THIN-FILM GaAs SOLAR CELLS

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ABSTRACT

By using an $n^+/p/p^+$ structure, we have fabricated GaAs solar cells with conversion efficiency of 21% (AM1) on single-crystal GaAs and Ge substrates. Two approaches are being used to lower the cost of such cells: preparation of GaAs solar cells on Ge-coated Si substrates and preparation of thin single-crystal GaAs cells on reusable GaAs substrates. Important advances have been achieved in both areas. Heteroepitaxial Ge films have been deposited on Si substrates, and epitaxial GaAs layers have been grown on such films producing 12% efficient solar cells. Single-crystal GaAs layers as thin as 5 μm have been separated from reusable GaAs substrates by the CLEFT process. A 17% (AM1) GaAs solar cell, only 10 μm thick and bonded to a glass substrate, has been fabricated. The thin-film techniques eliminate the cost and availability of GaAs as major obstacles to utilization of GaAs solar cells. With these developments, low-cost, high-efficiency GaAs cells for terrestrial and space applications may well become a reality.

INTRODUCTION

An active research and development program on GaAs solar cells for terrestrial and space applications has been underway at Lincoln Laboratory for several years. The overall objective of the program is to establish the technical feasibility of fabricating thin, low-cost, radiation-resistant cells with 20% conversion efficiency at AM1. In this paper, we will describe some of the important advances achieved toward this goal. As a result of these advances, we believe that GaAs solar cells have a promising future in both terrestrial and space applications.

TABLE I

Requirements for Solar Cells

Terrestrial	Spacecraft
Low cost	Radiation resistance
High efficiency	High efficiency
Low semiconductor usage	Light weight
	Low cost

Table I lists the required characteristics of solar cells for terrestrial and space applications. For terrestrial applications, the need for low cost is obvious, since cell module costs must be reduced from the present price of about \$10 per peak watt to about \$0.70 per peak watt in order for the electricity generated by solar cell modules to become competitive with other methods of generation. High efficiency makes a major contribution to reducing total system costs. If module efficiency is too low, not only are large areas needed for collection, but also balance of system costs will become predominant. Thus the power per unit area is important as well as dollars per peak watt. Low semiconductor usage is necessary to reduce the material cost and also to avoid limitations on material availability, especially for GaAs. Since GaAs absorbs sunlight very effectively, solar cells made of GaAs can be much thinner than those made of Si. Figure 1 plots the normalized photocurrent at AM1 as a function of thickness for GaAs and Si. For GaAs a 2-μm-thick layer can generate over 90% of the maximum photocurrent produced by an infinite thickness. Silicon, however, requires a layer over 100 μm thick to achieve the same ratio.

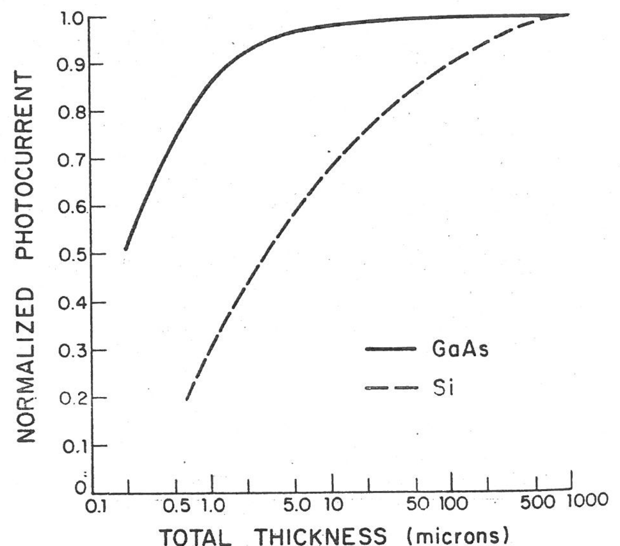

Fig. 1. Normalized photocurrent computed for Si and GaAs as a function of solar cell thickness for AM1.

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For space applications, the essential requirement is high radiation resistance. Space cells should also have high efficiency and low weight, in order to maximize the power to weight ratio. In addition, for large-scale deployment of space cells, lower cost will be necessary. Most of the requirements for space and terrestrial applications are thus very similar, and GaAs cells are found to simultaneously satisfy both needs.

SHALLOW-HOMOJUNCTION STRUCTURE

By using an $n^+/p/p^+$ shallow-homojunction structure, without a GaAlAs window layer, we have fabricated GaAs solar cells on single-crystal GaAs (1) and Ge (2,3) substrates with conversion efficiency as high as 21% at AM1 (see Fig. 2). The 21% efficient cells on Ge, which have a GaAs epilayer only 4 μm thick, are the most efficient thin-film cells prepared to date. The Ge substrates play a passive role that permits them to be substituted for GaAs substrates without any effect on cell efficiency.

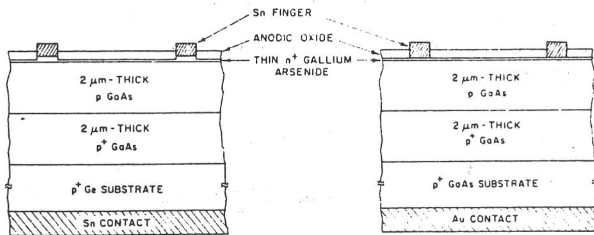


Fig. 2. Schematic diagram of GaAs shallow-homojunction solar cells on GaAs and Ge substrates.

We believe that the $n^+/p/p^+$ configuration is ideally suited for both terrestrial and space applications. The heavily doped layers on the front and back surfaces allow easy fabrication of good ohmic contacts. The thin n^+ layer is comparable in sheet resistance to the thicker p^+ layer in the p^+/n structure of GaAlAs/GaAs heteroface cells (4), mainly because the majority carriers in the n^+ layer are electrons and the electron mobility in GaAs is about 20 times higher than the hole mobility for similarly doped p-layers. This is an important property that makes the shallow-homojunction structure a prime candidate for utilization in concentrator cells. Preliminary results (5) have confirmed that this structure is indeed good for concentrator cells.

The p^+ layer in the shallow-homojunction structure facilitates the formation of low-resistance heterojunction contacts to foreign substrates, as demonstrated by the fabrication of GaAs cells on Ge substrates (2) and recently on Ge-coated Si substrates (6). Furthermore, the p^+ layer provides a back-surface field, minimizing recombination losses at the interface with a foreign substrate. Finally, in the shallow-homojunction structure almost all the photocurrent is generated in the p layer, which normally has a minority-carrier diffusion length (> 20 μm) that is much higher than the solar absorption length (~ 2 μm). Therefore, growth on a foreign substrate can cause a marked reduction in the electron diffusion length in the p-layer without producing a significant decrease in cell photocurrent. This is confirmed by the observation of a decrease of only 5% in the photocurrent in our GaAs cells on Ge-coated Si substrates, despite the large concentration of dislocations (~ 10^7 cm^{-2}) in the p-GaAs layer (6).

Moreover, the $n^+/p/p^+$ structure is advantageous for monolithic tandem devices because the heavily doped n^+ and p^+ layers on the front and back surfaces of the GaAs cells allow tunnel junctions to be more easily attained.

The $n^+/p/p^+$ structure is also ideal for space applications. Because the n^+ layer is so thin (< 1000 Å), almost all the electron damage effects will occur in the p layer, where a marked decrease in minority carrier diffusion length can occur without significant reduction in efficiency. Thus, the n^+/p configuration should be very radiation resistant. We have confirmed this superior radiation resistance in a series of experiments using high-energy electron bombardment (7,8).

The $n^+/p/p^+$ structures are grown by chemical vapor deposition (CVD) in an $AsCl_3$-Ga-H_2 system with a vertical fused silica reactor (2). Comparable cells can be obtained with either a Ga liquid source or GaAs solid source. The CVD technique potentially can be scaled up for mass production. The as-grown thicknesses of n^+, p and p^+ layers are about 0.15, 2, and 2 μm, respectively. The n^+ layer is doped with sulphur to about 5×10^{18} cm^{-3}, the p layer with zinc to about 10^{17} cm^{-3} and the p^+ layer with zinc to about 10^{19} cm^{-3}. We have found that cell efficiency is not very sensitive to the exact doping levels or to the thicknesses of the p and p^+ layers. However, the efficiency is sensitive to n^+ thickness (3). Our best cells so far have n^+ layers about 500 Å thick. Although efficient cells have been fabricated with as-grown n^+ layers of this thickness, it is advantageous to grow a thicker n^+ layer and then to use an anodization and stripping process (with the front contact fingers and bars already in place) for controlled reduction of the thickness (2). This process allows a variation in the as-grown n^+ thickness, as well as producing a larger separation between the front contacts and the junction, thus increasing the yield achieved in cell fabrication.

The cells are fabricated without any vacuum processing steps, utilizing an antireflection (AR) coating about 850 Å thick prepared by anodic oxidation of the n^+ layer and electroplated Au or Sn front and back contacts. With Sn front contacts, anodization and stripping are readily accomplished, because a thin film of SnO_2 is formed on the top surface of these contacts during anodization, thus limiting electrolytic current leakage through the contacts.

Having succeeded in developing the highly efficient and versatile $n^+/p/p^+$ GaAs shallow-homojunction structure as well as potentially low-cost device fabrication techniques, we are presently investigating processes to greatly reduce the material costs of such cells without a significant reduction in cell efficiency. To retain high efficiency, we believe that the cells should utilize GaAs layers that are either single crystals or composed of very large crystallites. Since single-crystal GaAs and Ge substrates are too expensive, two approaches are being investigated for lowering the material costs of such cells: preparation of GaAs on inexpensive Si sheets and preparation of thin single-crystal GaAs films on reusable GaAs substrates. Important advances have been achieved in both areas.

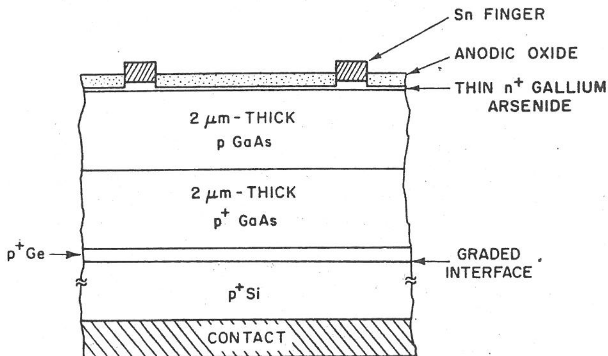
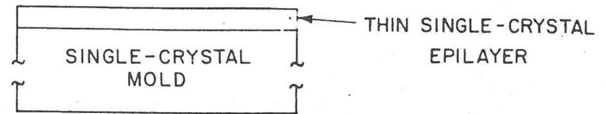


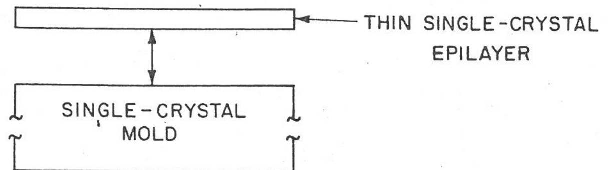
Fig. 3. Schematic diagram of a GaAs shallow-homojunction solar cell on a Si substrate with a Ge/Si alloy interface.

Single-crystal GaAs layers have been grown on Ge-coated single-crystal Si substrates (6,9), and cells with conversion efficiencies of about 12% (AM1) have been fabricated (see Fig. 3). The major obstacle facing this approach is the high dislocation density in the GaAs layers, resulting from the large lattice mismatch (~ 4%) between GaAs and Si. The potential economic advantage of this structure can be realized only if the dislocation density is reduced sufficiently to yield efficiencies approaching 20% (AM1). It should be pointed out that Si sheets for use as substrates need not be as high in quality as those used in Si solar cells, and certainly not as thick, because the Si substrates do not participate in photocurrent generation. Since this approach will be reported in detail (6) in another session of this conference, we will now concentrate on the second approach.

CLEFT PROCESS

The CLEFT process permits the growth of thin single-crystal GaAs films by CVD on reusable GaAs substrates. Since many films can be obtained from one substrate, this process should permit a marked reduction in material usage and cost; since single-crystal films are used, cell efficiencies should remain high.





PEELED-FILM TECHNOLOGY

Fig. 4. Schematic diagram showing the peeled-film technology.

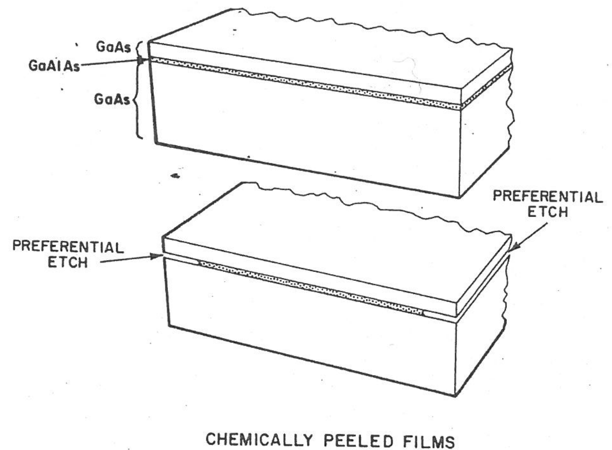


Fig. 5. Schematic diagram showing a chemical method for peeling a GaAs film.

The CLEFT process is a peeled-film technique. The basic idea of peeled-film technology is to grow a thin single-crystal epilayer on a single-crystal mold, to separate the epilayer from the mold, and then to use the mold again (see Fig. 4). A chemical peeled-film technique has been reported (10) for GaAs. A thin single-crystal GaAs film was deposited by molecular beam epitaxy on a GaAlAs layer about 5 μm thick grown on a GaAs substrate. The GaAlAs intermediate layer was removed by selective etching with HF introduced through small openings at the edge of the substrate, and the GaAs film was then separated from the substrate (see Fig. 5). Conversion efficiency of 13.5% has been achieved for GaAlAs/GaAs heteroface solar cells

using GaAs films ~ 50 μm thick separated by this chemical technique (10). Such a technique is inconvenient, however, even if the intermediate layer is relatively thick, since it is difficult to circulate an etchant through the small openings. The CLEFT process is an alternative that provides a practical way of separating epilayers from their substrates.

The key element of the CLEFT process is the use of lateral epitaxial growth performed in the $AsCl_3$-Ga-H_2 reactor (11,12). Our experiments have shown that if a mask with appropriately spaced stripe openings is deposited on a (110) GaAs substrate, the epitaxial growth initiated on the GaAs surface exposed through the openings will be followed by lateral growth over the mask, eventually producing a continuous single-crystal film that can be grown to any desired thickness (11). The upper surface of the film is then bonded to a secondary substrate of some other material. If there is poor adhesion between the mask material and the GaAs, the film will be strongly attached to the GaAs substrate only at the stripe openings. Since a weak plane has been created by the mask and because the (110) plane is the principal cleavage plane of GaAs, the film can be cleaved from the GaAs substrate without significant degradation of either (see Fig. 6). We have found that carbonized photoresist is a

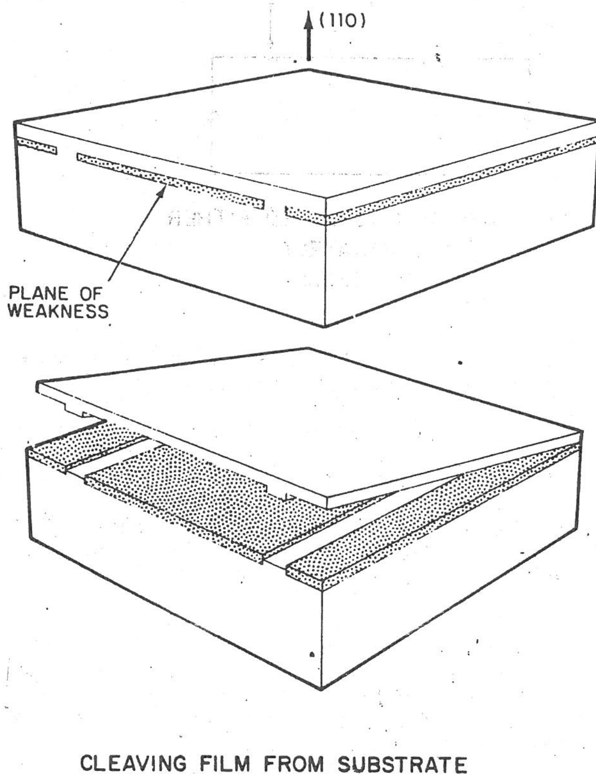


Fig. 6. Schematic diagram showing the CLEFT process of peeling a GaAs film.

suitable mask material, since it has the necessary poor adhesion to GaAs and is chemically inert under the conditions that we employ for CVD growth. Reference 12 also describes several alternate mask materials and configurations.

The technique used for separating the GaAs film from the GaAs substrate is illustrated by the schematic diagram shown in Fig. 7. The upper surface of the film is bonded with epoxy to a glass secondary substrate. The GaAs and glass substrates are then bonded to glass plates that serve as cleaving supports. A wedge is inserted between the two glass plates and tapped gently, causing the GaAs film to be cleaved from the GaAs substrate but leaving it mounted on the glass substrate. Finally, the GaAs primary substrate is removed from its glass cleaving support plate, leaving it ready for another cycle of the process.

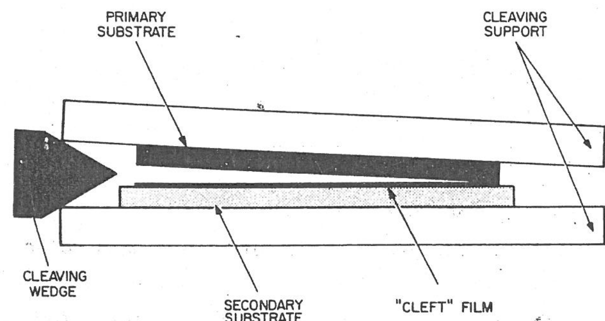


Fig. 7. Cross-sectional view of a CLEFT epitaxial film being transferred from the GaAs substrate.

As a demonstration that the CLEFT process can be used to prepare multiple GaAs films, we have carried out four CLEFT cycles with the same single-crystal GaAs substrate. Four successive films of excellent quality were obtained, with thicknesses of 5, 10, 10, and 8 μm, respectively. The area of each film is about 4 cm^2. The films prepared and separated in this manner have been shown by Hall measurements to be comparable in quality to conventional single-crystal CVD layers (11,12).

In a demonstration of the applicability of the CLEFT process to solar cell fabrication, we first grew the $n^+/p/p^+$ structure on (110) GaAs substrates that had been masked with carbonized photoresist. The structure was then processed in the manner described above to form Sn front contacts and an anodic AR coating on the upper surface (n^+ layer). The surface was bonded by epoxy to a cover glass, and the film was separated from the GaAs substrate. An electroplated Au contact was then made to the back surface. This procedure has been used to make three CLEFT cells, with GaAs films 10 μm thick, which have conversion efficiencies of 15 to 17% at AM1. The 17% cell has an area of 0.51 cm^2 (13).

CLEFT CELLS FOR TERRESTRIAL APPLICATIONS

The CLEFT process allows a drastic reduction in the usage of GaAs--an essential requirement for cells made of semiconductors that are much less plentiful than Si. The reduction in material usage does not result in significant degradation in the high efficiency of GaAs cells, which is their major advantage over Si cells. Cell modules having high conversion efficiency will provide a substantial economic advantage over modules of lower efficiencies with respect to the costs of total photovoltaic systems. It is expected that CLEFT cells, when fully developed, will achieve conversion efficiencies as high as 20% with GaAs layers only 5 μm thick. If this goal can be achieved, the cost of GaAs material will no longer be the major obstacle for this material system. Furthermore, there should be enough Ga available for large-scale deployment of GaAs cells (14).

BASIC MATERIAL COST

MATERIAL	CURRENT 1981 PRICE* ($/kg)	THICKNESS (μm)	WEIGHT (g/m^2)	MODULE % (AM1)	$\$/m^2$	$\$/W_p$
Si	60	125 (5 mil)	290	14	18	0.13
GaAs	450	5	26	18	12	0.07

*ELECTRONIC GRADE, POLYCRYSTAL

Fig. 8. Basic material cost of Si and GaAs solar cells.

Figure 8 lists the basic material costs for Si and GaAs cells, estimated from the current costs of electronic grade GaAs and Si raw material. For GaAs modules made from 5-μm-thick, 18% efficient cells the GaAs material cost is about $\$12/m^2$, or $\$0.07/W_p$. For Si modules made from 125-μm-thick cells, the Si material cost is $\$18/m^2$ or $\$0.13/W_p$. While the price of raw polysilicon may come down from the current price, especially if material of poorer quality than electronic grade can be used, the price of GaAs raw material may also be reduced for the same reason. In addition, the actual material costs in modules are dependent on the material processing techniques used. In any case, Fig. 8 indicates that the material costs of GaAs cells made by the CLEFT process should present no obstacle to their use in flat-plate modules. The same conclusion holds for thin-film GaAs cells on Ge-coated Si substrates if high-efficiency cells can be made on inexpensive Si sheets.

Concentrator cells made of GaAs have a basic advantage over Si cells because of their higher conversion efficiencies. However, to avoid a significant reduction in concentrator cell efficiency, it is necessary to maintain low operating temperatures. Since the thermal conductivity of GaAs is only about 1/3 that of Si, cooling of bulk GaAs cells has been a problem. This difficulty should not arise for CLEFT cells, which are so thin that excellent heat-sinking can be obtained by mounting them directly on cooling blocks.

Finally, CLEFT cells suggest a promising alternative structure for high-efficiency tandem cells. Instead of the commonly conceived monolithic structure, CLEFT cells of different materials can be stacked (Fig. 9) on top of a bulk cell. For a three-cell structure, for instance, a CLEFT GaAlAs cell and a CLEFT GaAs cell could be placed on top of a Ge cell. The resulting tandem cell should have conversion efficiency much greater than 30% (AM1). The three cells could be connected in series or parallel, depending on whether the bonding material is conducting or insulating. For tandem cells of the proposed structure to be practicable, the upper cells must have very thin layers in order to reduce parasitic optical absorption. The CLEFT cells satisfy this requirement very well.

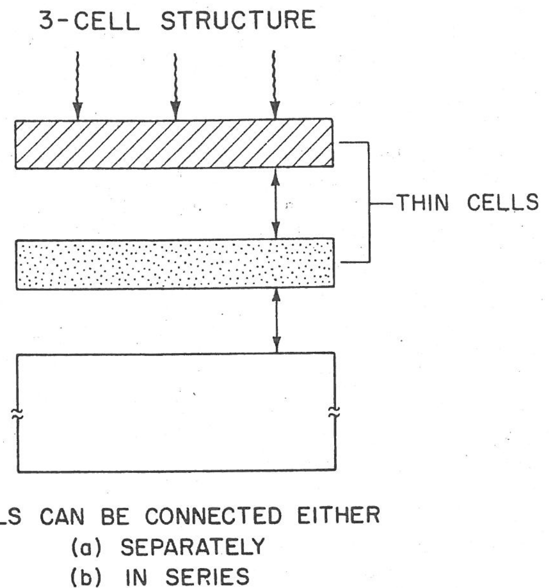


Fig. 9. A three-cell tandem structure illustrating a proposed application of CLEFT solar cells.

CLEFT CELLS FOR SPACE APPLICATIONS

As noted earlier, solar cells used in space must be radiation resistant, highly efficient, and light in weight. Our $n^+/p/p^+$ shallow-homojunction structure has already satisfied the efficiency and radiation resistance requirements. The CLEFT cells now offer the possibility of very light weight solar cell panels.

Because the density of GaAs is about a factor of two larger than that of Si, there is a common misconception that GaAs solar cells must be heavier than Si cells. However, because of the much stronger optical absorption of GaAs, GaAs cells actually have the potential to achieve specific power (power/weight) several times larger than that of Si cells. As an illustration, a 5-μm-thick 18% (AM0) GaAs solar cell will have a specific power of about 9.3 kW per kilogram of GaAs. The specific

power of the complete cell will be reduced by the weight of contacts and bonding material, which is not very significant, and also by the weight of the cover glass, which is indeed very substantial. Even for a 100-μm-thick cover glass, the glass will be many times heavier than the GaAs. Therefore, for ultralight cells even thinner glass must be used. A lower limit on the thickness is set by the requirement that the cover glass be thick enough to prevent cell degradation under proton bombardment. However, by using high-efficiency CLEFT cells with proper lightweight packaging it should be possible to produce panels with specific power over several kW/kg.

Although CLEFT GaAs cells are preferred for space applications, thin-film GaAs cells on Si substrates would also have a weight advantage over conventional GaAs cells because of the lower density of Si and because very thin Si films could be used as substrates.

POTENTIAL PRODUCTION SCHEMES

By means of the CLEFT process thin semiconductor sheets and grown p-n junctions can be prepared in a single operation. In addition, the reuse of the GaAs substrates will greatly reduce the material and processing costs of GaAs wafers. Overall, as illustrated in Fig. 10, the

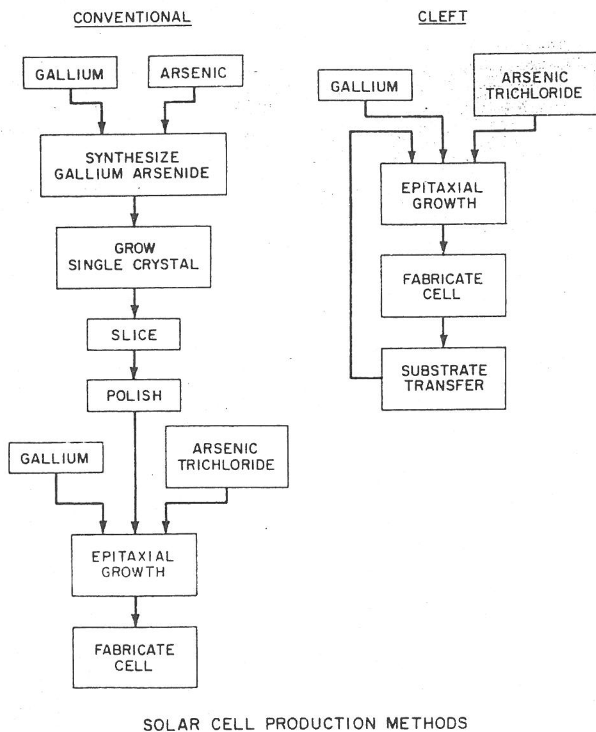


Fig. 10. Flow charts illustrating the processing steps required for conventional GaAs cells and for CLEFT GaAs cells.

CLEFT process makes it possible to eliminate many steps used in conventional solar cell processing, with substantial potential savings.

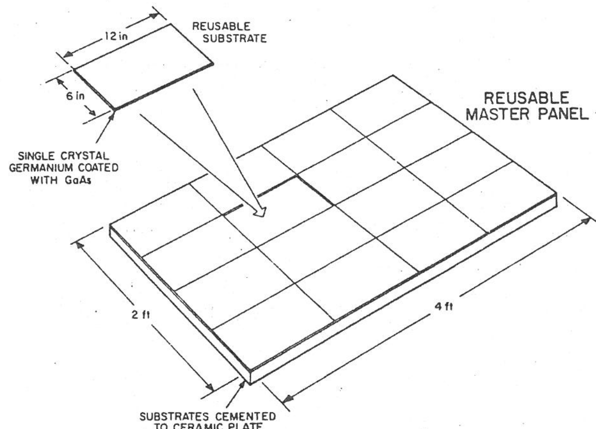


Fig. 11. Proposed GaAs reusable master panel composed of GaAs-coated Ge substrates bonded to a ceramic plate.

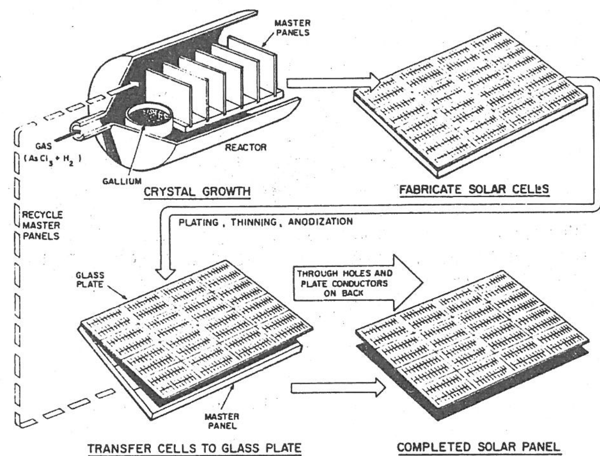


Fig. 12. Proposed production scheme for large-area CLEFT GaAs solar cell modules using reusable master panels.

The major development still required is the scale-up of the CLEFT process to much larger areas. A possible production concept is presented in Fig. 11, which shows a proposed master-panel structure for CLEFT growth. This panel is constructed by bonding a ceramic sheet to an assembly of GaAs tiles that are composed of GaAs layers pre-grown on single-crystal Ge wafers. The Ge wafers are used because crystals of Ge, which has a good lattice match to GaAs, can currently be grown with much larger dimension than GaAs crystals. The master panel shown has dimensions of 2 feet by 4 feet. While such a large size may be too ambitious initially, smaller panels may well be economical.

The master panels would be employed as the reusable GaAs substrates that we have demonstrated in the laboratory. These panels are placed in large CVD reactors for lateral overgrowth and formation of the p-n junction. After growth, front contacts and AR coatings are formed on the front surface. The whole panel is bonded to a large glass sheet, and all the GaAs cells, each from one GaAs tile, are simultaneously transferred to the cover glass. The back contacts, interconnects and back encapsulation are formed in the final operations (Fig. 12). The whole process not only saves many steps in cell fabrication but will also eliminate several encapsulation and packaging steps. There are, however, many difficult problems to be solved in implementing this scheme, including achieving uniform CVD growth over large areas and developing bonding, separation, and interconnect techniques.

SUMMARY

Our development of $n^+/p/p^+$ shallow-homojunction GaAs solar cells has demonstrated the feasibility of preparing high-efficiency, ultrathin GaAs cells. Both the material growth and device fabrication techniques should be compatible with mass production of these cells, and the cost and availability of semiconductor material no longer constitute major obstacles. Such cells have a bright future in both terrestrial and space applications.

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REFERENCES

1. J. C. C. Fan, C. O. Bozler, and R. L. Chapman, Appl. Phys. Lett. 32, 390 (1978).
2. C. O. Bozler, J. C. C. Fan, and R. W. McClelland, Proceedings of 7th International Symposium on GaAs and Related Compounds, St. Louis 1978 (Institute of Physics, London, 1979), p. 4296.
3. J. C. C. Fan, C. O. Bozler, and B. J. Palm, Appl. Phys. Lett. 35, 875 (1979).
4. J. M. Woodall and H. J. Hovel, Appl. Phys. Lett. 30, 492 (1977).
5. G. W. Turner, J. C. C. Fan, R. L. Chapman, and R. P. Gale, proceedings of this meeting (to be published).
6. R. P. Gale, B-Y. Tsaur, J. C. C. Fan, F. M. Davis, and G. W. Turner, proceedings of this meeting (to be published).
7. J. C. C. Fan, R. L. Chapman, C. O. Bozler, and P. J. Drevinsky, Appl. Phys. Lett. 36, 53 (1980).
8. J. C. C. Fan, G. W. Turner, R. P. Gale, and C. O. Bozler, Conference Record of 14th IEEE Photovoltaic Specialists Conference (San Diego, CA, 1980), p. 1102.
9. B-Y. Tsaur, M. W. Geis, J. C. C. Fan, and R. P. Gale, Appl. Phys. Lett. (to be published).
10. M. Konagai, M. Sagimoto, and K. Takahashi, J. Cryst. Growth 45, 277 (1978).
11. R. W. McClelland, C. O. Bozler, and J. C. C. Fan, Appl. Phys. Lett. 37, 560 (1980).
12. C. O. Bozler, R. W. McClelland, and J. C. C. Fan, Proceedings of 8th International Symposium on GaAs and Related Compounds, Vienna 1980 (Institute of Physics, London, 1981), p. 283.
13. C. O. Bozler, R. W. McClelland, and J. C. C. Fan, submitted for publication.
14. Final Report, "Gallium: Long-Term Supply," prepared for Solar Energy Research Institute by Charles River Associates, Boston, MA, Report No. CPA483, June 1980.