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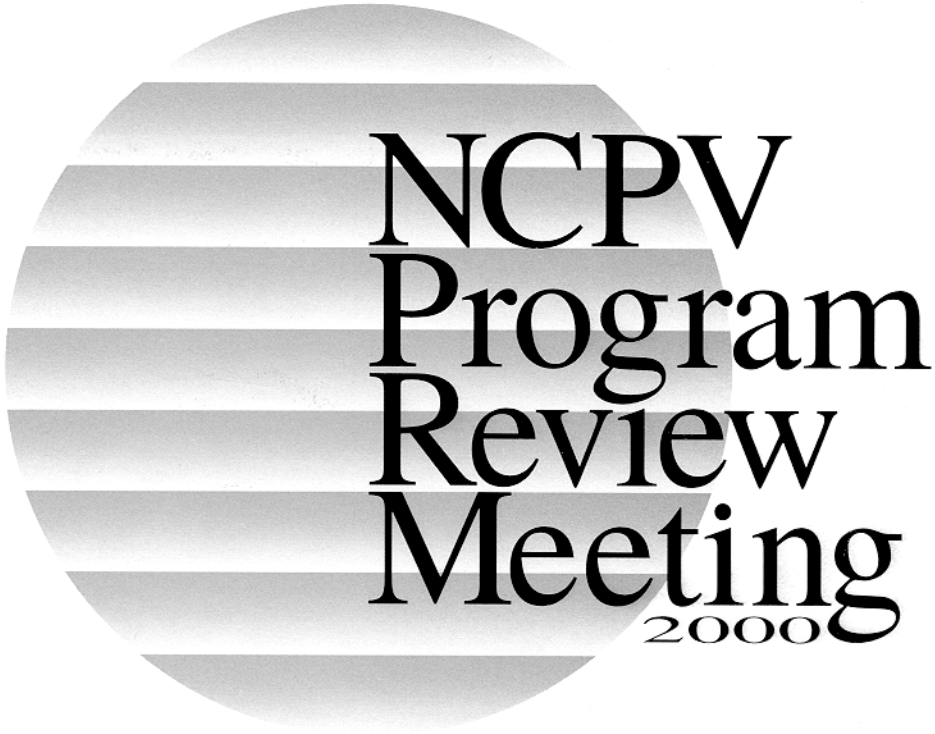

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BGaInAs Alloys Lattice Matched to GaAs for High-Efficiency Solar Cells

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ABSTRACT

A novel alloy, BGaInAs, may prove useful in high-efficiency III-V multijunction solar cells. We report the epitaxial growth of zinc-blende $B_xGa_{1-x-y}In_yAs$ and $B_xGa_{1-x}As$ on GaAs substrates with boron concentrations (x) up to 3%-5% by atmospheric-pressure metal-organic chemical-vapor deposition. The band gap of $B_xGa_{1-x}As$ increases by only 4-8 meV/%B with increasing boron concentration in this concentration range. We demonstrate an epitaxial zinc-blende $B_xGa_{1-x-y}In_yAs$ layer with a band gap of 1.34 eV nearly lattice matched to GaAs and a BGaInAs solar cell with an electron diffusion length greater than 0.4 μm.

1. Introduction

The high-efficiency GaInP/GaAs/Ge cascade solar cell is the current state-of-the-art device for space applications and is highly promising for terrestrial concentrator applications. Yet the combination of these three semiconductor materials does not consist of the optimal band gaps necessary for maximum efficiency. By reducing the band gap of the 2nd junction in a two- or three-junction cell or inserting a 1 eV junction between the GaAs and Ge junctions [1], the overall efficiency of the device can be significantly increased. In order to maintain high crystalline quality, we are attempting to band-gap engineer a new semiconductor material that would have a band gap in the range of 1.0-1.35 eV that can be grown lattice matched to GaAs or Ge. Although GaInNAs lattice matched to GaAs has been grown with band gaps ranging from 0.95 to 1.4 eV [2], no GaInNAs material grown to date has been demonstrated to provide sufficiently long diffusion lengths for high-quality solar cell devices [3].

We propose $B_xGa_{1-x-y}In_yAs$ as another material with the potential to be grown lattice matched to GaAs with band gaps below 1.4 eV [4]. The contraction of the crystal lattice by the addition of boron can be used to offset the expansion due to indium. Assuming Vegard's law and a BAs lattice parameter of 4.777Å [5], $B_xGa_{1-x-y}In_yAs$ should be lattice matched to GaAs when y = 0.46 x.

2. BGaAs

We have grown a series of $B_xGa_{1-x}As$ layers with varying boron concentrations by atmospheric-pressure metal-organic chemical vapor deposition (MOCVD) using diborane as a boron source [4]. These layers have specular morphology and a distinct epilayer peak in the double-crystal X-ray diffraction (DCXRD). Compositional analysis by DCXRD and secondary-ion mass spectrometry (SIMS) reveal boron compositions up to $1.4x10^{21}$ cm^{-3} (x = 3%-5%), the highest reported to date. Photoluminescence (PL) and absorption measurements indicate that the band gap increases by 4-8 meV/%B with increasing boron concentration in this concentration range. Figure 1 shows how the band gap of $B_xGa_{1-x}As$ varies with lattice constant. We have estimated an optical bowing parameter of 1.6-2.3 eV from these data. This estimate of the bowing parameter is much closer to other typical III-V alloy systems than the large bowing parameters observed in GaNAs alloys [6]. The lack of large bowing in the BGaAs alloys may allow for higher electrical quality material to be produced than is possible for GaNAs alloys.

3. BGaInAs

Figure 1 also shows an estimated ternary line for $B_xIn_{1-x}As$ alloys based on a similar bowing parameter to the $B_xGa_{1-x}As$ system. This assumption predicts that $B_xGa_{1-x-y}In_yAs$ alloys could potentially be lattice matched to

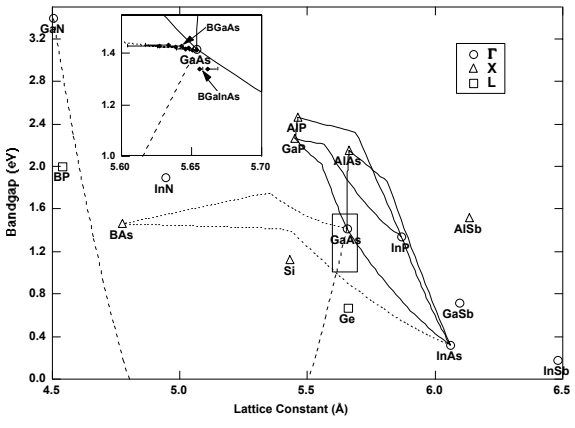

FIG. 1. Band gap vs. lattice constant of III-V semiconductors including boron and nitride alloys. The points in the inset show data for actual BGaAs and BGaInAs alloys grown to date.

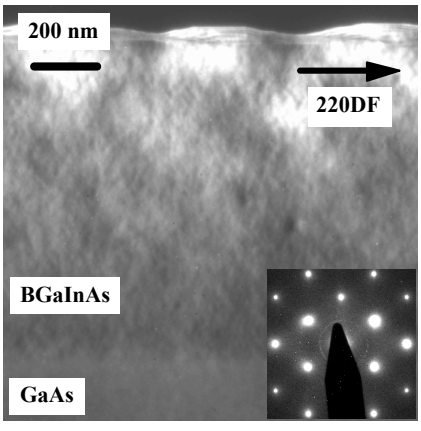

FIG. 2. <220> dark-field TEM image of $B_xGa_{1-x-y}In_yAs$ sample also characterized in Figures 2, and 4. Inset is <110> pole electron diffraction pattern from layer showing only spots expected for zinc-blende.

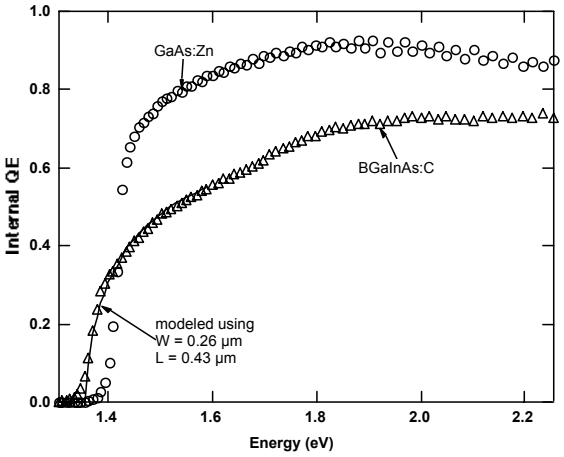

FIG. 3. Internal quantum efficiency (QE) spectra of BGaInAs and GaAs cells.

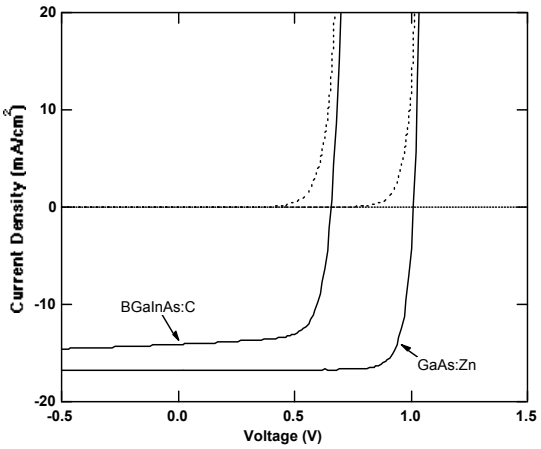

FIG. 4. IV curves of BGaInAs and Ga As cells under AM1.5D, one–sun conditions (solid lines) and dark (dashed lines).

GaAs with band gaps ranging from 0.9 to 1.42 eV depending on the extent of boron that can be incorporated onto group III sites within a zinc-blende structure. We have demonstrated a $B_{0.02}Ga_{0.92}In_{0.06}As$ layer nearly lattice matched to GaAs with a 1.34 eV band gap [4]. The composition was determined by SIMS, DCXRD, and Auger electron spectroscopy (AES). The transmission electron microscopy (TEM) image in figure 2 demonstrates that the layer is dislocation-free and zinc-blende in structure. Strong room-temperature PL emission indicates that this is a direct-gap material.

4. BGaInAs Solar Cells

Using BGaInAs with a band gap of about 1.34 eV (assuming sufficient electrical quality) could increase the efficiency of a two- or three-junction device by almost 2% absolute if it were used as the second junction. Towards such an end, we have fabricated and characterized the first BGaInAs solar cell. The single-junction n-on-p device consists of an 0.1-μm-thick Se-doped GaAs emitter, a 1.5-μm-thick C-doped $B_{0.03}Ga_{0.91}In_{0.06}As$ base, and GaInP window and back-surface-field layers.

Figure 3 shows the quantum efficiency (QE) of this device in comparison with a nearly identical structure that contains a Zn-doped GaAs base. The QE demonstrates that the BGaInAs material has a lower band gap (1.36 eV) than GaAs. The internal QE of this first BGaInAs device with a base carrier concentration of 1.5×10^{16} cm^{-3} exceeds 70% and is comparable to the best GaInNAs cells grown to date. Modeling of the QE indicates that the material has an electron diffusion length greater than 0.4 μm.

Figure 4 shows a comparison of the IV curves under AM1.5D conditions. The low Voc and FF of 0.66V and 73%, respectively, of the BGaInAs cell require considerable improvement before this cell can be used to improve on the GaAs cell in a multijunction device, but represent a significant first step. A better understanding of boron incorporation, doping of the material, and important defects should be helpful in improving this cell.

5. Summary

We have proposed the use of BGaInAs alloys for high-efficiency III-V multijunction solar cells, estimated the bowing parameter of BGaAs, demonstrated the first BGaInAs material lattice matched to GaAs with band gaps as low as 1.34 eV, and fabricated the first BGaInAs solar cell.

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