Research Opportunities in Crystalline III-V Photovoltaics

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Although III-V solar cells have been developed to a high level of performance, opportunities for fundamental advances still exist. For example, new structures could lead to substantial gains in conversion efficiency, multi-junction solar cells could achieve efficiencies well above 50%, and new materials could be developed for applications such as thermophotovoltaics. In this paper, the authors describe research opportunities that could provide the scientific base for substantial enhancements in the performance of crystalline III-V photovoltaic cells.

Key words: GaAs, Group III-V photovoltaics, solar cells

INTRODUCTION

Group III-V semiconductors have optoelectronic properties, which make them especially attractive for photovoltaics. High-quality films can be readily grown by a variety of techniques, and the band-gaps and lattice constants of III-V alloys can be varied, in some cases independently, over a wide range. This makes possible the fabrication of heterostructures, which includes wide-band-gap windows to passivate surfaces electronically, and monolithically stacked solar cells. Given these natural advantages, it is not surprising that III-V solar cells hold conversion efficiency records for both one-sun and concentrated-sun operation. Group III-V cell efficiencies are impressive, but the cells tend to be expensive because of the cost of the substrates and of epitaxial growth. As a result, the applications envisioned for III-V cells tend to be in concentrator systems, where expensive solar cell area is traded for less-expensive concentrator optics. For such applications, the cell efficiency is the prime consideration. Yablonovitch et al.[1] discuss opportunities for developing a low-cost III-V growth technology, but our emphasis will be on identifying opportunities for increasing cell efficiency.

Figure 1 compares progress in silicon[2] and GaAs cell efficiencies over the past few decades. Note that silicon, the material properties of which are not nearly as well suited for photovoltaics, has achieved a level of performance comparable to that of GaAs. Some obvious questions arise. Are III-V cells approaching their performance limits, and, if not, what fundamental issues need to be addressed? Our objectives in this paper are to identify some opportunities for fundamental research that might lead to some very substantial gains in III-V cell efficiencies.

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STATUS OF III-V PHOTOVOLTAICS

GaAs has attractive photovoltaic properties, and its surface is readily passivated with wide band-gap, lattice-matched layers. Its band-gap is nearly optimum for the solar spectrum.[3,4] High-quality films with minority-carrier lifetimes near the radiative limit are readily grown using organometallic vapor phase epitaxy (OMVPE) and other epitaxy-based growth techniques. The AlGaAs/GaAs heteroface cell shown in Fig. 2 has achieved an efficiency of 24.8% under an air mass (AM) 1.5 terrestrial spectrum,[5] and efficiencies exceeding 29% under concentration have been achieved.[6] The growth of the AlGaAs window does, however, present some problems because of its sensitivity to residual oxygen. $Ga_{0.5}In_{0.5}P$, which is also lattice matched to GaAs, has proven to be a good alternative. With $Ga_{0.5}In_{0.5}P$ as the passivating window layer, one-sun efficiencies of 25.7% have been reported.[7] The thermodynamic limiting efficiency of GaAs is about 32%,[4] leaving room for improvement.

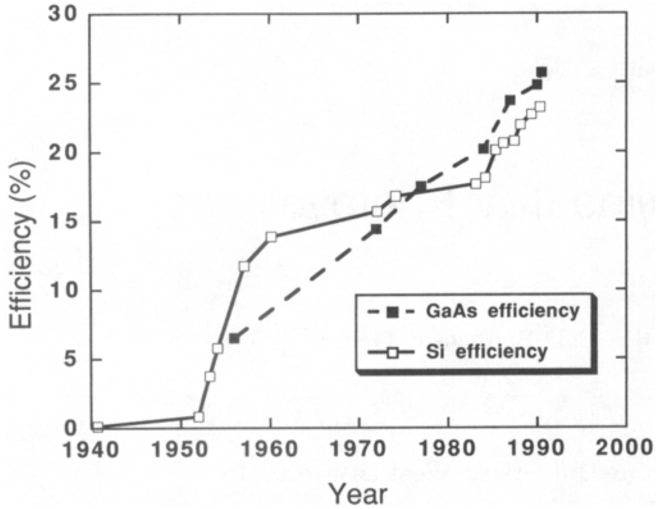

Fig. 1. Comparison of recent efficiency gains for crystalline Si and GaAs solar cells. (The silicon data are taken from Ref. 2.)

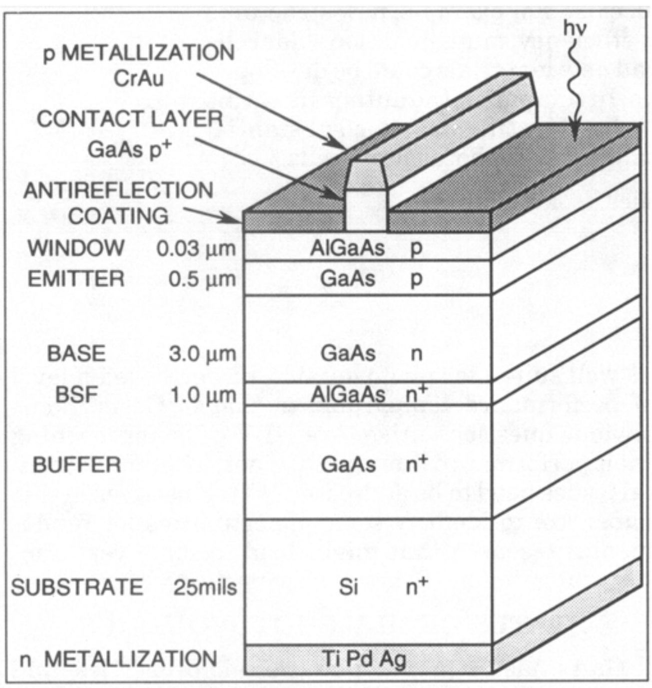

Fig. 2. Typical structure of an AlGaAs/GaAs heteroface solar cell (from Ref. 13).

For a single-junction cell, many of the incident photons have energies in excess of the band-gap, E_G, and the extra energy is simply lost as heat to the lattice. The use of tandem, or cascade cells, which consist of a series of cells with successively smaller band-gaps, promises to deliver significantly higher efficiencies. Limit efficiencies under concentration are as high as 86% if many cells are used.[3] Group III-V tandem cell research has mainly focused on the AlGaAs/GaAs system, but other material systems are now showing great promise. Two different approaches are possible: the first is to grow individual cells on separate substrates and to stack these mechanically one above another, and the second is to grow a monolithic stack of layers on a single substrate.

Most GaAs-based monolithic tandem cell research has centered on the well-developed AlGaAs/GaAs materials system. With 1.9 eV AlGaAs as the top cell and GaAs on the bottom, a 27.6% efficiency has been achieved.[8] AlGaAs presents problems, however, because of its sensitivity to oxygen contamination. A good alternative is to use a $Ga_{0.5}In_{0.5}P$ top cell passivated by AlInP, and such a device has achieved 27.3% under one-sun operation.[9] If low-resistance, low-optical-loss tunnel junctions can be achieved, then efficiencies of more than 30% seem achievable for this cell.

Both the AlGaAs/GaAs and GaInP/GaAs tandem approaches use a large/medium band-gap combination. Recent modeling studies have shown that medium/small band-gap combinations may offer higher efficiencies for two-junction tandem cells.[10,11] One promising example of the medium/small system is the $InP/Ga_{0.47}In_{0.53}As$ combination. The system is lattice matched and nearly current matched. Cells with an n^+/p InP top cell and a p^+/n GaInAs bottom cell have been grown and operated in a three-terminal mode. Under a terrestrial spectrum concentrated 50 times, an efficiency of 31.8% was reported,[11] which is the record for monolithic cells.

Although monolithic tandem cells represent the most promising long-term opportunity, mechanically stacked tandem cells are of near-term interest, and most clearly demonstrate the potential for cascade cells. When cells are fabricated and operated individually, the lattice and current matching constraints no longer apply and the tunnel junction interconnect is not problematic.

One of the most exciting recent developments in cascade cells has been the GaAs/GaSb mechanically stacked tandem cell developed at Boeing.[12] The cell has demonstrated over 35% efficiency under concentration. A similar approach is the GaAs/GaInAsP mechanical stack. With a GaAs top cell and the bottom cell grown on an InP substrate, an efficiency of greater than 30% has been achieved under concentration.[11] This combination has the potential to exceed 40% efficiency. Impressive results have been obtained with mechanical stacks, but it seems unlikely that they can compete with monolithic structures in the long term. Nevertheless, they demonstrate the great potential for cascade cells and show that materials developed for the optoelectronics industry can play an important role in photovoltaics.

Although our review has concentrated on cell efficiency, cost is also a primary consideration. The substrate cost is a key consideration, and this has led to work on the growth of GaAs on silicon. Although the defect densities are high ($\sim 10^7/cm^2$), respectable efficiencies have been achieved.[13] Modeling studies indicate that defect densities need to be reduced by another factor of 10–100 to eliminate their influence. Although germanium is more expensive than silicon, it is significantly less expensive than GaAs. Epitaxial growth of high-quality GaAs on germanium substrates is now used in the production of GaAs space cells.[14]

Group III-V cells could become a low-cost alternative if the cost of the substrate could be eliminated altogether. Thin films are also attractive for space applications, where weight is an important consideration. A variety of techniques for producing crystalline thin films exists.[15–17] The cleavage of lateral epitaxial film for transfer (CLEFT) process has produced self-supporting GaAs films of up to four inches in diameter;[18,19] cell efficiencies of 19% have been achieved. Another possibility is the epitaxial lift-off (ELO), or peeled-film technique.[20] High-quality films have been produced by this technique, but high-efficiency solar cells have not yet been reported. Viable techniques for producing large-area, high-quality thin films of Group III-V semiconductors do not currently exist, but such techniques could have a major impact on photovoltaics.

RESEARCH OPPORTUNITIES

Figure 1 shows that the efficiency of the GaAs-based heteroface cell continues to rise as work continues on improving grids and anti-reflection coatings, on optimizing windows, and on reducing contact resistance. The potential for significant efficiency gains in single-junction cells is, however, limited because the device is already operating near its theoretical limit. The best performing InP single-junction, one-sun cell is likely to achieve this level soon. It is important that known problems be addressed in order to extract the maximum efficiencies from current technology, but our objective in this paper is to identify promising opportunities for fundamental advances. Since the performance of the highest efficiency GaAs cells operating under optical concentration is now close to 30%, a reasonable long-term objective is to produce cells with efficiencies in excess of 50%. Only tandem cells seem capable of such performance. Single-junction cells could have a future if techniques can be devised to produce cells with very high-efficiencies at very low cost. They might also be competitive in other applications, such as thermophotovoltaics[21] and laser beaming of power.[22]

Leaving aside the research issues now being addressed, we consider three types of research opportunities. The first concerns the solution of known problems that are not being adequately addressed but the solution of which could lead to rapid progress in the near term. The second opportunity concerns exploratory research aimed at developing new structures, and the third involves long-range research directed at fundamentally new approaches. In summary, the opportunities identified below can roughly be described by activities that will lead to 1) near-theoretical performance in existing single-junction and tandem one-sun and concentrator cells, 2) further improvements in performance *and* reductions in cost, and 3) the final achievement of low-cost/high-efficiency cells and/or very high performance cells with efficiencies exceeding 50%.

Known Research Issues of Immediate Significance

This section identifies current research topics, the successful exploitation of which would lead to immediate improvements in performance and cost.

Tunnel-Junction Interconnects for Concentrator Cascade Cells

As reviewed above, the most successful tandem solar cells fabricated to date are those formed by mechanically stacking individual cells. Because mechanical stacks use two expensive substrates, it is unlikely that they will ever become sufficiently low in cost, even for concentrator applications. A more promising approach is to use a tunnel-junction interconnect between the upper and lower cells so that the device as a whole can be operated in a two-terminal mode. This would reduce costs and would be more compatible with system design.

The AlGaAs/GaAs system is an obvious choice for tandem cells, but results to date have been disappointing. The method of choice for interconnecting the top and bottom cells is a tunnel junction, but a wide-band-gap tunnel junction is required to minimize optical losses for the bottom cell. It has proven difficult to dope high-mole-fraction AlGaAs sufficiently, and the quality of the junction tends to degrade when the growth temperature is raised (as is necessary for making high-quality AlGaAs windows on the top cell). Work on producing thin, abrupt, degenerately doped AlGaAs tunnel junctions and maintaining quality during subsequent film growth continues. Promising results using atomic layer epitaxy (ALE) have recently been reported.[23] Alternative interconnection technologies, such as metal interconnects[24] and patterned germanium tunnel junctions[25] have been explored. High-performance tandem cells without a tunnel junction have been demonstrated[11] in a three-terminal cell but this approach adds cost. Also, the three-terminal configuration may not be advantageous for systems.

Olson et al. have recently demonstrated a high-efficiency GaInP/GaAs cascade cell with a tunnel-junction interconnect.[9] In this case, the tunnel junction was placed in the lower-band-gap, GaAs layer and its thickness was minimized to reduce optical losses. The InP/InGaAs combination is also attractive, but a tunnel junction interconnect has not been demonstrated for this system. For optimum performance in any material combination, the tunnel junction needs to be placed in the wide-band-gap layer and must have a peak current capability that permits operation under several hundred suns concentration or more. To achieve this, it will be necessary to dope both sides of the junction very heavily, a problem which is not always insignificant.

Two-junction tandem cells should be capable of efficiencies in excess of 35% if a suitable interconnection scheme is developed. The use of three or more junctions is expected to lead to efficiencies approaching, or even eventually exceeding, 50%. Tunnel junctions still seem to be the most appropriate method of interconnection. The development of growth techniques compatible with high-efficiency cells, and which produce low-resistance and low-optical loss interconnects, would have an immediate impact on III-V cell efficiencies.

Passivation of InP

One of the reasons GaAs cells perform so well is that their illuminated surfaces can be passivated using AlGaAs or GaInP. An equivalent passivating layer, and the associated benefits to devices, has not been demonstrated for InP cells. InP is important for space applications because of its radiation hardness,[26] and it is of interest for terrestrial cascade cells.[10,11] Possible materials which could perform as wide-bandgap window layers and confine the minority carriers include AlInAs, CdSSe and CdZnS. To the knowledge of the authors, none of these materials has been used for passivation. Undoubtedly, many other possibilities exist, and a full investigation is required.

Previous work on GaAs cells demonstrated that respectable efficiencies can be achieved without surface passivation by using shallow homojunction approaches, but for high efficiencies, surface passivation is essential. Surface passivation can be demonstrated by simple, photoluminescence decay measurements. Later, however, compatibility with solar cell film growth and fabrication would have to be demonstrated by examining the blue response and open-circuit voltage of a passivated cell. The detailed optical properties of the passivation layer and the electrical properties of the interface with the active layer of the cell will be important and need to be fully characterized.

Heteroepitaxial Growth of InP on Low-Cost Substrates

Although InP exhibits excellent radiation resistance and is potentially valuable as a space solar cell, in bulk form it is expensive, fragile, dense, and has poor thermal conductivity. Replacing the bulk substrate by an alternative, such as Si, becomes an attractive alternative only if the quality of the heteroepitaxially grown InP device layers does not degrade excessively. Early efforts to achieve this on a bulk GaAs substrate have been promising for concentrator cells,[27] but it is essential to replace the expensive GaAs by a low-cost substrate such as silicon or germanium. Equally important is the necessity of reducing the defect density in the device layers to ~10^7/cm^2 to achieve the ultimate performance.

The heteroepitaxial growth of GaAs on germanium is already used in the production of GaAs space cells. Success for InP could be most significant because it could be applied to both single-and tandem-junction, one-sun and concentrator cells. To achieve this, careful control over the growth of the films and a thorough analysis of their properties is essential.

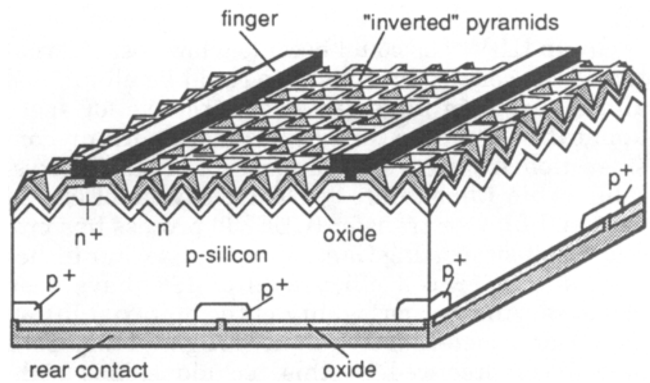

Fig. 3. The passivated emitter, rear locally diffused (PERL) Si solar cell (from Ref. 30).

Exploratory Applied Research Opportunities

In this section, we discuss research opportunities for producing significant improvements in current approaches to III-V photovoltaics. We address five topics: 1) the development of light-trapping techniques for III-V cells, 2) the characterization and understanding of III-V photovoltaic material properties, 3) the development of high-efficiency thin-film cells for concentrator applications, 4) the development of three-junction cascade cells, and 5) low-bandgap cells for thermophotovoltaic applications.

Light Trapping for III-V cells

Silicon solar cells have used so-called light-trapping techniques to great advantage.[28,29] As shown in Fig. 3, a textured top surface along with a reflective back surface effectively confines incident light. The optical thickness of the cell can be on the order of 50 times its physical thickness. The result is a high short-circuit current but, because the volume of the cell is reduced, recombination losses are lowered thus raising the open-circuit voltage. Typically, the front surface is texturized by chemical etching (different crystallographic directions etch at different rates), and a dielectric/metal back surface reflector is used. For silicon cells, which are typically a few hundred micrometers thick, these techniques have been highly successful and are a key reason for the recent efficiency gains in silicon cells (see Fig. 1).

Group III-V solar cells could also benefit from light trapping, but III-V cells are typically only a few micrometers thick; they are also attached to an inactive, crystalline substrate, so the processing techniques used for silicon cells cannot be applied. To absorb 98% of the incident photons, about 5 μm of GaAs is required. If the active layer of the cell could be reduced to 0.5 μm while maintaining the short-circuit current, however, the dark current would be reduced by about an order of magnitude. The resulting increase in open-circuit voltage would raise the efficiency of the cells by a couple of percentage points. Some work along these lines has been reported recently.[30] For example, an AlGaAs/GaAs semiconductor stack has been used as a back-surface reflector,[31] and texturizing has been considered.[32] The development of successful light trapping techniques for III-V epitaxial cells will require some new ideas; but if successful, would produce significant efficiency gains.

PV Materials Properties

The recent, very rapid progress in crystalline silicon cell efficiencies illustrates the need for a detailed understanding of photovoltaic materials properties. Detailed device models using these materials properties were used to identify the dominant internal losses in silicon cells.[33] Designs then evolved to suppress these losses.[28] Our understanding of the photovoltaic material properties of most III-V semiconductors is far behind that of silicon and is not adequate for the detailed device modeling needed for achieving maximum cell efficiency. Even for GaAs, the best-characterized III-V material, uncertainties remain. For example, estimates of the B-coefficient, the constant of proportionality that relates the impurity concentration in a semiconductor to its radiative recombination lifetime, vary widely.

There is a need to characterize the properties of other III-V materials such as InP, InGaAs, and GaInP, which are being developed for tandem-cell applications. We need a detailed understanding of optical absorption, mobilities, Auger and radiative lifetimes, and the np product. Also important is an understanding of how these properties vary with doping and temperature. Finally, it is important not only to measure these properties, but also to understand them theoretically. This theoretical understanding should permit us to predict the photovoltaic properties of the new III-V materials that will find use in advanced cascade cells.

Thin-Film Cells for Concentrator Applications

Figure 1 suggests that GaAs cell efficiencies are approaching a limit. Although silicon cells reached such a plateau several years ago, the use of new device structures to trap incident light and suppress recombination led to additional significant efficiency gains. GaAs cells now appear to be where silicon cells were several years ago. Lifetimes are high and surface recombination velocities are low. Further improvements in these parameters will have little impact on efficiency. An alternative design approach based on the use of thin films seems promising for two reasons. First, thin films may eventually be very low cost because they eliminate the substrate. Secondly, thin-film cells promise high efficiency. As discussed above, it seems clear that III-V cells could benefit from the light-trapping concept, which was so successful for Si, and light trapping might be most easily accomplished with thin-film cells. Group III-V cells might also benefit from another kind of light trapping; confining the photons emitted during radiative recombination to the active layer where they can be reabsorbed.

Figure 4 illustrates the potential benefits from trapping the emitted photons. The figure shows photoluminescence decays for an n-GaAs layer passivated on the top and bottom by $Al_{0.2}Ga_{0.8}As$ layers.[34] When the substrate is present, the critical angle for total internal reflection is 72°, so most of the photons emitted during radiative recombination are lost to the substrate. When the substrate is removed, however, the critical angle decreases to 17°, so most of the photons are confined to the GaAs layer where they are reabsorbed. The result is a significant enhancement in lifetime to about 30 times the radiative lifetime. For this moderately doped film, we find an unusually high minority carrier lifetime of about one microsecond. If solar cell structures to produce light trapping and photon recycling can be devised, efficiency gains of a few percentage points might be achieved.

The potential for substantial efficiency gains using thin-film cells can be illustrated with some simple arguments. The open-circuit voltage of a solar cell is

$$V_{oc} = \frac{kT}{q} \ln\left(J_{sc} / J_0\right) \qquad (1)$$

where

$$J_0 = \frac{qn_i^2}{N_A} \frac{W}{\tau_n} \left(e^{qV/kT} - 1\right) \qquad (2)$$

In these formulas, k is Boltzmann's constant, q is the electronic charge, n_i is the intrinsic carrier concentration, N_A is the impurity concentration, W is the width of the absorber layer, T is the absolute temperature, τ_n is the minority electron lifetime, J_{sc} is the short-circuit current density, and J_0 is the reverse saturation current density.

A p-type absorbing layer of width W and minority electron lifetime of τn has been assumed. If radiative recombination dominates, then

$$\tau_n = \phi / BN_A \qquad (3)$$

where B is a constant of proportionality, and ϕ is the recycling factor which represents the number of times a photon is recycled by radiative recombination reabsorption events.[35] From Eqs. 1, 2, and 3 we find

$$V_0 = \frac{kT}{q} \ln\left[\frac{J_{sc} B\phi}{qn_i^2 W}\right] \qquad (4)$$

Present day high efficiency cells have absorbing layers of $W \cong 5$ μm. If light-trapping techniques comparable in effectiveness to those employed for silicon can be devised, then W might be reduced by as much as a factor of 50. The results displayed in Fig. 3 show a recycling factor $\phi \cong 30$. So, if an ultra-thin structure to maintain J_{sc} while increasing ϕ can be devised, then the open-circuit voltage could be enhanced as follows:

$$\Delta V_{oc} = \frac{kT}{q} \ln(30 \times 50) \cong 0.15\text{V} \qquad (5)$$

Since current cells have a V_{oc} of about 1.03 V, these techniques could ultimately raise cell efficiencies by

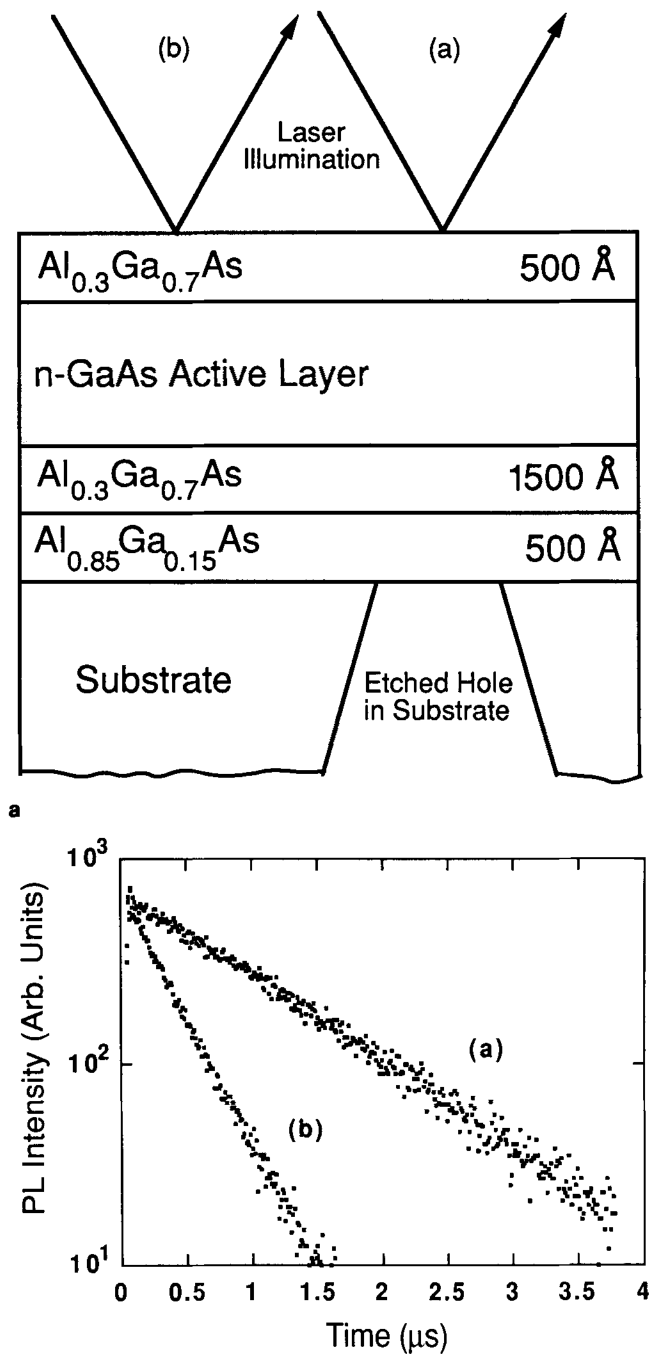

Fig. 4. Illustration of how the minority carrier lifetime is influenced by photon recycling. The device structure is a double heterostructure with and without the substrate present. The measured photoluminescence decays without (a) and with (b) the substrate present are displayed (from Ref. 34).

~3 percentage points, from ~26% to ~29%. The result would be single-junction cells with efficiencies quite close to the predicted thermodynamic limit of ~32%. The development of the structures to produce the required light trapping and photon recycling represent a major research challenge, but the benefits could be significant. At first, the applications would be for concentrators but, if inexpensive techniques to produce thin films were developed, one-sun applications might follow. The result would be low-cost but very-high-efficiency III-V cells.

Three-Junction Cascade Cells

Multi-band-gap cells promise the highest ultimate efficiencies. Only recently, however, have two-junction cells produced higher efficiencies than single-junction cells. Progress on the tunnel-junction interconnect is occurring, and the prospects for high-efficiency, two-junction cells are good. Ultra-high efficiencies for the long term will require many junctions, and the logical place to begin is with three-junction cells, for which material candidates are available. An obvious choice would be the GaInP/GaAs/Ge system, which can be grown lattice-matched. Another possibility is CdSSe/InP/GaInAs, particularly if a passivating layer for CdSSe can be developed. Three-junction cells should be capable of efficiencies significantly in excess of 40% under concentration. The major tasks to be addressed are the growth of photovoltaic-quality, lattice-matched semiconductors with the proper band-gap combinations, and the development of low-loss interconnects for the various cells.

Thermophotovoltaics

Low-band-gap alloys are relevant to applications similar to photovoltaics but which utilize a much longer wavelength incident spectrum. There is a considerable amount of waste heat in a spacecraft (and other vehicles), and this may be used to provide the source of illumination, leading to the name thermophotovoltaics (TPV).[21] The radiation may be black-body in character, or the emission from the hot surface may be modified using a selective emitter with a line spectrum. If a pure black-body spectrum is used, then it is necessary to reflect the sub-band-gap radiation back to the emitter to maintain its temperature. In the case of the selective emitter, there are two materials issues, these being the semiconductor converters of appropriate band-gaps tuned to the specific spectrum (emitter temperature) to maximize efficiency, and the development of highly selective emitters that can suppress the emission of radiation at wavelengths greater than the band-gap of the semiconductor. To a great extent, both of these factors are determined by the temperature of the emitting source. For these applications, it would be necessary to fabricate devices with much lower band-gaps than for the more conventional solar PV cells, and there are clearly opportunities for the development of some novel materials and device structures. As an example, if the source is operating at a temperature of 1000°C, then the appropriate band-gap would be approximately 0.53 eV.

Research into the Development of Novel Materials and Devices

This section describes longer range research that has the potential to achieve very high device efficiencies.

New Materials for Multiple-Junction Cells

The underlying principle of tandem cells is that each device absorbs a specific range of wavelengths not absorbed by the devices above it. In the theoretical limit, and with an infinite number of junctions, each of which absorbs only band-edge photons, the efficiency could reach 68% at one-sun.[3] Under optical concentration, the equivalent figure is 86%.[3] Clearly, there is an incentive to increase the number of junctions if this can be achieved economically.

An existing material system that has potential for this is the quaternary GaInAsP. Devices can be grown monolithically, and lattice-matched, from GaInP to GaAs on a GaAs substrate and in a descending sequence of band-gaps. A similar stack could be grown from InP to GaInAs on an InP substrate. If the system could somehow accommodate the band-gap and lattice-match discontinuity between GaAs and InP, a range of greater than 1 eV could be covered. Assuming that such discontinuities could be accommodated, then this range could be extended beyond both GaInP and GaInAs, to even higher and lower band-gaps, respectively.

Although this material is one possibility for growing a cascade stack, there are likely to be significant problems in achieving current matching, successful tunnel junctions, etc. Nor ought this system to be regarded as the only possibility. Others deserving attention may exist and could be developed.

Growth of High Quality Crystalline Sheets

For large-area, one-sun operation, it may be possible to develop techniques for the growth of semiconductor sheets. This is perhaps somewhat analogous to silicon ribbon growth, and it could lead to a significant reduction in material cost. With the epitaxial lift-off technique and CLEFT mentioned earlier, the substrate would be reusable. With the approach envisaged here, there would possibly be no substrate. The problems of mechanical stress and crystal purity can be expected and must ultimately be overcome.

Novel Structures for Optical and Electrical Confinement

As discussed previously (Section on Thin-Film Cells for Concentrator Application) cell efficiencies could be enhanced if the volume of the cell could be reduced while maintaining optical thickness. The resulting structures necessarily have a large surface-to-volume ratio. Some progress toward this objective can be achieved with thin films fabricated by techniques such as CLEFT or ELO. To achieve the ultimate in performance, however, novel structures, perhaps produced by the new growth techniques, will have to be devised. The structures should be physically thin (on the order of 0.1 μm) but optically thick (on the order of 5 μm). Modern growth techniques have demonstrated the capability of growing sophisticated structures.[36–38] The use of semiconductor superlattices has been considered[39] but, while some potential advantages can be identified, it is hard to make a compelling case that such a device would produce an efficiency significantly higher than that of a conventional double heterostructure solar cell. However, novel uses of heterostructures should be explored. If, for example, new structures for achieving light trapping and photon recycling could be produced by novel aspects of the growth process, substantial performance gains could be achieved.

SUMMARY

Group III-V crystalline solar cells hold the efficiency records for operation under one sun and under concentrated sunlight operation but, although III-V technology is highly developed, substantial efficiency gains are still required to make III-V photovoltaics economically competitive for large-scale, terrestrial applications. Our purpose in this paper was to argue that significant efficiency gains can still be achieved, and to identify research opportunities directed at achieving this objective. In particular, the heterostructure capability of the III-V's makes tandem-cell approaches, with their potential for very high conversion efficiencies, particularly attractive. In addition, modern III-V growth techniques have demonstrated the ability to produce novel semiconductor structures. Experience with silicon solar cells suggests that the use of new structures can enhance performance. Clearly, there are many opportunities for innovative research which may, at the same time, have some very significant practical benefits.

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