INCORPORATION OF SUPERLATTICE CRYSTAL LAYERS IN MULTIJUNCTION SOLAR CELLS

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SUMMARY

This paper proposes the application of superlattice growth techniques in the fabrication of high efficiency multijunction solar cells in order to improve their crystalline perfection and hence enhance their output. Previous research has shown that superlattice layers are effective in decreasing the density of dislocations in lattice mismatched heterostructures at least four orders of magnitude. Hence it is proposed to utilize this feature of superlattices to alleviate the problems due to misfit dislocations generated in the regions between two or more photovoltaic collecting junctions.

A further advantage is that the possibility is presented for using silicon as a low cost substrate as well as for the low band gap junction. In the test case proposed here, a silicon low gap cell will be connected to a $GaAs_{.7}P_{.3}$ high gap cell through a connecting region containing a GaAs/GaP superlattice.

INTRODUCTION

This paper proposes the application of superlattice* growth techniques for the fabrication of low cost substrates for high efficiency solar cells. Recent research has demonstrated the feasibility of achieving high photovoltaic conversion efficiencies (potentially above 35%) using multiple junctions in

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*A superlattice, as the term has come to be used in solid state electronics, is a thin (~1μm) semiconductor structure comprised of many ultrathin layers (~100 Å each) of two different semiconductors alternating with one another. A schematic diagram of a superlattice composed of two hypothetical semiconductors A and B is shown in Fig. 1. This structure exhibits properties which tend to be intermediate between those of the two constituent materials but may be somewhat different from either one. It offers the possibility of creating semiconductors with made-to-order properties such as the band gap or optical absorption coefficient. It was first proposed by Esaki and Tsu (1) in 1970 as a quantum mechanical curiosity which might some day give rise to devices with extremely high frequency response. Several other device proposals based on the superlattice concept have followed. Although most superlattice growth to date has been done by the MBE process, the technical feasibility of growing superlattices by a CVD process was demonstrated in 1969 by Blakeslee (2) and improved recently, using MO-CVD, by Dupuis and Dapkus (3).

optimum band gap materials (4,5). In addition, multijunction converters are excellent candidates for hybrid photovoltaic/thermal systems. A hybrid converter of this type could have an electrical conversion efficiency of 25% while providing a thermal energy output in the range of 150°C to 250°C (6).

The GaAs substrate, which is used in structures currently being developed, is a drawback to widespread implementation of these high efficiency converters due to its high cost and extensive consumption of gallium resources. In addition, dislocations due to lattice mismatch between the various compositional layers involved in these structures degrade the quality of the electrically active regions of the cells. If a low cost substrate such as silicon could be substituted for the GaAs, a major breakthrough would result not only for III-V based solar cells, but for III-V device technology in general. The application of superlattice growth techniques, which have already shown great promise in coupling non-lattice matched layers, is proposed for utilizing low cost substrates in high efficiency solar cell structures. The proposed approach would alleviate the problem of device degradation due to dislocation propagation into the active regions of the cell. Furthermore, it would demonstrate the possibility of using silicon as both the low cost substrate and the low band gap cell of a two-junction high efficiency photovoltaic converter.

THE CONCEPT

Presently, only the III-V materials technology has been advanced sufficiently to address the materials requirements for growth of monolithic cascade cells, but the GaAs substrates which have been used thus far for the development of cascade devices are very expensive. Silicon substrates are a factor of twenty or so less expensive than GaAs, but, unfortunately, silicon does not have the proper lattice constant to be lattice-matched to the other candidate cells.

We propose to use superlattice structures in the fabrication of high efficiency tandem solar cells, not for the active photoelectric conversion layers but rather as a means of alleviating one of the most difficult problems facing the construction of monolithic tandem cells, namely that of lattice mismatch. The mismatch occurs because the two cells of the tandem, a high band gap cell and a low band gap cell, will in general be created out of two semiconductor materials having different lattice parameters. Figure 2 indicates the lattice constant values and band gaps of a number of candidate semiconductors for multijunction converters. The crosshatched regions represent the optimal range of band gaps for the top and bottom junctions of two-junction cascade cells. Presently only Ge and GaAs are considered as viable substrates for the cascade cells. Unfortunately, the band gap of Ge is too low to be optimal for the low band gap junction. Although Si has the proper band gap for the low band gap cell, it does not have the proper lattice constant to match the high band gap cell. Typically, a transitional, i.e., compositionally-graded, layer or series of layers is grown between the two cell regions in order to reduce the density of dislocations that inevitably arise to relieve the misfit stress. At best these grading techniques, be they continuous or by steps, are only partially successful, and a large number of dislocations remains. They propagate through the active solar cell layers and cause recombination losses and, when present in extreme densities, can severly disrupt the crystal growth process. This is a very serious problem and one that is not generally sufficiently appreciated. It has been a major problem in achieving the necessary device quality layers in the present cascade cell structures.

However, a way around this problem does exist. Matthews and Blakeslee (7) have demonstrated that growth of a superlattice layer after the graded layer serves to confine all the dislocation lines in planes normal to the growth direction so that they do not propagate into the active solar cell region. They were able to reduce the dislocation density in a $GaAs/GaAs_{0.5}P_{0.5}$ superlattice from 10^8 per cm^2 to almost zero. The details as to why and how this dislocation elimination can be effected are quite subtle; they are fully set out in the basic patent for the process granted to Blakeslee and Matthews (8).

A method has been suggested for constructing solar cells on silicon substrates (9). It consists of connecting the Si substrate with a deposited Ge layer through a graded alloy layer of $Ge_{1-x}Si_x$, followed by growth of GaAs on the Ge, to which it is lattice-matched. A better approach is to use the silicon as both the substrate and the low band gap junction. This reduces the complexity of the cascade structure substantially, with the benefit of better yields in a production line. The grading layer and superlattice layer in this case would couple the high band gap junction to the junction formed in the silicon.

IMPLEMENTATION OF THE CONCEPT

There are several tandem cell concepts which could benefit from the incorporation of a superlattice to alleviate the lattice mismatch problem. One in particular seems especially attractive as a test vehicle because it not only offers a good chance of relatively rapid reduction to practice with the least difficulty, but, if successful, could have a large impact on the problem of cost and availability of substrates for high efficiency solar cells.

The project selected is to link, by using a superlattice, a Si wafer, which serves as both substrate and low band gap cell, and a GaAs-based high band gap cell. The structure will be grown by the method of metal-organic chemical vapor deposition (MOCVD) which was shown to be useful for growth of high efficiency GaAs/GaAlAs solar cell structures by Dupuis et al. (10) in 1977. It has also been used to make double heterostructure lasers (11), FETs (12) and superlattice-like structures known as Bragg reflectors (3). Its principal advantage over other techniques such as liquid phase epitaxy is the ability to grow very thin (tens of angstroms), uniform layers of controllable composition.

It is necessary to go from Si with a band gap of 1.11 eV and a lattice constant of 5.43 Å to some ternary alloy of GaAs with a band gap ideally around 1.8 eV while undergoing as small a change in lattice parameter as possible. In view of the latter requirement, the GaP system is the best choice for forming a ternary with GaAs, since the lattice parameter difference between Si and GaP is only 0.37% and acceptable heteroepitaxy of GaP on Si by MOCVD has already been demonstrated (13). Thus, the major steps of the process would be the following:

(1) Start with a Si substrate and make a p-n junction by diffusion or by homoepitaxy.

(2) Grow a thin layer of GaP on the Si from a vapor containing $Ga(CH_3)_3$ and PH_3.

(3) Grow the graded layer by decreasing the PH_3 content of the reactant vapor and replacing it with AsH_3. Continue this process until the top of the graded layer has approximately the composition $GaAs_{.7}P_{.3}$, with a band-gap of 1.80 eV. This grading should be accomplished within 10μm or less.

(4) Remove the threading dislocations by inserting a thin asymmetric GaAs/GaP superlattice region containing 10 or so oscillations. In order to lattice match the superlattice to the underlayer with composition $GaAs_{.7}P_{.3}$, the thickness of the respective constituent layers GaAs and GaP should be in the ratio of 7 to 3.

(5) Grow a 2-3μm layer of essentially dislocation-free $GaAs_{.7}P_{.3}$ atop the superlattice and fabricate a junction therein by epitaxy or diffusion.

In carrying out the above procedure, two of the operations are particularly critical. One is the need for very precise control of the composition of the graded layer and of the top cell layer. This can be effected mainly by careful control of the input flow of reactant gases but might eventually incorporate <u>in situ</u> optical measurement of the solid composition. The other critical point is the ability to switch back and forth rapidly and reproducibly from GaAs to GaP in creating the superlattice. Both of these points can be accommodated within the scope of present technology by making modifications to present MOCVD systems. Other points requiring careful consideration are meticulous substrate surface treatment in order to assure good initial epitaxy of GaP on Si and careful experimentation to determine the absolute minimum thickness for each layer, since it is very important to eliminate as much of the expensive Ga-containing material as possible.

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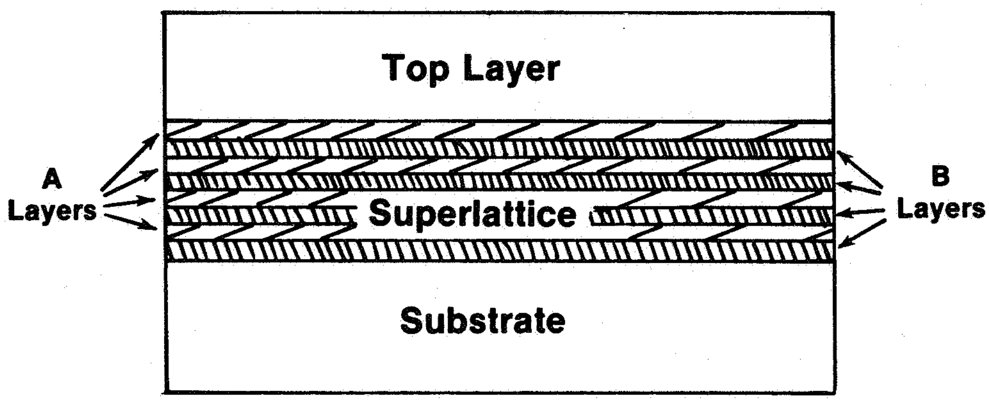

Superlattice Structure

FIGURE 1

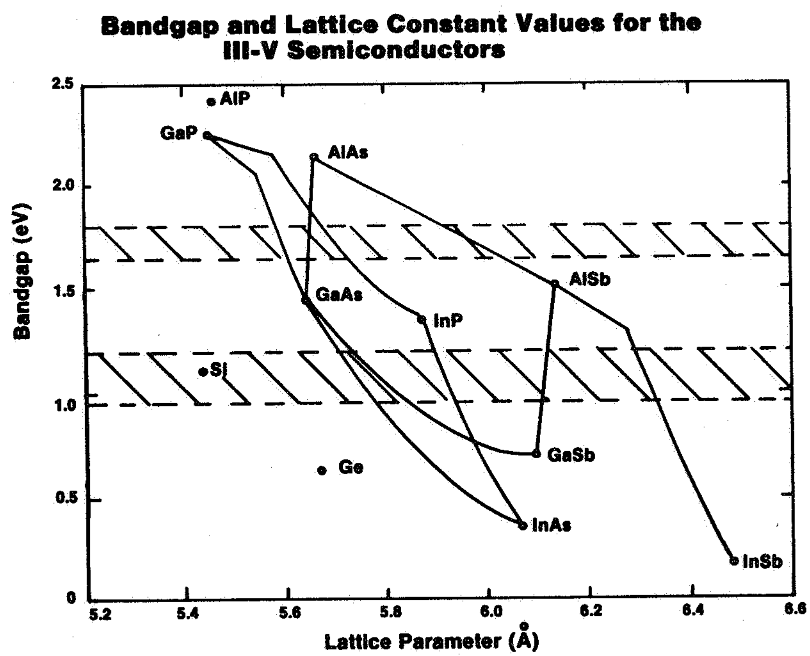

FIGURE 2