

ELECTROSTATIC BONDING OF THIN (~3 mil) 7070 COVER GLASS TO Ta₂O₅
AR-COATED THIN (~2 mil) SILICON WAFERS AND SOLAR CELLS

D. W. Egelkrout and W. E. Horne*
Boeing Aerospace Company

SUMMARY

Electrostatic bonding (ESB) of thin (~ 3 mil) Corning 7070 cover glasses to Ta₂O₅ AR-coated thin (~ 2 mil) silicon wafers and solar cells was investigated. An experimental program was conducted to establish the effects of variations in pressure, voltage, temperature, time, Ta₂O₅ thickness, and various prebond glass treatments. Flat wafers without contact grids were used to study the basic effects for bonding to semiconductor surfaces typical of solar cells. Solar cells with three different grid patterns were used to determine additional requirements caused by the raised metallic contacts.

INTRODUCTION

Thin covers are needed to exploit the advantages of thin solar cells planned for use in future space missions. Glass has proven to be the best cover material over many years of use. Historically, thick glass covers have been attached to thick cells using adhesives. In order to eliminate the adhesive layer, electrostatic bonding (ESB) of Corning 7070 glass using heated covers and cells has been accomplished under Air Force contract (ref. 1). Corning 7070 appears to have the best match of physical, optical, and electrical properties for use with silicon. In previous work, ~ 10 mil thick cells and glass were typical. Prior to the current effort the ESB process had not been successfully applied to thin (~ 2 to 3 mil) glass and cells. The present effort was undertaken to extend the use of the ESB process to thin cells and thin covers.

The electrostatic bonding process (also referred to as field assisted, glass-metal sealing) was first described in the literature in 1969 (ref. 2). In the ESB process glass and metal (or semiconductor) surfaces are placed in contact and heated to a temperature on the order of 300°C to 600°C. A voltage ranging from a few hundred to 2000 volts is then applied so that the glass is negative with respect to the metal. Under these conditions the glass forms a strong, permanent bond to the metal surface. The unique feature of this process is the relatively low temperature at which the bond is made. It is generally 200°C to 400°C below the softening point of the glass.

*Research Sponsored by NASA Lewis Research Center, under Contract NAS3-22216.

The application of this process to the formation of integral cover glass solar cell assemblies was first reported in 1975 (ref. 1). The application of the process to integral cover glasses has been of considerable interest for both terrestrial and space purposes (ref. 3). Development of the back surface, field enhanced solar cell which permits high efficiencies in thin (2 mil) cells has increased interest in the ESB process since the full exploitation of the potential of a lightweight array of thin cells requires a thin cover glass (2 mils is desirable) and since for such thin cells and cover glasses, the ESB technique offers significant advantages from the standpoint of reduced weight and ease of fabrication by eliminating the adhesive layer.

The physics of the processes responsible for electrostatic bond formation are not well understood. It is, however, generally assumed that the final bond is a chemical bond. This is based on the fact that the bond strength (typically 2000 to 3000 psi) (refs. 1,4) is usually as good as the strength of the glass itself. For chemical bonding of two materials to take place, it is necessary to bring the surfaces within molecular distances of each other. When one material is in a liquid form, this is called wetting. Solid surfaces normally considered to be flat are in fact usually quite irregular on a microscopic scale and particularly on a molecular scale so that when two solid surfaces are brought together, they are actually only in contact at a few points.

It has been postulated (refs. 1,4) that one role of the electrostatic field in the ESB process is to pull two irregular surfaces into the intimate contact required to form a chemical bond. Most glasses contain mobile positive ions compensated by almost immobile negative ions. Considering such a material sandwiched between two electrodes which are not sources for mobile positive ions, the positive ions in the glass would be pulled away from their respective anions toward the cathode. This is depicted in figure 1 which illustrates some aspects of the ESB process. Since electrons are available from the electrodes, they will move into the glass to combine with the displaced positive ions causing a net negative charge in the glass. Thus, the glass will be attracted to the positive anode with an electrostatic force. It was hypothesized that a negative space charge occurs initially over a thin glass region near the anode and widens as time progresses. For a given degree of polarization and space charge, the attraction between the glass and anode will be largest at the smallest gap points. As the space charge grows with time, the glass is pulled together from the gap edges and the field strength in the gaps will become larger so that initially wider gap areas are pulled together. Thus, intimate contact and bonding would progress outward with time from the initial points of contact consistent with observations of the ESB process. An electrostatic attraction of 350 psi between Pyrex and a metal anode has been measured with "zero" gap at 300°C, and 800 volts, under conditions which did not produce bonding (refs. 1,4).

The work reported in this paper was primarily empirical. Basic parameters of bonding glass to the semiconductor surfaces of solar cells were investigated using wafers having texturized surfaces similar to solar cells but without contact grids. The effects of varying bonding pressure, voltage, temperature, and time in the region of ≤ 55 psi, ≤ 800 volts, $\leq 550^\circ\text{C}$, and ≤ 10 s were determined. Effects of glass and wafer variables were also evaluated.

These variables included the thickness of Ta₂O₅ AR-coatings, silicon surface texture, and various glass treatments. The glass treatments involved 1) immersion in molten LiNO₃ in an attempt to exchange Na ions in the glass for more mobile Li ions, and 2) immersion in aqueous solutions of various metallic salts to produce adsorption of the metallic elements into the glass surfaces.

Bonding to solar cells having various grid patterns was also investigated. The most significant problem encountered in bonding to solar cells with contact grids was deforming the glass over the grid so that the glass and AR-coated silicon surfaces were close enough to allow the ESB process to progress. (The ESB process was restricted to solar cell temperatures below the softening point of the glass to avoid undue thermal degradation of the cells.)

Two methods of attacking the problem of deforming cover glasses over contact grids were investigated. One method involved heating the glass with a short burst of laser energy using a wavelength such that most of the energy was absorbed in the glass and not the cell. This method showed promise, however, optimization of bonding parameters, hardware configuration, etc., must still be worked out. The other method utilized a bonder cathode material with appropriate compressibility ("cathode pillow") such that the glass over the raised contacts presses into the pillow while the surrounding pillow material bends the glass into the valleys between the contact fingers. This method has been used to produce many well bonded samples without undue degradation in cell electrical performance.

BONDING APPARATUS AND BASIC PROCEDURE

The important aspects of the apparatus used to make electrostatic bonds in this investigation are depicted in figure 2.

In the bonding runs, the glass was laid on the cathode heater, C/H block, and the cell was laid front side down on the glass. The bell jar was evacuated at which time power was applied to heating coils in the C/H block to heat the cathode and glass. The cathode temperature was monitored using a thermocouple at the point indicated in figure 2. When the cathode temperature reached the desired value, the desired pressure was applied uniformly over the sample surfaces by raising the gas pressure in the anode bellows to an appropriate level. The cathode and anode surfaces were machined flat to close tolerances to apply pressure over the entire sample area. The anode temperature was also monitored with a thermocouple at the point indicated in figure 2. Whenever a temperature is given without qualification, it is understood to be the anode temperature averaged over the time of bonding. When the anode temperature reached a value which indicated that the sample had heated to the desired temperature, the bonding voltage was applied from anode to cathode and bonding proceeded. When the bonding interval was over, gas pressure was applied to the cooling bellows so that the cooling block contacted the C/H block and cooled the sample. When the temperature of the cathode dropped to a level so that it would not oxidize ($\lesssim 100^\circ\text{C}$), the bell jar was brought to atmosphere and the sample was removed.

The bonder was constructed to facilitate bonding of one sample at a time with the possibility of varying and monitoring important bonding parameters. The C/H block temperature, anode temperature, applied voltage, sample current, and integral of sample current were recorded on each bonding cycle as a function of time using strip chart recorders.

SAMPLE DESCRIPTIONS

The silicon wafers, glass samples, and solar cells were all 2 cm x 2 cm square. Glass samples were received in three lots. Based on random samplings of five each, the measured thicknesses were:

Lot I, $\bar{x} = 3.5$ mil and $s = 0.13 \bar{x}$;

Lot II, $\bar{x} = 2.7$ mil and $s = 0.09 \bar{x}$;

Lot III, $\bar{x} = 2.8$ mil and $s = 0.08 \bar{x}$.

The surface of the samples had considerable structure. A photograph of a wafer surface is shown in figure 3a. Figure 3b shows a wafer surface with a cover glass bonded to it. Figure 4 shows glass and wafer surface profiles determined with a Tally Surf (an instrument which mechanically tracks the surface profile by dragging a micro sharp needle over the surface). The wafer surfaces contain rounded pits of varying size separated by relatively sharp ridges. The wafers received could visually be separated into two classes based on dominant pit size and density. A random sample from each of these categories is represented as "large" and "small" grain in figure 4. Many glass samples had visible surface striations. An example surface profile of a typical striation is also shown in figure 4.

The surface structure of the wafers led to considerable bond structure on a microscopic scale. This is visible in figure 3b which shows the unbonded spots as light regions and the bonded areas as dark regions. A closer look at the degree of bonding on a microscopic scale is shown in figure 5. Unbonded regions are visible as regions with interference fringes. It was established that on a microscopic scale, bonding begins at the peaks between the pits and progresses with increasing time and other bonding parameters deeper into the pits filling the shallower pits first.

Three types of solar cells were used in this investigation. They are identified by the three grid patterns as shown in figure 6. The cells are referred to as herring bone, rectangular and bar grid. The thicknesses were respectively ~ 3 mil, ~ 2 mil, and ~ 3 mil. The surface finish of the herring bone and rectangular grid samples were similar to the wafers described above. The bar grid samples, however, had a surface which was much finer in structure. The surface appeared velvetized at magnifications similar to figure 5 and had a sharp, random, crystalline appearance at magnifications of 450x.

BASIC PARAMETERS FOR BONDING TO WAFER SURFACES

The initial intent of this portion of the effort was to establish the surface in the four dimensional pressure, voltage, temperature, and time, (P, V, T, t) space which separates the regions leading to adequate and inadequate bonding. However, due to the inherent physical variations between samples and the limited sample quantity available, the degree to which this could be accomplished was limited. Considering the large electrostatic forces that exist at small sample separations, it was expected that beyond initial flattening of the samples, variations in pressure below 55 psi would not have a great effect for the wafers without contact grids. It was thus decided that an adequate pressure should be selected and used so that more variations in the T, V, t space could be made. The rate of heat transfer from the C/H to anode through the vacuum, glass, and wafer layers, is a function of sample surface mating. Based on observations of the rate of anode temperature rise versus pressure it was concluded that ~ 15 psi was probably adequate to maximize initial sample contact in most cases.

Using 15 psi, glass samples primarily from lot II, and primarily small grain wafers, the (T, V, t) surface depicted in figure 7 was defined to the degree indicated by the vertical bars. The complete shape of the surface is a matter of speculation at this time. An example of the strip chart records of bonding voltage, bonding current, C/H temperature, and anode temperature is shown in figure 8. The temperature values used for plotting the data are the average anode values during the time of bonding voltage application. Experiments where a 1 mil ribbon thermocouple was bonded between a glass cover and flat silicon wafer showed that the interface temperature most closely tracked the anode temperature at a level of about 10 to 20 percent higher than the anode temperature. The individual data are plotted in figure 9. In the figure, the symbol, ∇ , means that a sample bonded at the corresponding axis values had an acceptable bond and the symbol \blacktriangle means that it did not. The definition of an acceptable bond was ≥ 50 percent bonding of the interface area on a microscopic scale and ≥ 95 percent bonding on a macroscopic scale. Typical examples of ~ 50 percent microscopic bonds were shown in figures 3b and 5.

The scatter in the data, or spread in the T, V, t surface determined, is due to the sample-to-sample variations. It appears that these variations are primarily in the cover glasses used. The evidence of striations in the glass indicate that factors affecting the glass composition varied during the glass microsheet fabrication. Experimental observations such as discussed below indicate that the degree of bonding is related to the magnitude of current that flows during bonding. Measurements of current variations from sample to sample using identical polished wafers supported the conclusions that the variation was primarily due to the glass.

A circuit was constructed to provide $\int_0^t I(t) dt$ during each bond run. Figure 10 is a scatter plot of the degree of bonding versus this integral at the end of the bond runs. The significant factor is that regardless of temperature, time, or voltage, an acceptable bond was essentially always observed above a value of $\int I(t) dt \geq 0.25$ mA-min. It was concluded that the optimum bonding time for each sample is best set by monitoring this integral. To test

this conclusion, nine samples were bonded using a C/H temperature of 550°C, a pressure of 15 psi, a voltage of 600 volts, and $\int I(t)dt \sim 0.5 \text{ mA-min}$. The anode temperature at the start of bonding for each sample was 320°C. Differences in $\int I(t)dt$ resulted in bond times ranging from ~ 0.75 minutes to ~ 7.6 minutes. Variations in bond times and to a lesser extent variations from sample to sample in heat transfer rate resulted in end point temperatures ranging from a low of 335°C to a high of 408°C. The resultant bonds were essentially identical in quality with about 50 percent of the interface area bonded in a randomly uniform manner on a microscopic scale and about 95 to 100 percent on a macroscopic scale.

All wafer data were obtained using a hard tantalum cathode surface. The bulk of the C/H structure was copper but initial experiments indicated that damaging effects possibly resulting from reactions between the glass and C/H surface were minimized with a highly polished Ta overlay between the glass and Cu. As discussed below, the hardness of the cathode surface was found to be a critical factor in bonding to solar cells with raised contact grids. Cathode surfaces having more compressible properties such as discussed in the next section might have been beneficial for bonding to wafers but were not tried.

BONDING TO SOLAR CELLS

Attempts were made to bond glass to solar cells using the procedures established for good bonding to wafers as discussed above. When applied to solar cells, these procedures resulted in no bonding at all. The application of higher pressures, voltages, temperatures and times resulted in some bonding but the results were unsatisfactory. The primary problem in bonding to solar cells of this type was the initial deformation of the glass over the raised contact grid. One solution to this problem would be to develop solar cells with recessed contact grids; however this increases manufacturing steps and cost. The objective of this effort was to establish conditions for bonding to existing solar cells and therefore means were sought to enhance the deformation of the glass over the grids at minimum solar cell temperatures.

Considering the ESB process with a hard, flat cathode, it is apparent that the glass over the contact grid bars must be compressed by the amount of the grid thickness before the glass and semiconductor surfaces can be put into intimate contact as illustrated in figure 11a. It was speculated that due to the thinness of the glass relative to the spacing between grid bars, it might be easier to bend the glass between the bars than to compress it over the bars. It was conceived that if a C/H surface were provided with appropriate viscosity or compressibility, such glass bending might be achieved as illustrated in figure 11b. The term cathode pillow was applied to this soft cathode concept.

A cathode pillow might be constructed by captivating a viscous solid, a liquid, or a gas inside a thin conducting membrane. However, it was felt that if a material could be found with the proper compressive, conductive, and heat resistance properties the desired result would be more easily attained using the bare material.

After considering the properties of a number of materials, a preliminary acceptable material was found which yielded results which were dramatically superior to a hard cathode. A typical bond formed using a cathode pillow is shown in figure 12a for comparison to the typical result using a hard cathode (fig. 12b). The conditions used to achieve the bonds shown in figure 12a and 12b respectively were: (44 psi, 600 volts, 426°C, 2.0 min, and 2.6 mA-min) and (44 psi, 600 volts, 470°C, 2.5 min, and 1.0 mA-min).

It has been determined by further bonding of about 40 rectangular grid cells using a soft cathode that acceptable bonds are fairly reliably achieved using the conditions: $P \sim 55$ psi, $V \sim 600$ volts, $\int I(t)dt \sim 3$ mA-min, and starting the bonds at anode temperatures of 415°C with cathode temperatures of about 55°C. Anode temperatures usually level out at about 495°C before the bonding voltage is removed. Bonding times under these conditions are typically < 3.0 minutes. The degree of microscopic bonding was found to increase considerably with further increases in $\int I(t)dt$ up to ~ 5 mA-min, however, the cell degradation also increases significantly. It has not yet been determined if the benefits of this increased degree of microscopic bonding are worth the extra penalty in electrical degradation of the cells. The changes in cell electrical parameters caused by ESB are summarized in figure 13 which shows the short circuit current, ISC, open circuit voltage, VOC, maximum power, P_{MAX} , and fill factor F.F. Level 0 and 1 refer to before and after bonding respectively. It was typical that considerably more degradation in ISC occurred than in VOL and in many cases the fill factor actually went up.

The above results pertain to the rectangular grid samples only. Herring bone samples were more difficult to bond and the bar grid samples did not bond at all under conditions which led to good bonds on the rectangular grid samples. The reasons for these differences have not yet been fully investigated, but seem to be due to thicker, closer spaced grid bars for the herring bone and a radically more complex semiconductor surface structure for the bar cells.

As shown by the above data, some cell degradation due to the thermal soak during the ESB process occurs even under the shortest bonding times. While this degradation can be slight for some cells, it could be catastrophic for other cell designs. In an attempt to develop means of further reducing the thermal stress to the cells, a technique using a pulsed laser beam to heat the glass to the softening point in a very short burst was conceived. The technique would involve a background temperature sufficient to allow ion migration in the glass to establish an electric field between the glass and cell in a manner similar to the standard ESB technique. The background temperature would be maintained below the level at which the solar cell would degrade. The laser pulse would then soften the glass allowing the electric field to form the glass into the solar cell surface and around the contact grid. During subsequent cool down the interface would be bonded by the standard ESB process. It was calculated that this would be accomplished with the cell temperature above the threshold temperature for degradation for times on the order of seconds rather than minutes.

Exploratory tests were performed to establish the feasibility of this technique. The cell-glass combination was mounted in a "picture frame" which clamped it together around the edges and permitted the application of bias voltage across the cell and glass as required for the ESB technique; however, electrical contact was only made around the extreme perimeter of the assembly by the "picture frame" clamp. The clamp was then mounted in a thermally insulating holder inside a vacuum chamber and bias voltage was applied. Background heating to 350°C was provided using an incandescent light beam concentrated onto the back of the solar cell. This shuttered light beam required about five seconds to heat the cell-glass assembly from room temperature to 350°C as indicated by a ribbon thermocouple between the cell and the glass. A CW CO₂ (10.6 μm) laser beam was then directed onto the glass surface through a shuttering mechanism which allowed continuous variations of the exposure time from ~ 3 ms to 30 seconds. Several exposures were made and it was found that with the laser intensity available (~ 20 watts/cm²) a pulse of about one second duration would soften the glass. As observed through a window in the vacuum chamber, in the configuration described, the glass would first buckle upward away from the cell surface during heating. When the softening point was reached the glass could be observed to instantaneously collapse into the cell surface as would be expected if an electric field were present. At this point the current across the assembly, monitored by a chart recorder increased dramatically (on the order of mA) and after a short interval the assembly would short apparently signaling breakdown of the glass. Examination of the cell and cover glass indicated that the glass had deformed around the contact grid bars and that bonding had occurred around the periphery of the cell to a distance of about 1/8 inch inside the periphery of the "picture frame" clamp where the voltage was applied. Evidence of electrical breakdown was observed near the edge of the glass under the electrode clamp assembly.

A photomicrograph of the resulting bond is shown in figure 14a compared to that of an ESB bond produced using the "cathode" pillow technique shown in figure 14b. It appears that the bonding produced by the pulsed laser technique is more complete on a microscopic scale and the deformation around the contact is more complete. This bonding was accomplished in a very short time interval (< 1 s following laser pulse).

So far, such laser bonding has not been achieved over a large cell area. This is no doubt due to lack of uniformity in the laser beam. The desired uniformity however should be obtainable with further effort. Thus, although further work is needed to fully develop the parameters and optimize the configuration, it appears that laser pulse softening of the glass can enhance the ESB technique. The advantages offered include better conformation between the glass and the silicon surface and greatly reduced bonding times which should minimize or eliminate thermal degradation of electrical parameters.

AR-COATING THICKNESS AND GLASS TREATMENT EFFECTS

A cursory empirical investigation was made of the effects of Ta₂O₅ thickness and also various prebond glass treatments to see if such parameters could be adjusted to provide better or more easily achieved bonds. The variations tried and the results obtained are discussed below under pertinent subheadings.

Ta₂O₅ AR-Coating Thickness

Since the AR-coating is a dielectric material it is reasonable to assume that it might behave electrically in a manner similar to the glass. If the AR-coating had significant ionic conduction with neutralization of the displaced ions similar to the glass, the residual negative space charge might screen out some of the attractive electrostatic force between the glass and silicon. Depending on the ionic content of the AR-coating and its thickness, it was thought that it could be a significant factor in the ESB process. Therefore, samples were prepared with varying thicknesses of Ta₂O₅ coatings. The samples were prepared by NASA Lewis Research Center. The thicknesses are listed in table I. The wafer surfaces were not texturized for this experiment.

Bonding conditions were determined which gave partial bonding on a macroscopic scale on the thickest of these samples and then two samples of each available thickness were bonded using these conditions. The conditions were: P ~ 15 psi, V ~ 600 volts, $\int I dt \sim 0.5$ mA-min, and an anode starting temperature of ~ 245°C. Assuming that the degree of bonding is proportional to $\int I(t) dt$ if other conditions are constant, glass variations should have been cancelled by using $\int I(t) dt$ instead of time. Thus any changes in bond completeness would have been due to the Ta₂O₅ variations.

The results showed remarkably identical degrees of macroscopic bonding for all available sample thicknesses for the Ta₂O₅ coated wafers but polished silicon wafers without any AR-coating bonded under identical conditions showed essentially complete bonding. Since the bare wafers were from a different source and of different thickness than the Ta₂O₅ coated wafers it is not certain if the effect is entirely due to the lack of AR-coating but it seems most likely. Typical examples of the resultant bonds are shown in figure 15.

Ion Exchange

It was hypothesized that the current during the bonding process might be the result of the movement of relatively mobile Li ions in the 7070 glass. This was in part based on the observation that bonding could not be achieved with an old batch of 7070 glass thought not to contain Li as opposed to newer 7070 which did bond and did contain Li. If the hypothesis were true, it might be that exchanging mobile Li ions for less mobile Na ions in the glass would result in enhanced bonding. The technique tried for increasing the Li ion content is commonly known as ion exchange. If an insoluble solid is brought in contact with a molten solution, its surface can exchange ions. The ion

exchange process is used routinely in the glass industry in chemical tempering of glasses (ref. 5). The tempering is accomplished by exchanging potassium ions from a molten potassium nitrate solution for the sodium ions in the surface layers of the glass. This exchange of larger potassium ions for smaller sodium ions creates compressive forces in the glass surface and effects the tempering.

On this program, glass samples were treated by immersion in solutions of molten, $\sim 300^{\circ}\text{C}$, LiNO_3 for varying periods of time. It was found that if immersion was maintained too long (usually ≥ 2 hours) the glass would become etched and milky in appearance. Since this was considered intolerable, the immersion time was reduced to a level just short of causing this effect (usually ~ 1 hour). To avoid confusion due to the sample to sample variation in the glass, samples were immersed only halfway into the molten LiNO_3 . Samples were pretreated by cleaning with detergent and rinsing in distilled H_2O and also by immersion in H_2O_2 . It was assumed based on visible change in the glass color (reflection) in the treated areas that the glass composition had been changed by the treatments.

Samples treated as described above were bonded to Ta_2O_5 coated texturized wafers using conditions which normally lead to marginal bonding. No significant difference was detectable in the degree of bonding between the treated and untreated parts of the samples. If the treatment was of any value the treated parts should have been bonded to a greater microscopic degree.

Cation Adsorption

The configuration of tantalum in Ta_2O_5 might strongly affect the adhesion of SiO_2 with Ta_2O_5 antireflection layers. For example, the SiO_2 - Al_2O_3 system is very compatible and bonds readily since both Si and Al are in tetrahedral configurations. On the other hand, it is known that SiO_2 and Cr_2O_3 do not adhere probably due to the octahedral configuration of Cr which results in poor "mixing" of these systems. Based on such considerations, treatment of the glass surface with metallic ions to form better matching properties was thought to be one possible means of improving the bondability of cover glasses.

It has been observed that glass surfaces exposed to aqueous solutions of heavy metal ions will adsorb varying amounts of the metal ions (ref. 6). In an attempt to introduce metallic ions which might have better matching properties with the Ta_2O_5 layer, samples were half immersed in saturated aqueous solutions of the metallic salts listed in table I. That some change in the glass took place for most of these treatments was evidenced by visible changes in the reflective properties of the glass. These samples were bonded to Ta_2O_5 coated texturized wafers using conditions leading to partial bonding. In no case was there any significant difference in the degree of bonding in the treated versus untreated sides.

Cleaning With H₂O₂

Cleaning processes are known to be very important in glass to metal bonding and wetting. Because of this and also due to the possible significance of interstitial oxygen atoms in the bonding process, some samples were cleaned in an ultrasonic bath of 30 percent H₂O₂ (a strong oxidizing agent) for times ranging from 1 to ~ 240 hours. As with many other treatments, a visible change in glass color and or reflectivity occurred indicating that the treatment had changed the glass. However, no effect was noted in the degree of bonding between treated and untreated parts of the glass in any case.

CONCLUSIONS

It was determined that bonds with ≥ 95 percent interface area coverage on a macroscopic scale and ≥ 50 percent coverage on a microscopic scale were adequate to withstand Scotch type 810 tape peel tests and -175°C to +60°C temperature cycling. With this definition of a good bond, the conditions of pressure, voltage, temperature and time required to make good electrostatic bonds to Ta₂O₅ coated texturized silicon surfaces typical of solar cells were established. To minimize thermally induced degradation of solar cells, a minimum time and temperature are required. The optimum conditions for this are to use a maximum voltage. For anode pressures of 15 psi, glass of ~ 2.8 mil mean thickness, and hard smooth cathode and anode surfaces, it was usually possible to apply 800 volts at chamber vacuums in the range of 1 μ m to 10 μ m of Hg without arcing. However to reliably avoid arcing, a 600 volt bias was found to be more appropriate. At this voltage, an anode starting temperature of 320°C was adequate with a cathode temperature of 550°C. Since a correlation between the total integral of bonding current and the degree of bonding was established, it appears that the current integral is a good parameter to use in determining when bonding voltage should be removed to minimize the bonding time. A value of 0.5 mA-min was found to be best for the Ta₂O₅ coated Si surfaces.

In bonding glass to solar cells, deformation of the glass over the contact grid was found to be the dominant problem. This problem was greatly alleviated by employing a "cathode pillow" with the appropriate compressibility so that the thin glass is bent around the grid as opposed to compressing the glass over the grid as required with a hard cathode. Maximizing the pressure with this method yields significant benefits, but, enhanced arcing around the edges of the glass as the glass is pushed into the pillow was a sporadic problem. Careful control of cathode pillow size and alignment of all elements were usually successful in allowing arc free bonding. Thus far, many good bonds of ~ 2.8 mil glass to 2 mil cells have been made with acceptably small thermal degradation of cells. The best conditions appear to be ~ 55 psi, 600 volts, a C/H temperature of 550°C, an anode starting temperature of 415°C and a total bonding current integral of ~ 3 mA-min. Bond times for these conditions typically ranged from 1 to 5 minutes. Additional softening of the glass during the bonding process using a short burst of laser heating was achieved over a small region of solar cell. This procedure shows promise for improving the bond quality while reducing the cell thermal stress. Further development is required however to determine if the laser method is practical and to optimize the process.

Investigations of the effects of Ta₂O₅ AR-coating thickness and various glass treatments indicated no significant effects on bonding. Inherent variations in the glass however were quite significant. These were manifest as variations in the rate of heat transfer, and the bonding current under fixed bonding conditions. As a result, to obtain the same degree of bonding from sample to sample, different bond times were required resulting in different degrees of cell degradation. To minimize degradation further investigation of the factors causing these observed variations from sample to sample is needed.

REFERENCES

1. Kirkpatrick, A. R., Kreisman, W. S., and Minnvcci, J. A., Stress Free Application of Glass Covers for Radiation Hardened Solar Cells and Arrays, AFAPL-TR-77-28, May 1977.
2. Wallis, G, and Pomerantz, D. I., "Field Assisted Glass-Metal Seating," Journal of Applied Physics, Vol. 40, No. 10, pp. 3946-3949, Sept. 1969.
3. Younger, P. R., et al., Integral Glass Encapsulation for Solar Arrays, Interim Report No. 1, JPL Contract No. 954521, Nov. 1977.
4. Wallis, G., "Field Assisted Glass Sealing," Electrocomponent Science and Technology, Vol. 2, No. 1, pp. 45-53, 1975.
5. Hutchins, J. R. III., and Harrington, R. V., Encyclopedia of Chemical Technology, Vol. 10, 2nd Edition, Kirk-Othmer, Ed. (Wiley and Sons, New York, 1966).
6. Weyl, W. A. and Marboe, E. C., The Constitution of Glass, (John Wiley and Sons, N.Y. 1960).

TABLE I. AR-COATING THICKNESS AND GLASS TREATMENTS

| TA ₂ O ₅ THICKNESS | GLASS TREATMENTS |
|--|---|
| NONE | LiNO ₃ |
| 385 Å | H ₂ O ₂ |
| 431 Å | H ₂ O ₂ + LiNO ₃ |
| 570 Å | MgCl ₂ ·6H ₂ O |
| 610 Å | KCL |
| 660 Å | CdCl ₂ |
| 760 Å | |

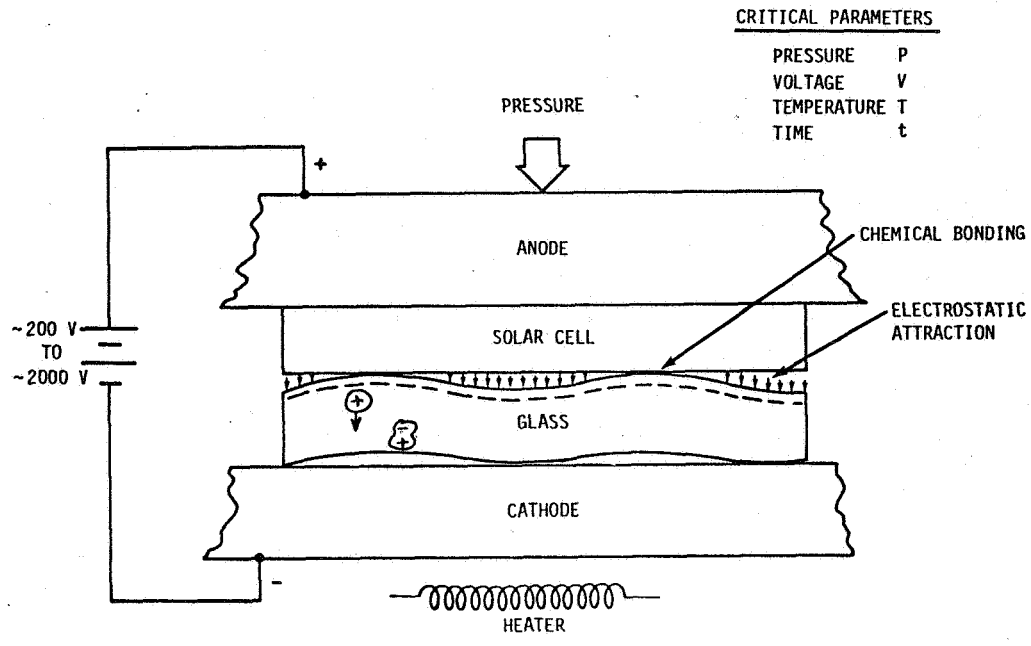


FIGURE 1. SCHEMATIC SHOWING ASPECTS OF ELECTROSTATIC BONDING

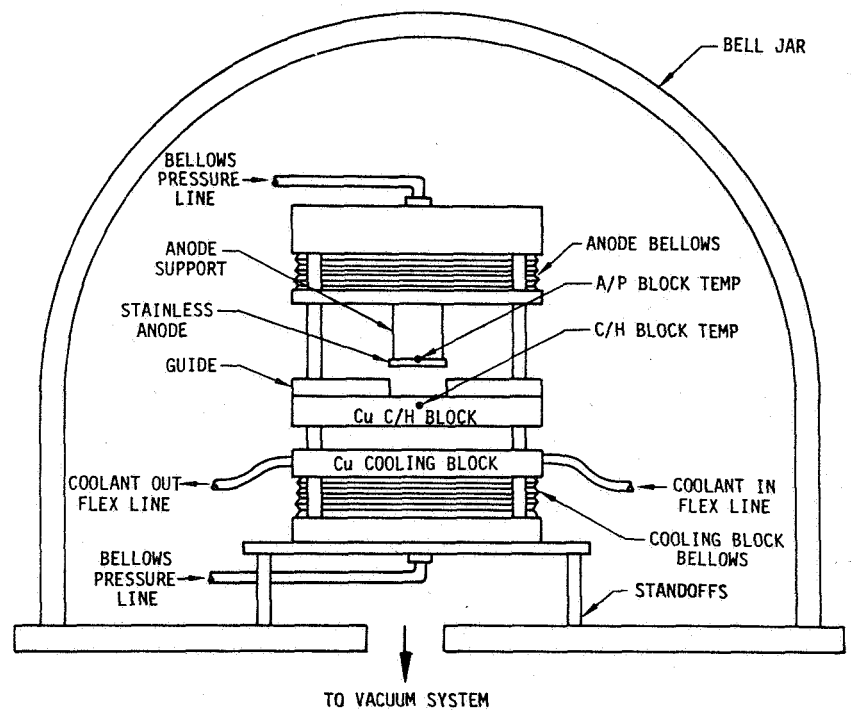


FIGURE 2. CONCEPTUAL DRAWING OF BONDER HEAD

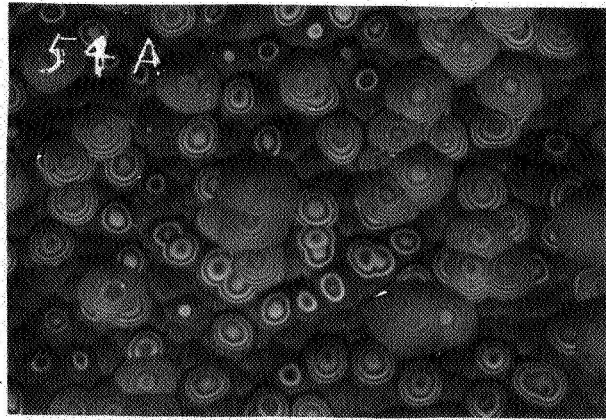


FIGURE 5. EXAMPLE PHOTOMICROGRAPH OF WAFER WITH GLASS BONDED

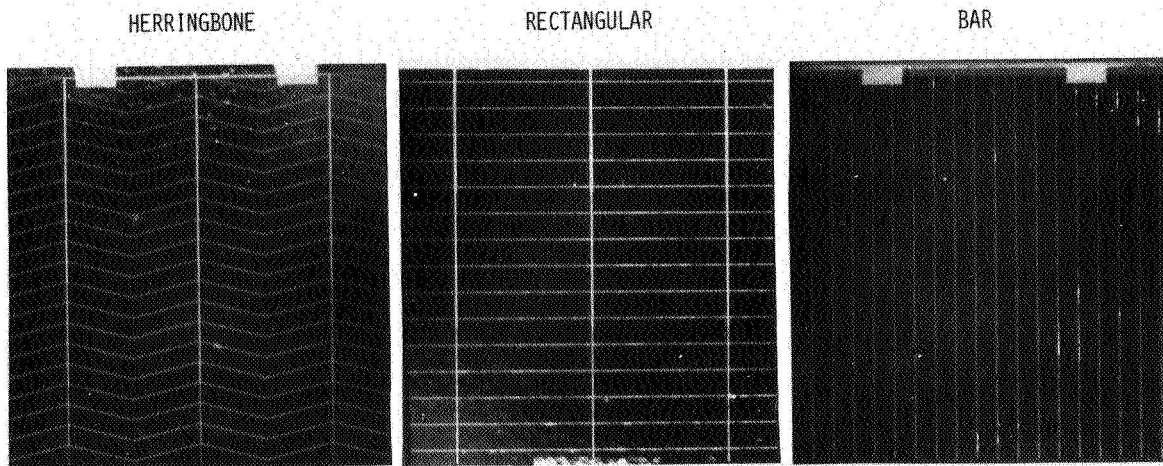


FIGURE 6. SOLAR CELL GRID PATTERNS

(A) BARE WAFER

(B) WAFER WITH GLASS BONDED

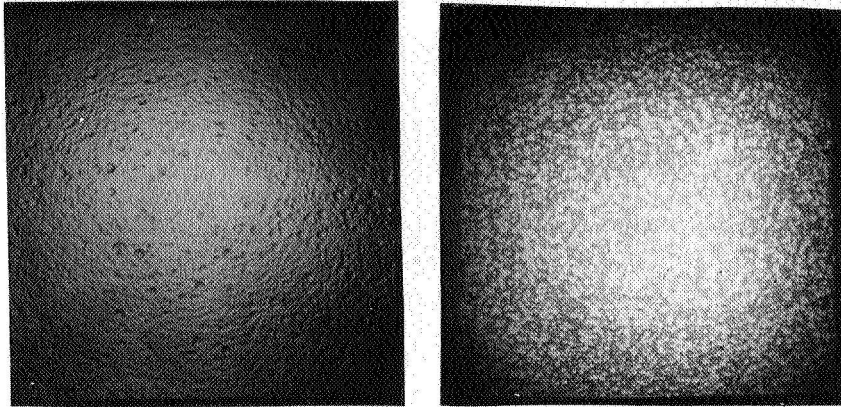


FIGURE 3. EXAMPLE PHOTOS OF WAFER SURFACES

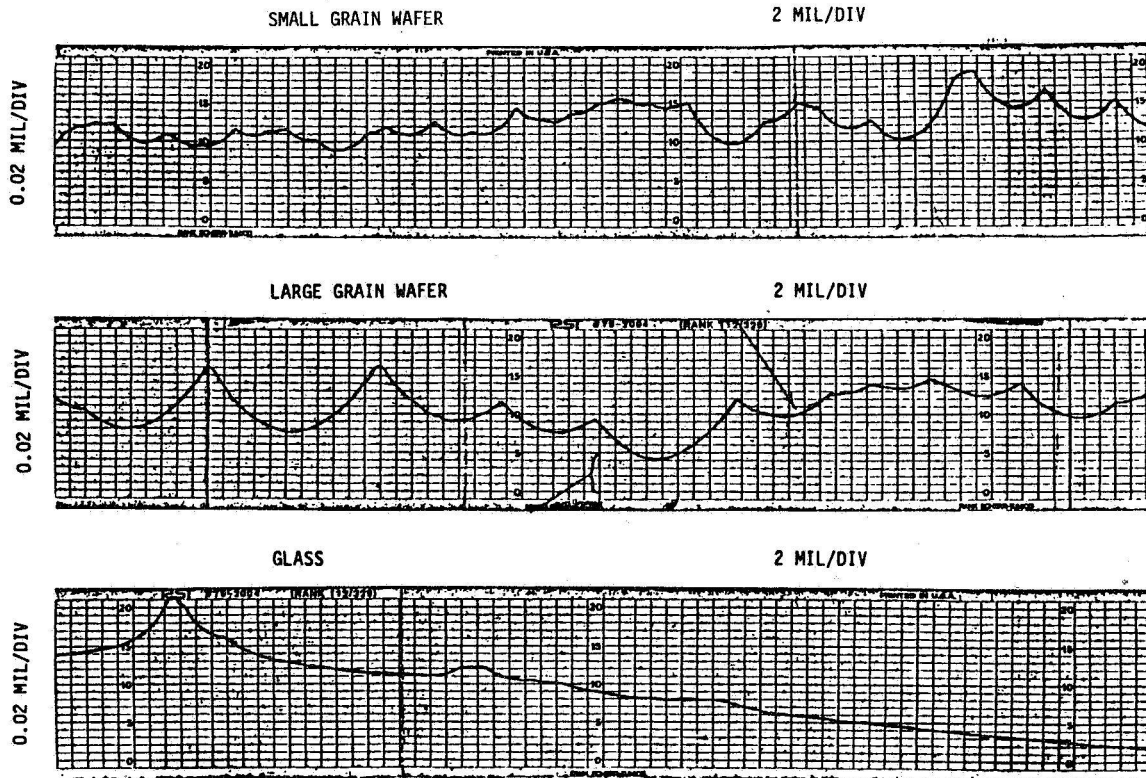


FIGURE 4. WAFER AND GLASS SURFACE PROFILES

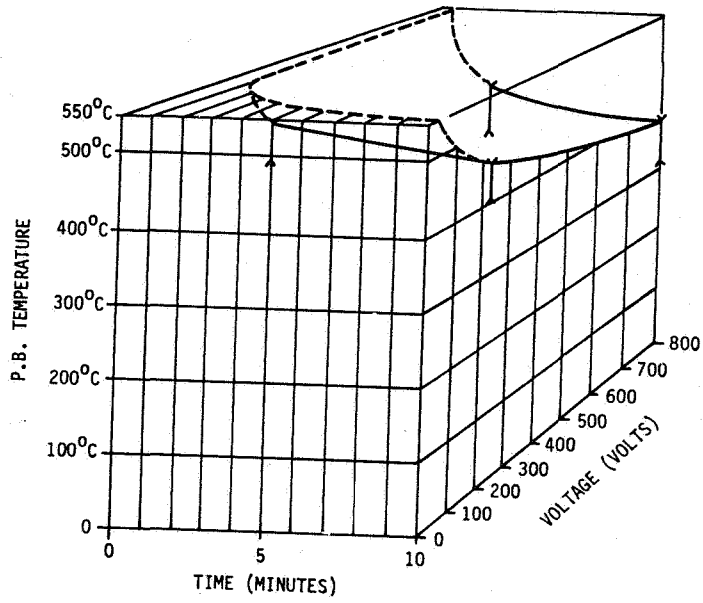


FIGURE 7. ELECTROSTATIC BONDING T, V, τ SURFACE

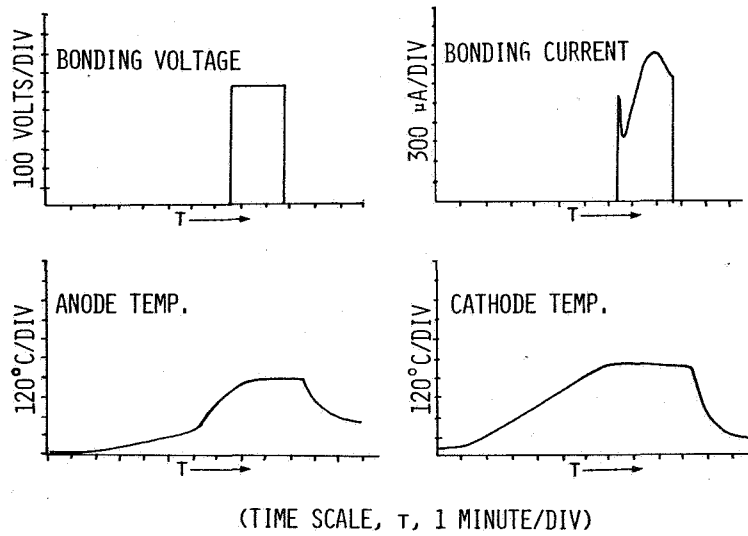


FIGURE 8. EXAMPLE STRIP CHART RECORDS OF BONDING PARAMETERS

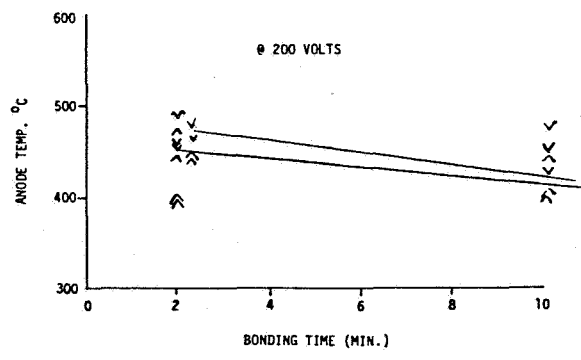
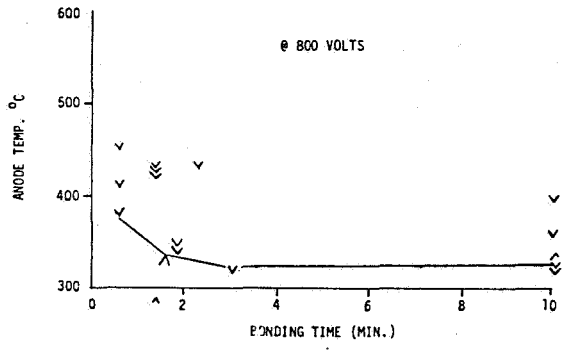
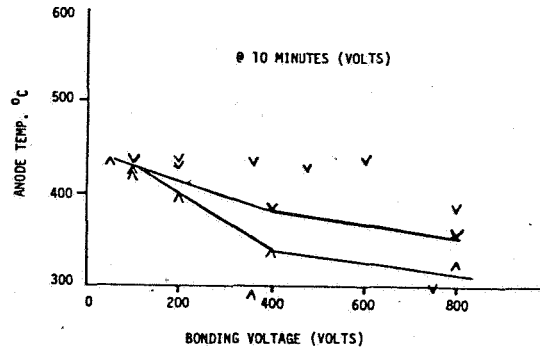


FIGURE 9. TWO-DIMENSIONAL PLOTS OF BONDING PARAMETER DEPENDENCES FOR WAFERS (△ BAD BOND, ▽ GOOD BOND).

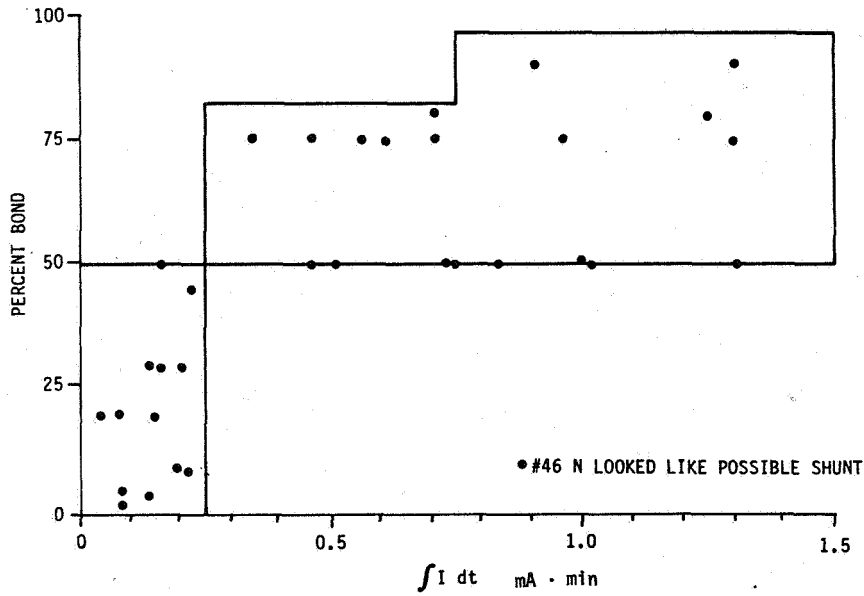


FIGURE 10. MICROSCOPIC PERCENTAGE BOND VERSUS $\int I(T)DT$

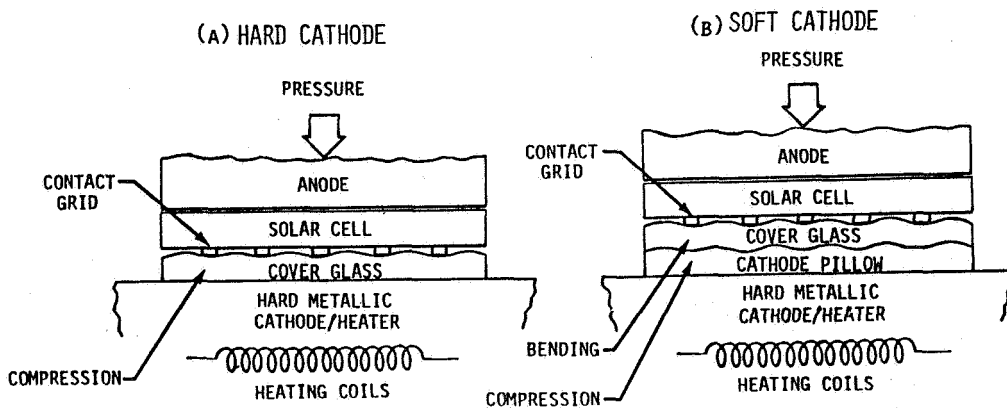


FIGURE 11. PHYSICAL FEATURES OF ESB PROCESS USING HARD AND SOFT CATHODES

(A) CATHODE PILLOW

(B) HARD CATHODE

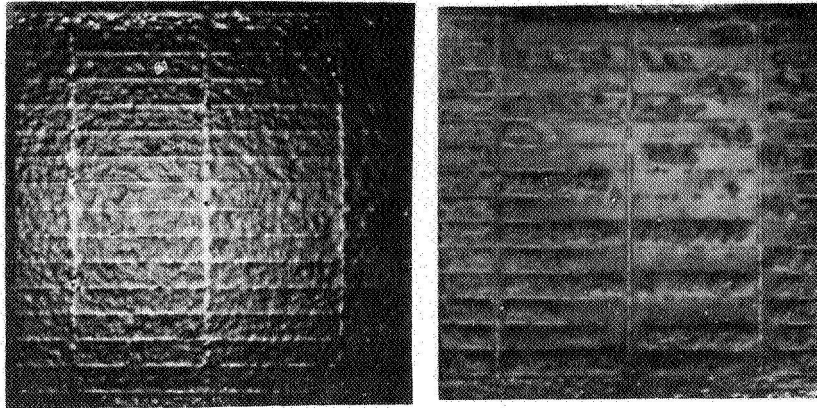


FIGURE 12. EXAMPLE SOLAR CELLS WITH GLASS BONDED USING HARD AND SOFT CATHODE

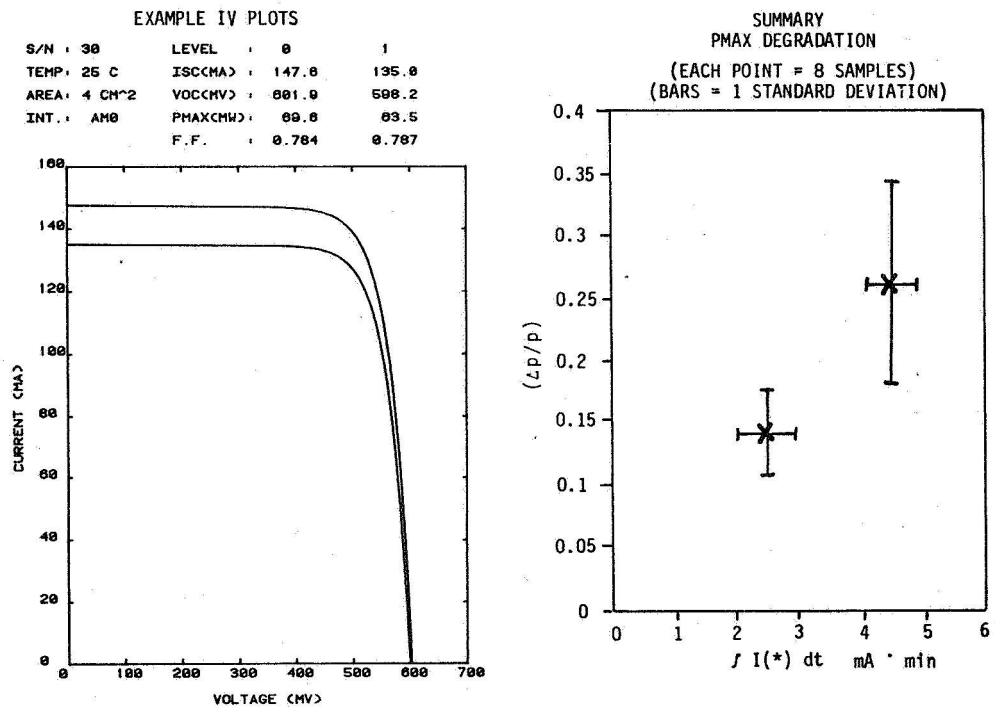


FIGURE 13. EFFECT OF ESB ON CELL ELECTRICAL PARAMETERS

(A) LASER HEATING

(B) CATHODE PILLOW

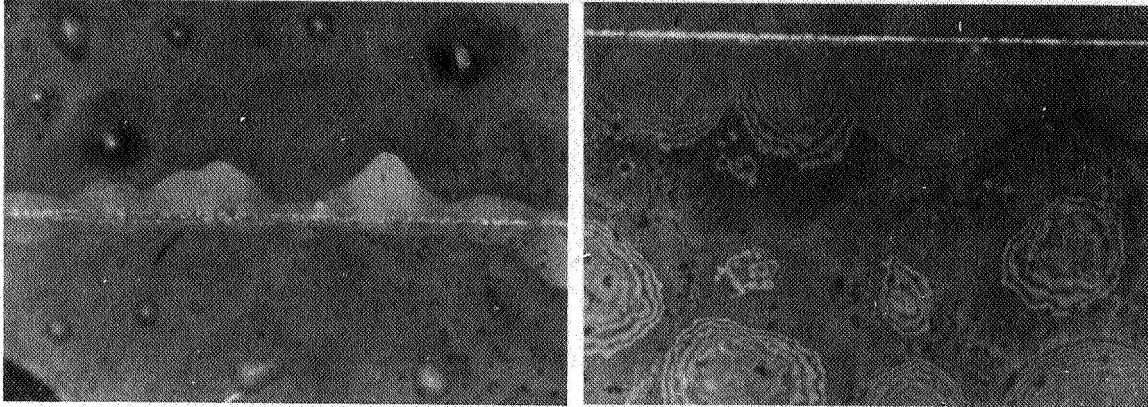


FIGURE 14. COMPARISON OF MICROSCOPIC BONDING USING CATHODE PILLOW AND LASER HEATING

BARE WAFER

335 Å Ta_2O_5

760 Å Ta_2O_5

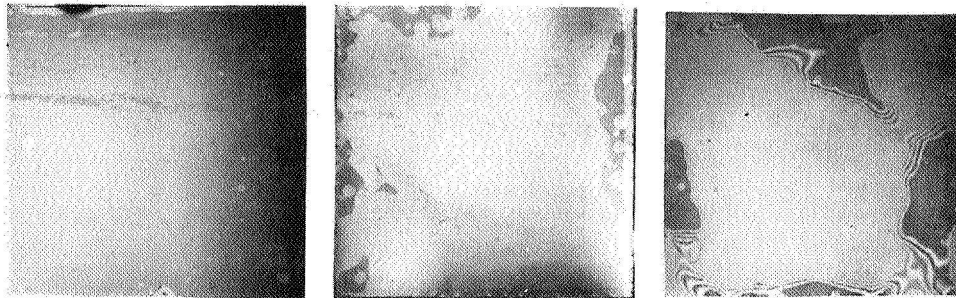


FIGURE 15. EXAMPLE OF BOND DEGREE VERSUS WAFER SURFACE COATING THICKNESS (USING IDENTICAL BONDING CONDITIONS)