurity diffusion from a highly doped tunnel junction during the growth of the top cell increases the resistivity of the tunnel junction. A double heterostructure (DH) was found by one of us (Yamaguchi) and his coworkers to be useful for preventing diffusion and obtaining a stable tunnel junction [4]. Effective suppression of the impurity diffusion from tunnel junction by the use of a wider bandgap has also been used [24]. This is attributed to the lower diffusion coefficient for impurities in the wider bandgap energy barrier layer and tunnel junction.

Fig. 4 shows a schematic cross section of a high-efficiency InGaP/GaAs 2-junction cell. InGaP/GaAs cell layers were grown on a GaAs substrate using the MOCVD method by Japan Energy Co. [12]. An InGaP tunnel junction connected
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Fig. 4. Structure of the cell of efficiency 30.3% fabricated by Japan Energy Co.

Fig. 5. Illuminated current–voltage (I–V) curve of a high-efficiency InGaP/GaAs two-junction cell measured at the Japan Quality Assurance Organization.

the top and bottom cells. Fig. 5 shows the illuminated current–voltage (I–V) curve of a high-efficiency InGaP/GaAs tandem cell.

High-efficiency (30.3% at one-sun AM1.5) has been obtained by improving the GaInP top cell layer quality and introducing DH structures in the GaInP top cell, GaInP tunnel junction and GaAs bottom cell. This value is the highest ever reported for the two-junction cells under one-sun illumination.

The mechanically stacked three-junction cells of monolithically grown GaInP/GaAs two-junction cells and GaInAs bottom cells have reached the highest efficiency of 33.3% following joint work by Japan Energy Co. and Sumitomo Electric Co. [13]. For multijunction cells to be used extensively, it is necessary to improve their conversion efficiency and reduce their cost. As shown in Fig. 1, three- and four-junction cells under concentration have great potential for realizing super-high-efficiency of over 40%. As a three-junction combination GaInP/GaAs/Ge cell on a Ge substrate will be widely used because this system has already been developed. The four-junction combination, an AlGaInP ($E_g = 2.0$ eV) top cell; a GaAs ($E_g = 1.43$ eV) second-layer cell; a third-layer cell with a bandgap of 1.05 eV for example made of GaInPAs or GaInNAs and a Ge ($E_g = 0.664$ eV) bottom cell, is lattice-matched to Ge substrates and has a theoretical one-sun AM0 efficiency of about 42%. This system has also potential of over 45% under 500 suns (AM1.5 Direct spectrum). Although this system is ideal for maximum theoretical efficiency, the selection of third-layer cell material having suitable properties is a problem still to be overcome.

IV. VERY HIGH CONCENTRATION OPERATION

As presented in Fig. 6, an efficiency of 23.0% at 1295 suns (130 W/cm²) has been demonstrated experimentally at the Polytechnic University of Madrid (UPM) by using a one-junction GaAs cells. Although moderate when compared with the other efficiencies reported in this paper this is the highest efficiency reported at this concentration [11] and has been confirmed externally by the Fraunhofer Institute. The cell, with an area of 0.1 cm², consists of a p-AlGaAs window layer grown by LPE on n-substrate accompanied by Be-diffusion to form the photoactive emitter. More recently an efficiency of 20.8% at 4280 suns has been attained at the UPM [25]. No prismatic covers have been used in these cells. Their use—very common in high-efficiency concentrator cells—might increase the efficiency but they cannot be easily integrated in high concentration optics. An efficiency of 24.8% with a prismatic cover at 1678 suns and of 23% at 5817 suns has also been recently achieved [26].

Very low specific series resistance, 2.5 mΩ·cm² or less, is needed for operation at these concentrations. The grid component of the specific series resistance [27] is proportional to the cell area and is usually the dominant component for cells areas above about 1 cm²; in such cells achieving a sufficiently low series resistance becomes a difficult task. Below 0.1 cm² the grid fingers component—in our case 3 μm wide, 0.3 μm thick fingers with a grid coverage of 7.5–9%—ceases to dominate; the contact resistance between grid and semiconductor is the dominant component. A contact resistance of 1.3 × 10⁻⁴ Ω·cm², produced by means of a graded emitter with high surface doping permits achieving the efficiency maximum at over 1000 suns.

In the more efficient two-junction monolithic cells, the tunnel junction may limit the achievement of low series resistance. It has been pointed out that by using a large bandgap material for the tunnel junction the tunnel current is reduced. NREL has used a GaAs tunnel junction, with a smaller bandgap for their concentrator cells, instead of...
the GaInP tunnel junction used by Japan Energy Co., thus obtaining over 30% (with prismatic cover) at concentrations up to 260 suns [10]. They indicated that efficiencies of 31% at 1000 times will be achievable with their structure. The best solution could be the fabrication of a tunnel junction with a bandgap energy between those of the InGaP and the GaAs, able to carry high tunneling current but not absorbing in the bottom cell (GaAs) active range.

V. CONCENTRATORS

We present in Fig. 7 a sketch of the HERCULES high concentration concentrator, being developed in a European Commission project. It is what we call a RXI (refraction-reflection-total internal reflection) lens [28] designed by the SMS (simultaneous multiple surface) method which provides a very large angular aperture. The large acceptance angle is needed to relax the manufacturing requirements and specifications of the tracking system. Light from the sun is first refracted by the front lens surface then reflected by the metalized back surface to finally undergo total internal reflection at most of the front surface. The illumination on the cell is almost isotropic which is the condition for very high concentration. Geometrical concentration of 1256 times with circular entrance aperture of 4 cm diameter and measured angular acceptance of 1.4° (at 90% transmission) has been achieved [29]. The calculated optical efficiency from a model fitting with measurements is 84%.

Small cells use a three-dimensional (3-D) path for the conduction of the heat toward the surroundings while larger cells are limited to a one-dimensional path. Since the energy falling on the cell is proportional to the cell area—that is to the square of its diameter—and the 3-D thermal resistance (spread resistance) between the cell and the infinity is inversely proportional to this diameter, the thermal drop is proportional to the diameter [30]. The heat sink uses this property and is presented in Fig. 7. It is a copper cone that reduces the heat flux from some 80 W·cm⁻² at the cell to about 2 W·cm⁻². The lower bases of these cones are attached to an ordinary natural-convection heat sink separated from it by an electric insulator to allow series connection of the cells in the module. Smaller cells have the lower cell temperatures. For cells with a side of 1 mm (the most cost-effective size), the temperature drop is (depending on the wind speed) less than 50 °C, similar to the one experienced in the EUCLIDES prototype [31] operating at only 32 times with much larger silicon cells.

A mosaic of concentrator units like the one in the figure forms a module. Although the concentrator is of rotational symmetry, cutting it into squares or hexagons to form the module only affects the angular acceptance and that would follow the same pattern. Given the large acceptance achieved this is of no concern.

VI. A COST EXERCISE

Cost analyzes constitute a difficult topic very dependent on assumptions. However, the PV R&D is largely aimed at reducing costs. Such costs analyzes are often used for technology comparison rather than for cost prognosis and for that, they are a good guidance.

However, in the PV field methods for cost analysis have been developed mainly for modules [32], [33]. Such costs analyzes are sometimes applied to concentrator modules, but for this they are less satisfactory because they exclude aspects such as the structure costs or the plant operational condition that are very different for concentrators and for flat modules.

Thus, we present here an exercise including all these aspects. It has been used elsewhere [34] for comparing flat and concentration systems. Indeed, the results of this exercise should not be taken as a prognosis and the reader must make her or his own judgment on the value of the assumptions, which are briefly described. Nevertheless, such results may help in establishing a strategy concerning ultra-high-efficiency cells operating at very high concentration.

A problem associated with a small concentrator size is the assembly cost. The formula 1943/N²/2 + 0.033 × N fitted with real data [35] of optoelectronic products, similar to the concentrator unit, represents the cost in $/m² of the optics plus the assembly. N is the number of concentrator units per m². The optimum is N = 957 or a concentrator unit 32 × 32 mm² and a cell dimension of 1 × 1 mm². The corresponding cost is $94/m². To this cost we add that of the finned heat exchanger and obtain $131/m².

We present in Table II the result of our calculation of the electricity cost based on present cost and efficiency at 1000 suns of the GaAs cells. The module cost is the one expected

| TABLE II COST ANALYSIS FOR CELLS OF DIFFERENT EFFICIENCIES AT 1000 TIMES |
|--------------------------|--------------------------|
|                          | Short term | Long term |
|                         | 1.2 | 2.2 |
| Substrate wafer ($ per cm² wafer area) | 8.50 | 8.50 | 8.50 | 2.37 |
| Cells ($ per cm² cell area) | 13.4 | 15.85 | 15.85 | 4.43 |
| Cells ($ per m² aperture area) | 134 | 159 | 159 | 44 |
| Optics, heat sink & assembling ($ per m² aperture area) | 131 | 131 | 131 | 13 |
| Module ($ per aperture area) | 250 | 290 | 290 | 113 |
| Cell efficiency (%) | 23.1 | 27 | 45 | 45 |
| Module efficiency (%) | 19.0 | 30.5 | 37.1 | 37.1 |
| Module ($ per Wp) | 1.39 | 0.95 | 0.78 | 0.31 |
| Area related BOS ($ per m² aperture area) | 114 | 114 | 114 | 66 |
| Power related BOS ($ per Wp) | 0.22 | 0.22 | 0.22 | 0.17 |
| Plant price ($ per m² aperture area) | 525 | 589 | 607 | 271 |
| Module NDI (W/m²-year-1) | 1626 | 1626 | 1626 | 1626 |
| Performance ratio | 0.606 | 0.606 | 0.606 | 0.606 |
| Electricity costs in EGL ($ per kWh) | 0.186 | 0.130 | 0.110 | 0.095 |
| Electricity costs in EGL ($ per kWh) | 0.131 | 0.091 | 0.077 | 0.038 |
for the prototype. This cost tends to be smaller than that of the real prototype, but it usually becomes realistic at some early stage of manufacturing due to the learning experience.

For the BOS we have taken the prototype costs of the EUCLIDES demonstration power plant, a concentration plant of 480 kWp just installed in the Canaries, and we have reduced them by the historic learning rate of PV modules, which is 17.5% [36] in constant dollars. The learning rate is the price reduction every time the cumulated production doubles. For the short-term columns, the reduction has been calculated for a cumulated production of 100 MWp. A 25% mark-up has been allowed on the plant to account for the plant-assembler indirect costs and profit.

We calculated the electricity cost for Madrid and for an exceptionally good location (EGL) with a normal direct irradiation (NDI) of 2600 kWh/m²-year⁻¹, a value which is often used in the USA for calculations. Notice that Izaña, in the Canary Islands, receives a higher NDI, of 2954 kWh/m²-year⁻¹. The performance factor [37] (to be multiplied by the module efficiency to give the annual system efficiency) for the EUCLIDES prototype is 0.606 [31]. It has been taken for the calculations. The performance factor accounts for several effects among which the operating temperature of the modules is an important one. The losses due to temperature seem to be smaller for the HERCULES modules than for the EUCLIDES arrays, so that the performance factor can be regarded as a conservative estimate with room for improvement.

The cost of the electricity is assumed to be the annuity for the loan needed to paying the installation plus a yearly O&M cost of $1/m² of module. This annuity is calculated on an interest rate (in constant dollars) of 6% and an amortization period of 30 years.

Assumption changes may be examined by using an Excel spreadsheet containing the calculations. This file is available (luque@ies-def.upm.es) under request.

Present one-junction technology costs in this table are well below present costs of PV installations and very similar to those achieved with the EUCLIDES prototype, using lower concentration but cheaper Si cells.

If we consider that the price of the electricity in industrialized countries is about $0.1/kWh for customers and the average generation cost for utilities is $0.05/kWh, we realize that the present one-junction technology is not yet competitive for such markets. However, with the efficiency considered achievable for the two-junction technology and the use of very high concentrations the PV electricity could become cost-effective for the customer in locations with exceptionally good solar reserve (EGL). This result is expected regardless of the fact that no learning rate reduction to the module cost has been applied or any performance improvement (apart form the cell efficiency improvement). Indeed, this may lead to big markets, and not only in such favorable locations.

In the long run, with four-junction tandems operating at 1000 times, the electricity cost could not compete with generation costs if learning reductions are not included. But this is unrealistic. If we apply the historic learning rate of the PV modules to all the components for a cumulated production of 1000 MWp—the one already reached today for the whole PV industry—the calculated costs of electricity could become competitive for a wide range of solar resource.

We must point out that there is no reason to expect that the utilized 17.5% historic learning curve for modules (mostly of silicon) will be the same for concentrators. This is a much less mature product and learning rate might be higher. As a reference, the learning rate of the microelectronics is estimated to be of 32%. In this respect conclusion that we may extract from the table is that, roughly speaking, learning rate will have an effect on costs even bigger than efficiency. However, by fostering new niche markets, efficiency improvements may shorten the time in which costs competitive in the terms of this paper would occur.

VII. CONCLUSIONS

To summarize, present efficiencies exceeding 30% both at one sun and under concentration brings attention to the potential of multijunction cells for increasing PV efficiency. Also the achievement of efficiencies of 23% at concentrations as high as 5817 suns show that the present high cost of multijunction cells should not be a deterrent for their cost-effective use. On the contrary, very high concentration may be the way to large markets presently requiring substantial cost reductions for PV-generated electricity. Simple cost calculations—using a set of generic financial assumptions that may be applicable for some utility investments—indicate that PV electricity can be produced at costs competing existing electricity user prices. Furthermore, the potential for penetrating the huge electricity generation market using tandem-cell concentrator approaches is real and improving.

ACKNOWLEDGMENT

The authors consider that the paper has been substantially improved by the comments of one of the referees.

REFERENCES


Masafumi Yamaguchi (M’87), for a photograph and biography, see this issue, p. 2137.

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