THE ROLE OF THE AlGaAs WINDOW LAYER IN GaAs HETEROFACE SOLAR CELLS

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ABSTRACT

The AlGaAs window layer plays a dominant role in the performance of GaAs solar cells. This paper discusses the various effects of the layer on cell performance, and shows how the window layer properties have been combined effectively for either liquid phase or vapor phase epitaxial layer growth, to provide high efficiency cells for space or for use at high concentrations.

BACKGROUND

In 1972, Hovel and Woodall (1) significantly increased the efficiency of homojunction GaAs solar cells by adding a heteroface (window) layer of AlGaAs. In subsequent papers (2-4), they analyzed the role of the AlGaAs layer, and also established an optimum blend of properties needed to achieve highest efficiencies. Their understanding was thorough, even when considering developments in cell technology in the past twelve years.

The purpose of this paper is to re-emphasize the dominant effect of AlGaAs layers in current heteroface GaAs solar cells, including additional experience from use of vapor phase epitaxial deposition, and with greater emphasis on providing cells ready for use on satellite arrays.

The AlGaAs layer properties affect several aspects of cell design and performance, and below we discuss the best blend of layer properties to optimize cell performance.

INFLUENCE OF AlGaAs LAYER ON CELL PERFORMANCE

AlGaAs is the best example of an effective heteroface window. We will discuss its effect on the light entering the cell, on photon absorption, and on carrier collection, proceeding to its interaction with the formation of front surface grid contacts, and with cell stability.

Reflectance

AlGaAs has a fairly high refractive index (slightly lower than GaAs), with correspondingly high reflectance. In designing for lowest reflectance for AlGaAs on GaAs solar cells, it is necessary to include the optical properties of both materials.

The procedure for designing an effective AR coating is similar to that used for most cells, namely to measure the spectral response of the cell for the solar spectrum of interest, and to choose suitable thin dielectric coatings to give lowest overall reflectance when illuminated. The refractive indices of AlGaAs and GaAs are combined with the optical characteristics of the dielectric materials in a computer program to determine the optimum layer thicknesses. The AlGaAs layer becomes one of the AR coating layers, and when the AlGaAs is thinner than 1um, its thickness is a critical parameter.

When the AlGaAs layer is very thin (~0.1um) it forms visible interference films on the GaAs. Close control of the deposited AlGaAs layer thickness is needed to ensure uniformly effective AR coatings, and the film color provides qualitative evidence of deposition consistency. Also, measurement of AlGaAs layer refractive index, thickness and reflectance can be used quantitatively for process control.

In practice, coatings with satisfactorily low reflectance have been achieved by both single-layer (quarter wave) coatings, and by use of multiple dielectric layers.

Absorption

The absorption properties of AlGaAs depend on the Al-content in the ternary alloy. In the formulation $Al_xGa_{1-x}As$, when x is 0.2, 0.4, 0.6, 0.8, and 1.0, the respective bandgap values are 1.7, 1.95, 2.05, 2.1 and 2.15 eV. In addition, for $x \leq 0.45$, the bandgap is direct, and is indirect for $x > 0.45$. Thus, for lower x-values, the cut-off wavelength for intrinsic carrier excitation moves to longer wavelengths, and also the absorption coefficients are higher; both of these trends reduce the sunlight entering the GaAs cell.

This leads to choice of window layers with high x-values, typically $x > 0.85$, and also as shown below, with thinner AlGaAs layers to minimize absorption. The upper bound for x is determined by stability considerations (see below).

The layer growth conditions used to form high efficiency cells are controlled to minimize absorption by scattering center caused by lower quality growth.

We have used modeling to explore the effects of

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the AlGaAs layers. The model uses published absorption coefficients and GaAs cell parameters typical of those used on current high efficiency cells. To conform to the most-used configuration, we have modeled P-AlGaAs/P-GaAs/N-GaAs cells in this paper; by suitable parameter adjustment, most of the conclusions also apply to the N/P sequence. Table 1 lists the model parameters used in the study.

Table 2 shows the external quantum efficiency (EQE) for cells with different thickness of AlGaAs (with $x=0.87$). Thicker layers have most effect at shorter wavelengths.

The computed effect of the window layer thickness on the I-V parameters under AMO illumination is shown in Table 3. This table also includes the separate Jsc contributions from the emitter region, the bulk region, the space-charge layer, along witha small current arising from the AlGaAs layer. The emitter contribution is most affected by the varying thickness.

If lower x-values are used, to obtain equivalent Jsc values, the layer thickness must be reduced below the values computed for $x=0.87$. If the AlGaAs layer is below 0.1um, modeling shows less than 1% power loss for x-values as low as 0.75.

Carrier Collection

Because GaAs is a direct bandgap semiconductor, incoming photons, especially at shorter wavelengths, are absorbed very close to the surface. This near-surface absorption leads to high chance of carrier recombination at the front GaAs surface. This recombination was reduced somewhat by combining very shallow PN junctions with passivation by thin insulating layers.

Significant and reproducible decrease of this surface recombination was achieved by use of the AlGaAs layers. AlGaAs has a very close lattice match to GaAs (only ~ 0.2% misfit over the x-range from 0 to 1) and also a suitably large bandgap difference (~2eV compared to 1.43eV) to provide an electric field which retards minority carriers approaching the surface. Calculations show that the energy step in the conduction band prevents electrons from entering the P-AlGaAs layer; the very small step in the valence band does not prevent the AlGaAs layer from serving as a transparent Ohmic contact.

Table 4 shows model calculations of EQE as a function of surface recombination velocity (s) at the AlGaAs/GaAs interface. When s falls below 10^4cm sec^{-1} very little loss occurs for carriers absorbed near the GaAs surface. The greatest effect was not short wavelengths. Although accurate EQE measurements are difficult, especially for high s-values, where light-biasing must be used, the improvements in AlGaAs layers can be monitored by measuring the increase in Jsc and in the EQE values at short wavelengths. By interpolation in theoretical tables such as Table 4, we can conclude that s-values $\leq 10^4$cm sec^{-1} are obtained for good quality growth conditions.

Combining the numbers in Table 4 with the AMO spectrum, we can calculate I-V values for cells with varying s, and the results are shown in Table 5. Note that as s increases, the major loss is in Jsc (mostly from the emitter), with lower losses in Voc.

Contacting

In addition to its passivating effect, the AlGaAs layer has been used to reduce the sheet resistance of the surface layers of the cell, leading to low series resistance, and to reduced doping and increased carrier collection from the P-GaAs layer.

Because the AlGaAs layer is deposited over the front surface of the cell, it must be considered when designing a suitable grid contact structure. In practice, three different contact designs have been used for GaAs heteroface cells:

(a) Direct contact to the AlGaAs layer (5). This method is suited to relatively thick, highly doped AlGaAs layers. It may also involve additional doping of the layer, and the deposition of thin (often sputtered) layers of refractory metals to increase contact adhesion.

(b) The use of masking and etching to remove the AlGaAs in the required grid pattern, followed by deposition of contact metals directly on the GaAs emitter (6). This approach adds a controlled etch step, but does not require high doping concentration in the AlGaAs layer. On the other hand, the GaAs emitter layer must have suitably low sheet resistance, obtained by combination of emitter doping concentration and emitter depth. Using current grid design and technology, it is possible to form low resistance grid contacts with low shaded area, for emitter doping levels around 10^{18}cm^{-3} and emitters as shallow as 0.2um.

(c) Growth of a thin additional GaAs layer over the AlGaAs, usually in the same deposition run (7). The grid metals are deposited onto this GaAs cap layer, and the uncontacted cap layer is preferentially removed (by plasma or wet etching). This method may not require very high doping levels in the AlGaAs.

Each of these approaches has advantages and disadvantages. All have yielded high efficiency cells with good contact stability. Selection of the most suitable approach depends on the overall details of the cell design, fabrication and application, and on available technology.

Stability

One problem introduced by the use of AlGaAs layers, especially for high x-values, is susceptibility to attack by moisture, such as in the environmental exposure tests required for space-cells.

The discussion above suggested that higher x-values ($x > 0.85$) can reduce absorption in AlGaAs. To minimize moisture attack, it has been customary to use the AR coating layers to prevent moisture from reaching the AlGaAs.

At one time, AR coatings were applied immediately following AlGaAs layer growth, before additional process steps were applied; this involved additional patterning to remove the AR coating where the front contact was required.

Lately, processing of the AlGaAs layers has improved so that it is customary to process the AlGaAs/GaAs slices unprotected until an AR coating is applied near the end of the process sequence.

With close control of the x-value, and AR coating techniques, present heteroface GaAs cells can withstand typical space-cell humidity testing. However, it is still preferable to reduce exposure of the AlGaAs to corrosive solutions, and this limits the choice of photolithography or plating solutions.

Work is proceeding to determine if a practical trade-off with lower corrosion possibility, can be found by use of thinner layers with lower x-value. This possibility is well suited to the vapor phase methods of AlGaAs deposition.

The stability factors of the AlGaAs layer must also be considered when choosing the best contacting system. For methods (a) and (c) above, the contact is placed on the AlGaAs layer; for method (b) the etched slots in the AlGaAs layer can leave exposed edges of the layer open to moisture penetration.

Comments

Based on the modeling, and confirmed by experience cell performance can be optimized by the following AlGaAs properties:

Al Composition:	x 0.85 to 0.9
Bandgap:	2.1 to 2.15eV
Layer Thickness:	~0.1um(VPE),≤0.3um (LPE)
Doping Concentration:	10^{18} cm^{-3}
Stability:	x < 0.9

Thin passivating window layers, with fairly high x-values have led to high Jsc, values showing that low reflectance AR coatings can be applied and that layer absorption is low. Good interface quality, measured by the effective s-value, has resulted from the close lattice match and the ability to grow AlGaAs layers with good purity and crystalline perfection. Estimates show that effective passivation can be obtained for AlGaAs layers as thin as 0.01um, an important factor in possible use of lower x-values.

In addition to good electrical performance, tests have shown that cells made with these layer properties have successfully withstood typical humidity and space-cell contact-pull tests. Also, these cells have been incorporated into arrays, involving techniques for applying cover glasses and for bonding to interconnects.

EFFECT OF LAYER GROWTH METHOD

For many years, the AlGaAs and GaAs layers have been grown mostly by liquid phase epitaxy (LPE). In the most used LPE sequence, the AlGaAs deposition also involves in-diffusion of the doping atoms in the AlGaAs to form the PN junction in the GaAs. Liquid epitaxy ensures good crystalline quality, and also reproducibility of the x-value, because the melt composition is fairly constant. In most cases, the thicknesses of the AlGaAs layer and of the GaAs emitter layer are coupled, and it is difficult to grow very thin AlGaAs layers from liquid solutions.

Vapor phase epitaxy (VPE) allows independent deposition of the GaAs emitter and the AlGaAs layer, and with VPE (also called CVD) methods, suitable window layers as thin as 0.03um have been formed. Figure 1 shows a plot of x-value as a function of depth into a VPE-grown AlGaAs layer less than 0.1um thick; the control and uniformity are satisfactory.

With VPE, the x-value is determined by control of the Al vapor fraction in the Ga and As vapor streams. The quality of the AlGaAs/GaAs interface is determined by the cleanliness of the gases, the environment in the deposition chamber and by careful changes in the gas composition. VPE methods can be controlled to give high quality, thin AlGaAs layers with good uniformity over large areas.

In some cases, growth under non-ideal conditions showed the sensitivity of the surface passivation to the growth conditions, and some illustrative results are presented in the next section.

ANALYSIS OF AlGaAs LAYERS

Overall, the effectiveness of the AlGaAs layer can be assessed by I-V or EQE measurements on finished cells. Individual properties can also be measured to check if the layer is as-planned. Thickness can be measured interferometrically or by a sensitive profilometer. As mentioned, for thin layers, visual checking, backed-up by optical measurements can be used. The x-value is difficult to measure, but use of X-ray rocking curves and Auger electron spectroscopy (which gives profiles such as that in Figure 1), are effective.

The s-value is best checked by using EQE measurements, and locating the position of the values X in the modeled sequence such as in Table 4.

Sequential Cell Testing

It is instructive to sequentially process cells to separate the optical and electrical effects of the AlGaAs. Table 6(a) shows the results of Jsc and Voc values for four conditions. In A, the deposited slice (AlGaAs/GaAs) is processed as a cell; no AR coatings are added, the AlGaAs layer acts as a partial AR coating.

In B, an AR coating is added to the cell in A. This shows that for A, passivation was achieved, but Jsc was low because of high reflectance. In C, the AR coating and the AlGaAs are carefully stripped from the cell, leaving the contacts on the GaAs homojunction cell. Now the large loss in Jsc is caused by loss of passivation, and to a lesser extent by loss of AR coatings. Table 6(b) shows the various percentage losses.

In D, a good AR coating is applied to the GaAs surface; Jsc is increased, but is still well below the value obtained in B, demonstrating that the main function of the AlGaAs layer is to provide surface passivation.

Associated EQE measurements support these conclusions.

Analysis of Reduced Quality AlGaAs Layers

During some CVD runs, including the evolution of suitable large scale deposition equipment, some AlGaAs layer problems were found.

When the gas flow conditions were perturbed by air-leaks, contamination of the Al-source or by back pressure of contaminants, the AlGaAs properties changed. In some cases, visual signs, such as color changes or poor surface morphology, were present. In other cases, the x-value increased, resulting in AlGaAs attack by processing environments.

For these runs, and for a few more subtle effects, the marked reduction in Jsc and short wavelength EQE indicated that the AlGaAs/GaAs interface was the main problem. As Jsc decreased, there was systematic reduction of EQE at short wavelengths. As mentioned above, for higher Jsc values, the EQE values corresponded to s-values $\leq 10^4$ cm sec^{-1}.

Table 7 presents Jsc values for cells with a wide range of AlGaAs conditions. The table also contains some measurements for cells measured before AR coating was deposited on the AlGaAs, or after the AlGaAs layer (and AR coating) had been removed.

It can be seen that despite the wide variation in Jsc on finished cells, the bare GaAs Jsc values were similar. This indicates that the GaAs cell properties were fairly constant, and that indeed the major cause of reduced cell output was insufficent passivation at the AlGaAs/GaAs interface.

In a separate set of tests, the oxygen concentration near the interface was measured and found to affect the cell output, higher oxygen concentrations leading to reduced passivation. These samples are also included in Table 7.

Measurement of dark diode characteristics showed that the Voc decreases corresponded to a shift of the diode curve to lower voltages.

DISCUSSION

With good lattice match, greater bandgap and careful deposition conditions, AlGaAs layers on GaAs cells give significant improvement by providing effective surface passivation.

The passivation conditions are critical, but for a cell fabrication line with good control of processes this leads to some sensitive monitoring methods, principally measurement of Jsc or EQE for carefully controlled test conditions. The sensitivity of these monitoring methods aids in overall process control.

Despite interactions of the AlGaAs with most aspects of cell formation it is possible to find acceptable trade-offs in layer properties and deposition conditions. Performance under irradiation (even low energy particles) does not appear to be influenced by the AlGaAs properties.

The passivation process involves reduction of recombination centers at the interface, with greatest effect on Jsc. Intriguingly, there is smaller effect on Voc. Contact methods (a) and (c) should lead to slightly higher Voc values, because the metal-to-GaAs contact has an intermediate passivation layer of AlGaAs. In practice this increase is not observed, perhaps because the GaAs PN junction leakage currents are not dominated by surface generation.

Already there is evidence that for cells with thin bases, some increase in Jsc and Voc could be obtained by use of a similar passivating layer at the back of the cell. In this case, there is wider scope in choice of x-value, since reflection and absorption are not important.

In conclusion, the concept of surface passivation by a bandgap transition has been demonstrated and incorporated into current GaAs cells. The beneficial effects of these layers have a dominant influence on the overall performance of the cells.

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TABLE 1

PARAMETERS USED IN MODEL

PARAMETER	WINDOW	EMITTER	BASE
DIFFUSION COEFFICIENT ($cm^2\ sec^{-1}$)	1.79	72.52	6.61
MINORITY CARRIER DIFFUSION LENGTH (um)	0.7	5.0	2.0
THICKNESS (um)	0.05 to 10*	0.5	9.0
DOPANT CONCENTRATION (cm^{-3})	10^{18}	10^{18}	10^{17}
SURFACE RECOMBINATION VELOCITY ($cm\ sec^{-1}$)	10^7	0 to 10^7	$2x10^4$
ALUMINUM CONTENT	0.87	-	-

NOTES:
- USED PUBLISHED ABSORPTION COEFFICIENTS FOR GaAs AND AlGaAs.
- INCLUDED FREE CARRIER ABSORPTION.
- INCORPORATED MEASURED REFLECTANCE WITH AR COATING.
- ASSUMED GRID SHADING 5%.

TABLE 2

EXTERNAL QUANTUM EFFICIENCY VERSUS AlGaAs LAYER* THICKNESS

LAYER THICKNESS (um)	WAVELENGTH (um)					
	0.40	0.50	0.60	0.70	0.80	0.86
0.05	.866	.969	.900	.925	.845	.627
0.1	.787	.966	.899	.925	.845	.626
0.2	.656	.959	.899	.924	.845	.626
0.5	.398	.940	.897	.923	.843	.625
1.0	.188	.904	.895	.920	.841	.623
5.0	.001	.565	.873	.898	.821	.608
10.0	0	.299	.848	.872	.796	.590

* x = 0.87

TABLE 3

I-V VALUES (AMO) VERSUS AlGaAs LAYER* THICKNESS

LAYER THICKNESS (um)	Voc (mV)	Jsc ($mAcm^{-2}$)	FF	EFF (%)	J_e ($mAcm^{-2}$)	J_b ($mAcm^{-2}$)	J_{SCR} ($mAcm^{-2}$)	J_w ($mAcm^{-2}$)
0.05	1010	31.53	.838	19.7	24.58	4.69	1.72	0.54
0.1	1009	31.05	.838	19.4	23.76	4.69	1.72	0.88
0.2	1009	30.28	.837	18.9	22.60	4.68	1.72	1.28
0.5	1007	28.80	.837	17.9	20.82	4.67	1.71	1.59
1.0	1005	27.34	.836	17.0	19.60	4.66	1.71	1.38
5.0	1000	23.43	.834	14.4	17.01	4.54	1.65	0.23
10.0	997	21.88	.833	13.4	15.78	4.41	1.59	0.10

* x = 0.87

TABLE 4

EXTERNAL QUANTUM EFFICIENCY VERSUS SURFACE RECOMBINATION VELOCITY

S-Value ($cm\ sec^{-1}$)	WAVELENGTH (um)					
	0.40	0.50	0.60	0.70	0.80	0.86
0	.792	.970	.903	.927	.847	.627
10^3	.792	.970	.903	.927	.847	.627
10^4	.787	.966	.899	.925	.845	.626
10^5	.744	.925	.868	.905	.831	.619
10^6	.483	.677	.681	.785	.749	.576
10^7	.121	.335	.420	.619	.634	.517

TABLE 5

I-V VALUES (AMO) VERSUS INTERFACE S-VALUES

S-Value ($cm\ sec^{-1}$)	Voc (mV)	Jsc ($mAcm^{-2}$)	FF	EFF (%)	J_e ($mAcm^{-2}$)	J_b ($mAcm^{-2}$)	J_{SCR} ($mAcm^{-2}$)	J_w ($mAcm^{-2}$)
0	1010	31.20	.838	19.5	23.87	4.69	1.72	0.89
10^3	1010	31.15	.838	19.5	23.86	4.69	1.72	0.89
10^4	1009	31.05	.838	19.4	23.76	4.69	1.72	0.88
10^5	1005	30.06	.839	18.7	22.82	4.69	1.72	0.83
10^6	984	24.10	.843	14.8	17.16	4.69	1.72	0.53
10^7	960	15.84	.843	9.5	9.31	4.69	1.72	0.12

TABLE 6(a)

Jsc AND Voc FOR FOUR CONDITIONS

CELL CONDITION		Jsc (mA/cm^{-2})	Voc (mV)
A	WITH AlGaAs, NO AR COATING	22-23	990-1000
B	WITH AlGaAs + AR COATING	29-30	1000-1010
C	NO AlGaAs, NO AR COATING	10-11	935
D	NO AlGaAs + AR COATING	13	940

TABLE 6(b)

PERCENTAGE CHANGES FOR DIFFERENT CONDITIONS

CASE	TESTING	Jsc	Voc
B-A	AR COATING ON AlGaAs	+31	+1
A-C	AlGaAs ELECTRICAL & OPTICAL	+114	+6
B-D	AlGaAs ELECTRICAL (APPROX.)	+127	+7
D-C	AR COATING ON GaAs	+24	+0.5

TABLE 7

Jsc VALUES FOR WIDE RANGE OF AlGaAs QUALITY

SAMPLE NO.	OXYGEN CONC. NEAR INTERFACE (cm^{-3})	CELL Jsc (AMO, mAcm^{-2})		
		WITH AR ON AlGaAs	NO AR ON AlGaAs	NO AR OR AlGaAs
482-1	-	30	22.5	11
481	-	29	22.2	10.2
482-2	-	28	21.2	10
434	-	24.2	-	10
485-1	-	20	15	9.5
499	-	18.7	15	11.2
387	2x10^{19}	28	-	-
482-3	5x10^{19}	23	-	-
495	8x10^{19}	18	-	-
485-2	10^{20}	17	-	-

FIGURE 1

Al PROFILE IN AlGaAs LAYER