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Abstract

The inherent electro-optical properties of gallium arsenide (GaAs) and related III-V compounds make this class of semiconductors an optimum choice for use in very high efficiency solar cells. The ability to alloy GaAs with other column III and V elements while maintaining the single crystal zincblende structure allows the photovoltaic properties to be tailored to specific needs. The current understanding and control of the properties of these materials is more advanced than for any other semiconductor except single crystal silicon. For these reasons, the Advanced High Efficiency Concepts Program supports materials research to improve the properties of III-V semiconductors needed to achieve the maximum attainable photovoltaic conversion efficiencies.

Introduction

The goals of the Advanced High Efficiency Concepts Program in the next few years are the laboratory demonstrations of thin film solar cells with one sun efficiencies of 20% and concentrator solar cells (greater than 100 suns) with efficiencies of 30% or more. A long term goal is to increase efficiencies to more than 35% under concentration.

Clearly the goals of this program are quite high. In order to reach these goals and push beyond them, we can accept neither an isolated theoretical effort nor an unguided experimental approach. We need a coherent fusion of the best that experimental and theoretical science in this country has to offer today.

The best theory of photovoltaic devices available today is the well developed body of single crystal device theory. This provides a foundation upon which the experimental results can be examined, compared and interpreted to yield the maximum amount of information possible.

The best experimental results have been in gallium arsenide (GaAs) based single crystal cells, although Si is not far behind. GaAs is a near optimum material for use in single junction solar cells and has achieved higher reported efficiencies both in bulk (22%) and thin film (17%) form than any other solar cell material. The ability to alloy GaAs with other III-V elements permits the growth of single crystal semiconductors with electro-optical properties which can be tailored to optimum values for various applications. In addition, single crystal GaAs based devices are also of interest for applications other than photovoltaics. The electronic and optical properties of GaAs offer advantages for use in high speed integrated circuits, microwave FETs and optical sources and detectors. Thus, as with silicon solar cells, the development of GaAs photovoltaic technologies benefits from the efforts of a larger community researching device fabrication technology. This allows the photovoltaic efforts to concentrate on a narrower range of concerns.

Current Program Structure

Based on this combination of high performance, ability to control physical properties, and well developed research efforts, the family of III-V semiconductors has been selected as the basis of study in Advanced High Efficiency Concepts. The research can be broken up into three broad overlapping areas. These are thin films, III-Vs on silicon and multiple junction cells. In the first area several concepts are under study for preparing GaAs films for single junction cells and high bandgap materials for stacking in multijunction cells.

The second area, heteroepitaxial growth of III-Vs on silicon, offers the potential of building upon the mature silicon photovoltaic technology. Higher efficiencies could be obtained from the modules by adding a III-V layer to the silicon. By itself, a thin film GaAs cell could improve efficiency. A dramatic increase in performance could be achieved by using a high bandgap alloy with an active silicon cell to form a two-junction cascade cell. The module technology would remain largely unchanged.

The third area addresses improving the quality and understanding of ternary and quaternary III-V alloys. The emphasis is on use in multiple junction concentrator cells. The results of this research can also be used to improve the results in the first two areas.

High Efficiency Thin Films

4 to 5um thick GaAs cells grown on single crystal GaAs substrates exhibit the highest one-sun efficiencies measured to date. In the high efficiency thin film area we are looking at the trade-offs involved when one eliminates the substrate and retains only the 4 to 5um thick active cell.

There are three subcontracted programs whose primary interest is the thin film area. One is at the United Technologies Research Center (UTRC). This involves growing GaAs cells on sacrificial NaCl substrates (1). To date this program has rapidly acquired the technology to grow 20% efficient GaAs cells on GaAs, demonstrated that NaCl does not contaminate the GaAs, (using a Ge interlayer) demonstrated an active GaAs cell grown on a NaCl substrate, and demonstrated a plasma-enhanced OM-CVD technology which allows the growth of GaAs at 450°C (at this temperature the lattice constant of NaCl exactly matches that of GaAs, providing an excellent surface for GaAs nucleation and growth). In the near future UTRC will begin the growth and fabrication of thin GaAs cells from NaCl substrates and begin analyzing the efficiency trade-offs.

The second program is at Southern Methodist University. In this effort several techniques are under investigation to develop substrates that will yield single crystal or very large grain GaAs films (2). The current research involves horizontal zone recrystallization by a graphite strip heater of GaAs or germanium on coated graphite substrates. The recrystallized films serve as a substrate for GaAs film growth. Solar cells with grain sizes greater than a square millimeter have been prepared by this technique.

The third thin film program is underway at MIT-Lincoln Labs where the anisotropic growth rates of III-V compound semiconductors are used to prepare low-defect thin films (3, 4). In the process, known as CLEFT (Cleavage for Lateral Epitaxial Film Transfer), a GaAs substrate is masked to expose only a small area of stripes, oriented along a specific crystal axis. When additional material is grown on this substrate, it nucleates on the small surface of exposed GaAs. If the orientation of the exposed strips is chosen correctly, the lateral (horizontal) growth rate will be much greater than the vertical growth rate and the material will rapidly spread out over the entire surface. The interfaces where two lateral growth planes meet show no signs of crystal imperfections. A thin cell can then be grown on this single crystal thin film (which is attached to the bulk substrate by only a few thin columns of GaAs). The cell can then be bonded to glass and then cleaved from the bulk GaAs cell, leaving an easily handled thin cell and a reusable substrate.

In work supported by NASA, single crystal GaAs cells with an efficiency of 17% have been fabricated from CLEFT films 5um thick and films on thin as 2um with an area of 4cm^2 have been seperated from the reusable substrate. The Advanced High Efficiency Concepts program is supporting research to extend these results to CLEFT ternary cells. Recently the lateral overgrowth of AlGaAs and GaAsP has been demonstrated. Work is currently underway to improve the quality of these materials for use at the top cell of a two cell cascade structure. A proof-of-concept CLEFT GaAs on Si cascade structure exhibited an efficiency of 19.5% (one sun, AM1, no AR coating, nonoptimized structure).

III-Vs on Silicon

Another broad area of materials research is the growth of GaAs on silicon with the end-product being either a high-efficiency thin-film GaAs cell (using the Si solely as a substrate) or a two-junction cascade cell (using an active Si solar cell). Historically, this has involved the growth of a Ge layer between the Si and GaAs, but this is no longer the case. Early last year SPIRE Corporation announced the growth of GaAs directly on Si using OMCVD. While the Si/GaAs interface exhibits a high defect density ($10^{12}/cm^2$) this drops off to roughly $10^6/cm^2$ 3000 Å into the GaAs layer. SPIRE has also demonstrated the growth of AlGaAs directly on Si (5).

The ability to grow III-V's directly on Si does not mean that the Ge interlayer technology is no longer of interest; Ge still offers a number of advantages. First, there is a large thermal mismatch between Si and GaAs. The Ge layer can help to relieve the mechanical stress when cooling from the growth temperature. Secondly, the Ge layer may improve the electrical interface between the Si and GaAs. The third point to be made is that the highest efficiency GaAs cell grown on Si (14% by MIT-Lincoln Lab) was grown using the Ge interface technology (4). And finally the Ge technology is still undergoing vast improvements. Recent work at Southern Methodist University has shown that a linear grading layer of Si_xGe_{1-x} ($Ge/Si_xGe_{1-x}/Si$) can reduce the dislocation density in the Ge layer to $10^6/cm^2$, three orders of magnitude below that in Ge layers grown directly on silicon. This improvement in the Ge surface is expected to result in still higher efficiency GaAs cells.

High Efficiency Multiple Junction Cells

The third broad area of interest is high efficiency (greater than 30%) multiple junction cells for use in concentrator systems (greater than 100 suns). At present, the program is looking at materials for high efficiency <u>two</u> junction cells, optically cascaded (a high bandgap material in front of a low bandgap material). For any given set of materials, devices can usually be fabricated in two, three or four terminal configurations; the final choice will probably be dictated more by power system engineering considerations than by cell materials and is not, therefore, a key concern of this (materials research) program.

The SERI program is looking at two top cell materials (AlGaAs and GaAsP at 1.8 eV bandgap) and two bottom cell materials (Si and GaInAs at 1.1 eV bandgap). Varian Associates, under a prior SERI subcontract, attained 21.5% efficiencies with a GaInAs cell over the range of 175 to 320 suns concentration. Under their current SERI the research emphasis is on a two-pronged thrust to find a suitable top cell material. To attain a 30% efficient two junction cell the front/top cell must be 20% efficient. The first approach is to monolithically grow an AlGaAs cell on top of the GaInAs using a high bandgap (optically transparent to the GaInAs) AlGaInAs grading layer to grade from the GaInAs lattice constant to that of AlGaAs. The materials quality of the AlGaAs is good (85% internal quantum efficiencies) but not yet sufficient for 20% cells. The cells will be electrically connected in either two or three terminal configurations using Varian's metal interconnect technology. The second approach at Varian is in GaAsP. While this material is not as well understood as AlGaAs and does not yet have a mature contacting technology, it does appear to be more 'robust' or 'forgiving' when it comes to defects. Unfortunately, the lattice constant is even further away from GaInAs than that of AlGaAs. To simplify the current effort, Varian will be looking at GaAsP grown on thin GaP substrates. GaP is transparent to the GaInAs cell. A 20% GaAsP/GaP cell can be mounted on top of the GaInAs bottom cell to provide a proof-of-concept 30% device.

New Ideas

In January of 1983, SERI released a solicitation for Letters of Interest in "New Ideas for Photovoltaic Conversion." Four of the subcontracts that resulted from this solicitation are of particular interest to the Advanced High Efficiency Concepts program and will be mentioned here even though they are funded under the SERI Innovative Concepts program.

The first is work being done at Rensselaer Polytechnic Institute (RPI). There is both theoretical and experimental indication that a graded bandgap semiconductor will, under high (1000 suns) illumination, exhibit an EMF (7). The work at RPI is a joint theoretical and experimental effort to verify and quantify this effect. If this is true, it is hoped that a graded bandgap semiconductor grown on top of a small bandgap p-n junction will provide efficiencies greater than 30% under high illumination.

The second program is a joint effort between Brooklyn College of CUNY and the IBM Watson Research Center. The approach is to improve the efficiency of a high quality AlGaAs/GaAs heteroface cell near theoretical limits by lowering the sheet resistance, increasing the fill factor and improving the current collection via very heavy p-type doping in the AlGaAs layer (8). Recent studies have shown that levels of $6 \times 10^{19}/cm^3$ can be obtained via MBE in GaAs. This program will see if these results can be extended to AlGaAs.

The third program is being pursued at the Research Triangle Institute (RTI) which is addressing the problem of an optically transparent, low resistivity, high current tunnel junction interconnect for multiple junction cells under high concentration (9). A major problem with tunnel junction interconnects in the past has been the inability to obtain sufficiently high doping levels in a high bandgap material. RTI is approaching the problem by growing the tunnel junction in a low bandgap material and then etching it away except for those areas that will later be covered by the upper grid lines. The top (high bandgap) cell is then grown over the top of this patterned tunnel junction. The materials systems will be an AlGaAs/GaAs two junction cell with a patterned Ge tunnel junction.

The last research effort here is work being carried out by the General Electric Company. This program has a goal of reducing the surface recombination velocity of a bare GaAs surface from 10^6 cm/sec to less than 10^3 cm/sec (10). This will be done via a controlled OMCVD reaction of TMAl with oxygen producing a thin (50 Å) aluminum oxide film.

Future Directions

It is likely that the goals of 20% efficient thin film and 30% efficient concentrator cells can be achieved through continued improvements in the active semiconductor layers. The current program structure is directed towards obtaining these improvements. In order to push efficiencies significantly above these levels, the solar cell structures must be improved. Looking at the recent improvements in efficiency in single crystal silicon cells, it can be seen that the cell structures are much different from those of five years ago. The new cells take advantage of effective surface passivation techniques, reduced recombination velocity due to contacts, improved anti-reflection and optical trapping. The two basic designs of planar, single-junction GaAs cells are largely unchanged over the last five years. New structures cannot be implemented without materials research to develop the necessary components of the structure. As was and is being done in silicon, the III-V photovoltaic research will need to participate with the non-PV community in establishing control and understanding of all aspects of the materials.

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