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DEVELOPMENT OF A LIGHTWEIGHT, LIGHT-TRAPPED, THIN GaAs SOLAR CELL FOR SPACECRAFT APPLICATIONS[1]

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ABSTRACT

This paper describes ultra-lightweight, high performance, thin, light trapping GaAs solar cells for advanced space power systems. The device designs can achieve 24.5% efficiency at AMO and 1X conditions, corresponding to a power density of 330 W/m2. A significant breakthrough lies in the potential for a specific power of 2906 W/kg because the entire device is less than 1.5 μm thick. This represents a 440% improvement over conventional 4-mil silicon solar cells. In addition to being lightweight, this thin device design can result in increased radiation tolerance. The attachment of the cover glass support to the front surface has been demonstrated by both silicone and electrostatic bonding techniques. Device parameters of 1.002 volts open-circuit voltage, 80% fill factor, and a short-circuit current of 24.3 mA/cm^2 have been obtained. This demonstrates a conversion efficiency of 14.4% resulting in a specific power of 2240 W/kg. Additionally, this new technology offers an alternative approach for enabling multi-bandgap solar cells and high output space solar power devices. The thin device structure can be applied to any III-V based solar cell application, yielding both an increase in specific power and radiation tolerance.

PERFORMANCE CAPABILITY

III-V materials such as GaAs make excellent candidates for thin devices because they are direct bandgap materials. The high absorption coefficient of such materials for light of an energy greater than the bandgap makes it possible to fabricate cells in which the thickness of the active region is considerably less than in indirect materials such as silicon. Light of photon energy greater than the bandgap is absorbed within the first few microns of entering a direct bandgap semiconductor, so an ultrathin device design is both feasible and advantageous. Conventional high performance GaAs solar cells are usually comprised of epitaxial layers of GaAs and $Al_xGa_{1-x}As$ formed on a GaAs substrate. When GaAs devices are fabricated on a thick GaAs substrate, the substrate acts only as a support and does not contribute to the overall performance of the device.

The advantages gained from fabricating thin solar cells include a high power-to-weight ratio (specific power) which is important for space applications. In addition, with a sufficiently thin device structure (base thickness on the order of a diffusion length) the free carrier absorption is minimized and a light trapped device becomes feasible. Light trapping increases the effective optical path length with the use of a reflector and/or a textured surface. Incorporating light trapping into the device increases the performance by increasing the short circuit current, while the reduced GaAs base thickness lowers the reverse saturation current. Both of these effects enhance the open circuit voltage [ref. 1].

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Because the device is thin, back surface recombination becomes an important issue. Recombination of the carriers at the back surface is reduced by adding an $Al_xGa_{1-x}As$ ($x > 0.5$) back surface passivation layer. This layer also reflects carriers back to the p-n junction due to the built-in electric field. Because the GaAs base is thin (< 2 microns), the carriers can reach the junction before they recombine. The front surface is also passivated by an $Al_xGa_{1-x}As$ ($x = 0.85$) layer which has a large indirect bandgap. There is very little absorption in such a layer, allowing light into the underlying cell. Because of the good lattice match to the GaAs, this layer eliminates the surface states and other imperfections on the GaAs p-n junction surface that would ordinarily result in a high recombination velocity and decreased diffusion length.

The use of liquid phase epitaxy (LPE) to fabricate thin devices offers significant advantages over other techniques such as MBE and MOCVD. This technique produces high quality material while maintaining low cost and simplicity. Inherent to the LPE technique is the fact that the dislocation density of the epitaxial films produced is generally lower than the starting substrate. Therefore, the material is superior in terms of diffusion length and lifetime. These benefits are partly attributed to the tendency of impurities to segregate to the liquid (solvent) as opposed to the solid (epitaxial film). The ability to grow multiple layers of controlled electrical conductivity is also useful in the proposed device design. Segregation coefficients are well known so that the proper conductivity type and carrier concentrations can be obtained in the epitaxial films. Phase equilibria for the Al-Ga-As system have been extensively studied, resulting in the ability to precisely control composition.

The high efficiency and light weight of the cover glass supported GaAs solar cell can have a significant impact on space solar array technology. **Fig. 1** shows the specific power (power to weight ratio) and power density of several candidate solar cells. AstroPower's GaAs solar cell design offers a 440% increase in specific power over that of a 14.5% efficient silicon solar cell. The specific power is calculated assuming a 3-mil cover glass and a 1-mil silicone adhesive on the front surface of the solar cell.

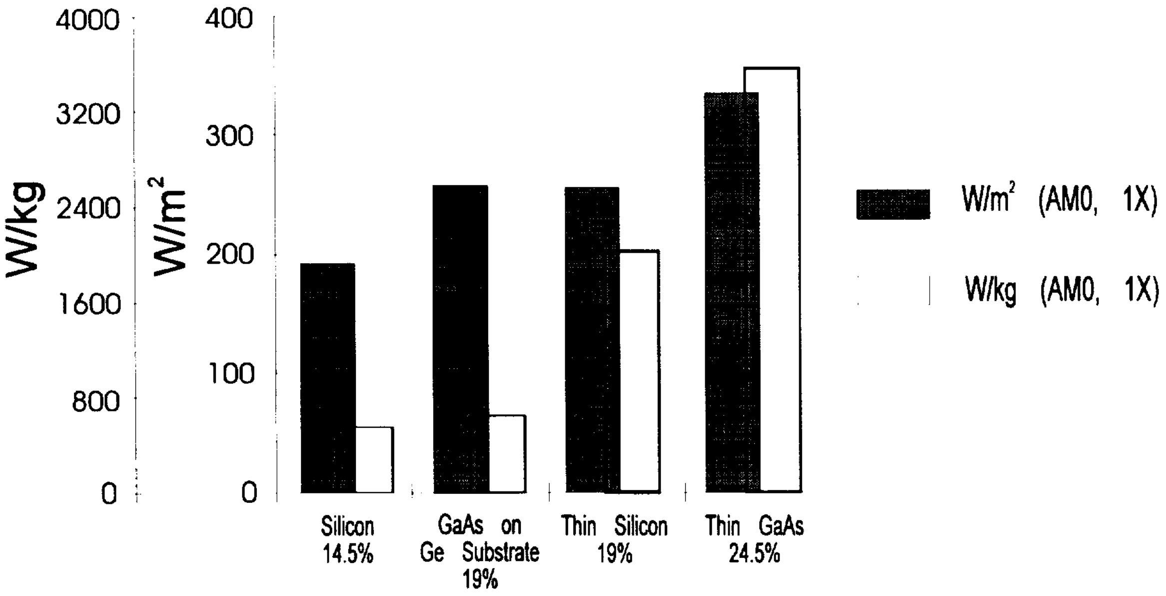

Fig. 1. *Comparison of specific power and power density of candidate space solar cells.*

AstroPower's approach combines the technology for a thin, light trapped GaAs solar cell with the electrostatic bonding of GaAs to glass and a coplanar back contact technology. Rather than working with p-type front contacts that interfere with the bonding of the glass to the solar cell, contact to the p-type layers is made from the back of the device. This all back contact design also eliminates grid shading which further enhances the performance of the GaAs solar cell. Since both contact grids are located on the back surface, cell degradation from grid flattening and metals migration, associated with electrostatic bonding of raised contact devices, is eliminated. Also eliminated are the bonding difficulties and the low quality bond yields that typify electrostatically bonded, raised contact solar cells.

In order to obtain the highest efficiencies from thin (1.65 micron) GaAs solar cells it is necessary to incorporate a high degree of light trapping in the cells. To generate the same level of current from a thin device as is possible from a conventionally thick GaAs cell, the optical path length of the light must be extended beyond the physical thickness of the device. The light must travel obliquely and be internally reflected many times, allowing more of the light to be absorbed at a given thickness. Chemical micromachining or random texturing can be achieved on the front or back surfaces to redirect the light at an oblique angle. Scattered light which is obliquely incident on the front surface at angles less than the critical angle (16° for GaAs), will be totally internally reflected. Such optical confinement leads to effective optical path lengths 2 to 10 times greater than the thickness of the active layers. The factor by which the optical path is increased due to light trapping is called the z-ratio. For example, when the z-ratio is equal to five, the optical absorption for confined light is equivalent to that of a solar cell with a thickness five times greater.

The optimum reflector should have the maximum reflection over the appropriate wavelength range. This aspect of light trapping is important since many reflector options (e.g. quarter-wavelength dielectric films or distributed Bragg reflectors) are optimized for maximum reflectance at one wavelength and exhibit high reflectance over only a narrow bandwidth. A 1-micron thick base requires a back reflector which is effective over the wavelength range of 730 to 880 nm [ref. 1].

Using the LPE technique to grow a thin structure, bonding to a cover glass, and ultimately removing the GaAs substrate allows for access to the back of the active region of the device. Thus an optical reflector (such as Au or Ag) can be applied directly to the back surface. This offers significant advantages over other techniques such as the use of Bragg reflectors grown by MOCVD on GaAs substrates. The spectral width of Bragg reflectors is restricted, and to achieve a z-ratio higher than 2, multiple Bragg reflectors must be used. As pointed out by Tobin et al., [ref. 2], "the added complexity of multiple Bragg reflectors" does not make this a practical approach. The use of the appropriate metal reflector on the back surface provides reflection over a broad spectral range. This technology also removes the excess weight of the substrate thus significantly increasing the specific power.

Modeling the thin GaAs solar cell shows benefits similar to those achieved in light trapped silicon. For silicon devices, reducing the thickness of the device decreases the reverse saturation current, while trapping the light leads to an increase in the short circuit current. In GaAs, however, the current gains are smaller and most of the increased performance is realized from enhanced open circuit voltage. The three most important features which lead to improvements in the efficiency of GaAs thin-film solar cells are: increased optical absorption, improved collection efficiency, and photon recycling [ref. 3]. Photon recycling is when photons generated by radiative recombination are optically confined so they can be re-absorbed to generate minority carriers again. The enhanced optical absorption and improved collection of minority carriers provide a modest increase in the short circuit current (I_{SC}). Because the solar cell volume is reduced by thinning the device, the bulk recombination is reduced which reduces the dark current. The reduced dark current and improved I_{SC} result in an increase in the open circuit voltage. Also contributing to an increase in the open circuit voltage is the fact that higher carrier concentrations can be used to further reduce the dark current since a low minority carrier diffusion length can be tolerated in a thin device. As light trapping increases for a given back surface recombination velocity, the solar cell efficiency increases. When light trapping is considered, the p/n structure is more efficient than an n/p structure since the long base diffusion length in the n/p structure is not as important when the solar cells are very thin.

RADIATION RESISTANCE

Radiation damage is the primary mechanism of degradation of GaAs solar cells deployed in space. This gradual degradation in solar cell performance is due to a reduction in the minority carrier lifetime that results from cumulative damage to the crystal lattice. As high energy particles bombard the cell, the number of recombination centers is increased, resulting in a decrease in the minority carrier lifetimes. The fact that light is absorbed in a shallow depth indicates that GaAs should have a better radiation resistance than silicon. Since the minority carrier transport is over much smaller distances, the diffusion length can be reduced by irradiation to much smaller values before having a significant effect on the carrier collection at the junction [ref. 4] The thin light trapped GaAs solar cell design further enhances the radiation tolerance because damage created several microns into the material by high energy particles has no effect on photo current collection. The recombination region is thinner, thus increasing the resistance to high-energy radiation. The cover glass can be specified to screen out low energy particles corresponding to the chosen orbit, which normally cause damage at the surface [ref. 5].

Optimized emitter thickness and absorber layer doping can also contribute to radiation tolerance. The emitter thickness is kept below 0.5 microns in order to reduce the distance which minority carriers generated near the surface must travel to be collected. Because the entire device is less than 2 microns thick, carriers generated deeper in the material can still reach the junction before recombining. This becomes important when radiation has decreased the minority carrier diffusion length.

In conventional thick GaAs solar cells, the base layer carrier concentration is kept below $3x10^{17}cm^{-3}$ to improve the end-of-life (EOL) efficiency. In our thin device this effect is not as important because of the reduced dependence on diffusion length. Higher carrier concentrations are incorporated in order to reduce the dark current and thus enhance the open circuit voltage, while maintaining a radiation tolerant device.

EXPERIMENTAL RESULTS

A schematic cross-sectional representation of the AstroPower prototype thin GaAs solar cell design is shown in **Fig. 2**.

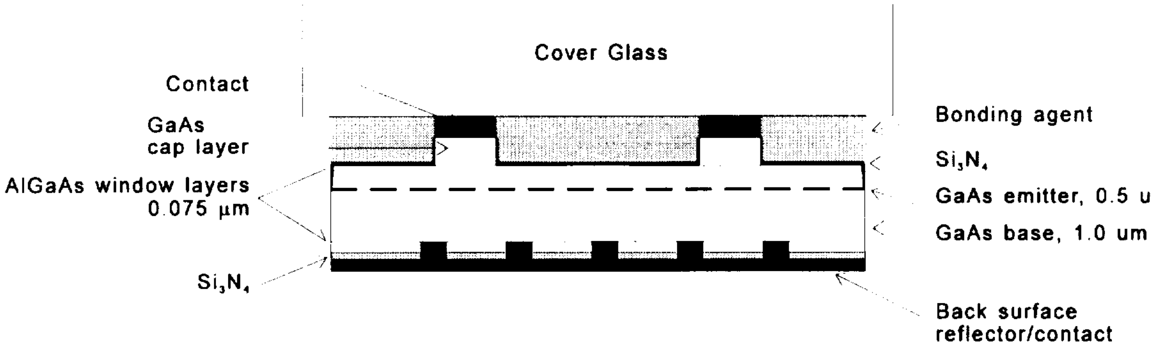

Fig. 2. *Ultra-thin GaAs solar cell with light trapping.*

A key requirement for high performance ultra-thin GaAs solar cells is the incorporation of light trapping into the devices. Light trapping was demonstrated by growing a thin (1.5 micron) GaAs base layer on an AlGaAs passivating layer using liquid phase epitaxy. The sample was then bonded to glass and the substrate was removed.

Comparisons were made between samples with and without a metal reflector, and the effectiveness of the reflector in projecting photons back toward a junction was determined. Silver was used as the reflector in this case. Reflection + transmission (R + T) measurements were performed before and after the substrate removal. The absorption can be obtained from the reflection and transmission data(absorption = 1 - (R+T)). These results are shown in **Fig. 3**.

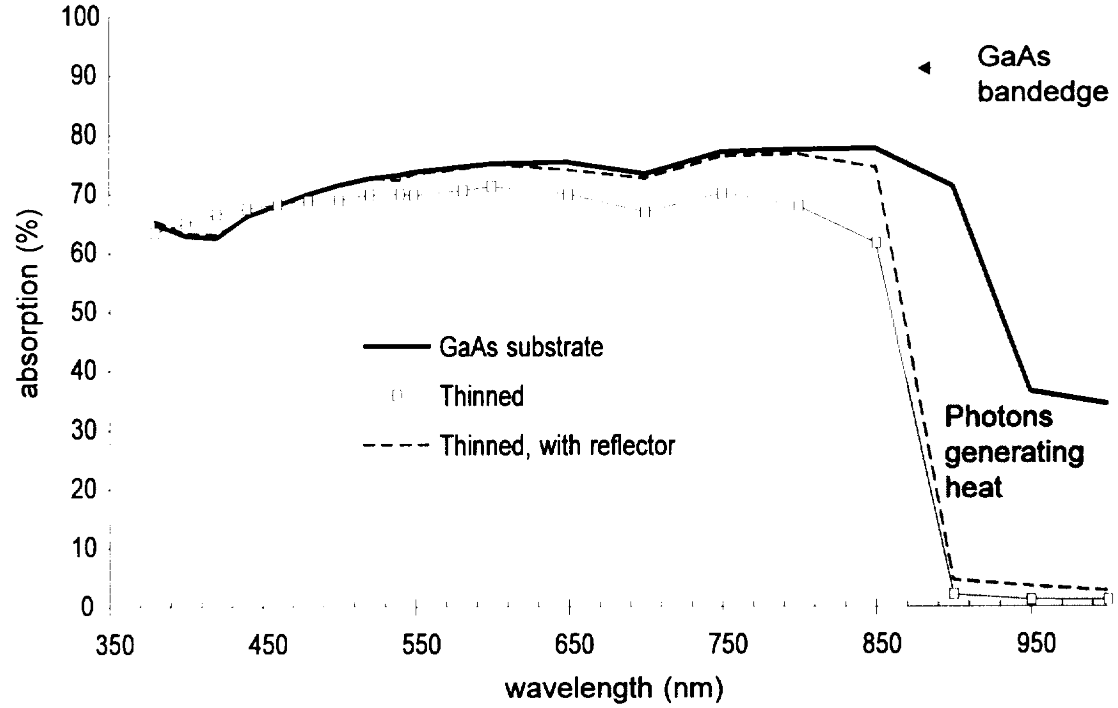

Fig. 3. *Absorption results for: 1.5 μm GaAs LPE layer on a GaAs substrate; 1.5 μm glass bonded GaAs layer, and glass bonded 1.5 μm GaAs layer with a reflector.*

As expected, the amount of light absorbed decreases as the GaAs structure is thinned, particularly over the 550 nm to 850 nm range where there is a higher flux density and the photons are more weakly absorbed. Application of a silver reflector resulted in increased absorption which closely matched the measurements of the thin material on the GaAs substrate. As much as 70% of the light is absorbed over the 550 nm to 850 nm range. By incorporating a silver reflector, we have been able to successfully light trap a 1.5 micron thick structure of GaAs. This will enable high short circuit currents to be obtained on a thin, ultra-lightweight GaAs solar cell.

Note that there is little absorption of sub-bandgap photons in the thinned material both with and without a reflector. This is advantageous for space solar cells because sub-bandgap photons that are absorbed generate heat in the device but do not contribute to the efficiency. As shown in **Fig. 3**, the structure on a GaAs substrate absorbs as much as 70% of the photons at 900 nm while the thinned structure with a reflector absorbs only 4% of the photons at 900 nm. Standard thick GaAs solar cells absorb these lower energy photons in the substrate.

Device layers are grown by liquid phase epitaxy (LPE) [ref. 6]. The front and back surfaces are passivated by an $Al_xGa_{1-x}As$ window layer in order to reduce the surface recombination. The GaAs base layer is approximately 1 micron thick and the emitter layer is formed by diffusing the p-type dopant during the growth of the front passivating (window) layer. The junction depth is easily controlled by adjusting the window layer growth time.

Fig. 4 shows the quantum efficiency of a free-standing 1.65 µm, 1-cm^2 device. The short circuit current, as corrected for grid shading and reflection losses, was 29.13 mA/cm^2.

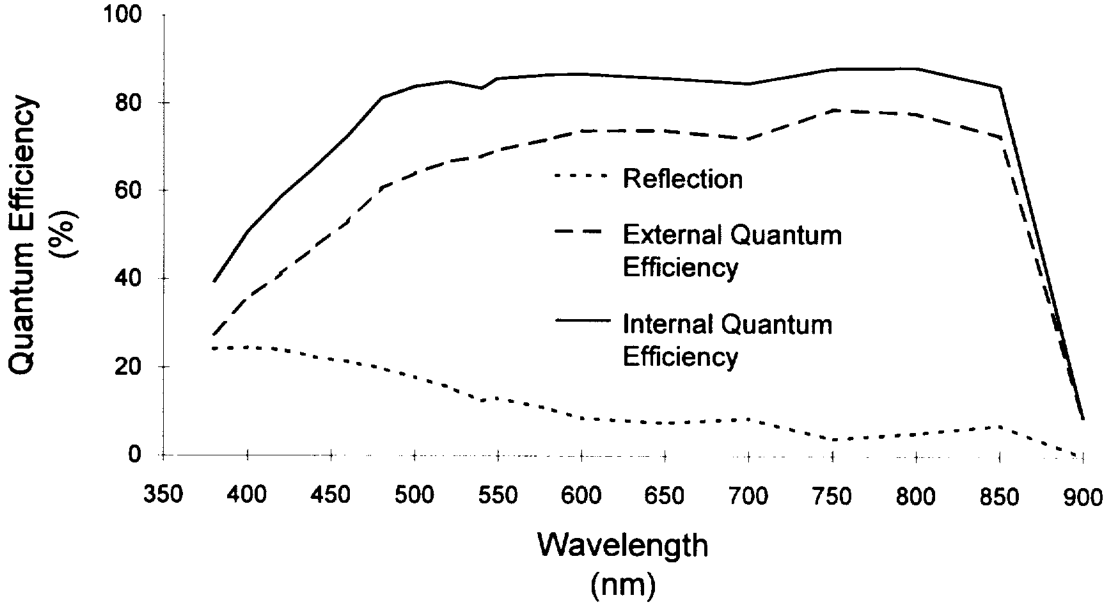

Fig. 4. *Quantum efficiency results for free-standing device F12314B.*

The results of the current-voltage measurement (F12314B) is shown in **Fig. 5**. This thin solar cell demonstrated an efficiency of 14.4%, as measured. From the quantum efficiency curves, it can be seen that the antireflection coating is not properly optimized and results in a lower than optimal current generation from 350 to 600 nm. When corrected for reflection losses, the potential of this material would yield a 17.3% efficiency at AM0.

Cell Data: F12314B	
V_{oc}	1.001 v.
J_{sc}	24.3 mA/cm^2
Fill Factor	80%
Efficiency	14.4%

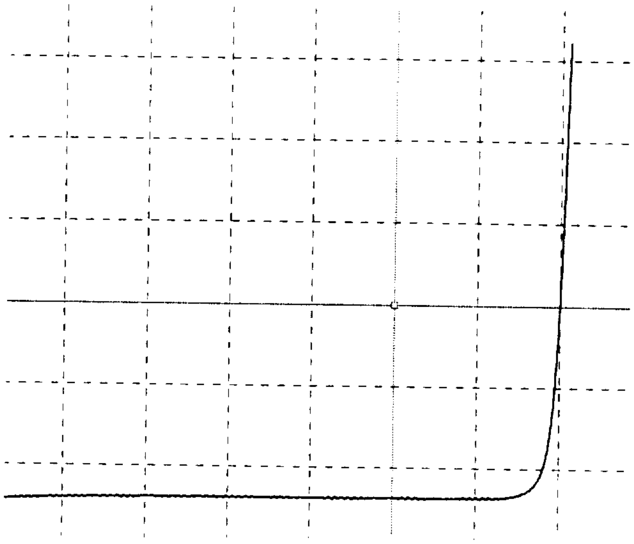

Fig 5. *Current-voltage measurement results for free-standing device F12314B*

The best parameters obtained from conventional GaAs devices fabricated at AstroPower were an open circuit voltage of 1.020 V, a short circuit current of 35.6 mA/cm^2, and a fill factor of 82.7%. This demonstrates the potential for a solar cell efficiency of 22.2%. As can be seen, the measured open-circuit voltages and fill factors are close to the best devices fabricated on GaAs substrates. Optimization of the thickness, doping, and antireflection coatings will yield an increase in the performance of the thin GaAs solar cell

The improved device design which utilizes electrostatic bonding and an all back contact technology is shown in **Fig. 6**. The p-type region is diffused form the back of the device to the emitter after thinning. The temperature required for this diffusion step necessitates a high temperature survivable electrostatic bond. This superior solar cell design solves many fabrication problems and enhances the manufacturability of the high performance GaAs solar cell. Development of this design is currently in progress.

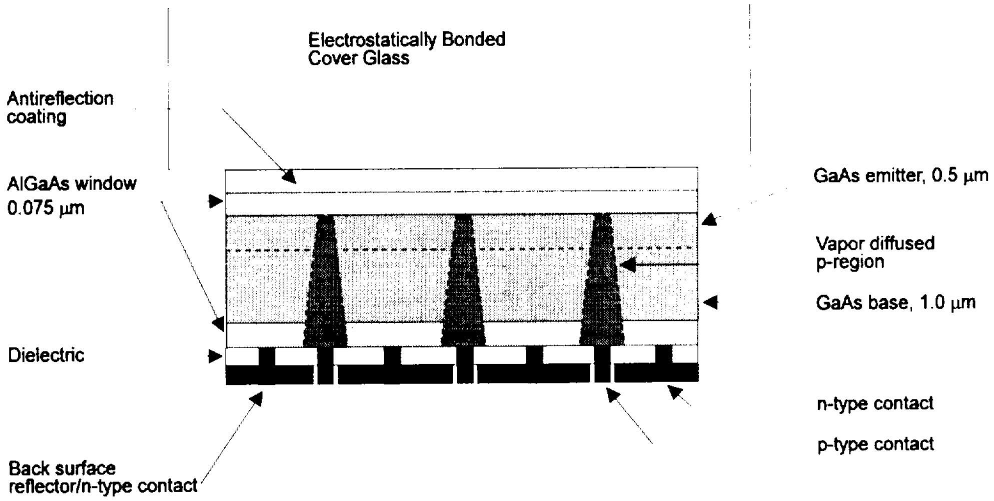

Fig. 6. *Electrostatically bonded, all back contact, ultra-thin GaAs solar cell.*

CONCLUSION

The results of this program have demonstrated the feasibility of the ultra-lightweight, high performance, thin, light trapping GaAs solar cell. This is a high payoff program and the resulting applications can have a dramatic positive effect on space solar power generation. Development of the thin light trapped GaAs solar cell will result in a new class of GaAs solar cell designs that can replace conventional GaAs solar cells because of their high specific power, radiation resistance, and durability.

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