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**CONFERENCE RECORD  
OF THE TENTH IEEE  
PHOTOVOLTAIC SPECIALISTS CONFERENCE**

**November 13-15, 1973**

**Palo Alto, California**



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**Session on Solar Energy Conversion**

**PRINCIPLES OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION**

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*Introduction*

The photovoltaic effect (PVE) is the generation of an electromotive force (emf) as the result of the absorption of ionizing radiation. It can occur in gases, liquids and solids, but it is in solids, specifically in semiconductors, that acceptable efficiencies for conversion of solar energy into electricity have been observed<sup>1</sup>. We shall therefore, limit the discussion to the PVE in semiconductors.

Three processes are essential to the PVE. First of all, positive and negative carrier pairs in excess of thermal equilibrium concentrations must be generated by the ionizing radiation. Secondly, the excess charges of opposite sign must

be separated at some electrostatic inhomogeneity either a metal-semi-conductor junction or a p-n junction. Thirdly the carriers generated must be mobile and must continue in their separated state for a time which is long compared with the time they require to travel to the localized charge — separating inhomogeneity.

Let us examine each of these processes and explore their relation to more fundamental properties of a semiconductor.

*Absorption of Light In Semiconductors*

Consider a monochromatic beam of light incident on a homogeneous solid. Let the x-axis be normal to the plane of



constant phase of the incident electromagnetic wave. Then the number of photons  $N_{ph}(x)$  remaining in the beam after it traverses a thickness  $x$  of the material is given by

$$N_{ph}(x) = N_{ph}(0) e^{-\alpha x}$$

where  $N_{ph}(0)$  is the number of photons at  $x = 0$  and  $\alpha$  is the absorption constant. The parameter  $\alpha$  is a function of the wavelength  $\lambda$  or photon energy  $h\nu$  of the incident beam.

Figure 1 is a plot of  $\ln \alpha$  vs  $h\nu$  for a number of semiconductors of interest for PVE solar energy conversion. These curves are characterized by a threshold for absorption which corresponds to photon energy equal to the forbidden energy gap  $E_g$  of the semiconductor. For  $h\nu < E_g$  the value

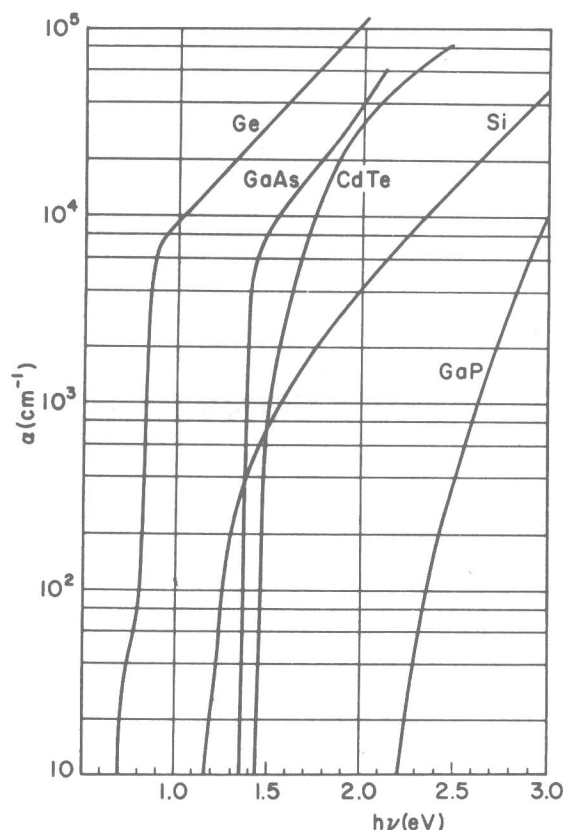


Figure 1. Absorption constant  $\alpha$  vs  $h\nu$  for some semiconductors of interest as solar cells.

of  $\alpha$  is very small ( $< 10^{-1} \text{ cm}^{-1}$ ) while for  $h\nu > E_g$  the value of  $\alpha$  rises rapidly so that within a few tenths of an eV of the energy  $E_g$ ,  $\alpha$  attains a value in excess of  $10^4 \text{ cm}^{-1}$ .

As shown in Fig. 1, there are basically two kinds of absorption curves: a) those of GaAs, CdTe, Ge, CdS, etc., which rise very sharply from the low values in the vicinity of the threshold to the range  $\alpha > 10^4 \text{ cm}^{-1}$  and b) those of Si and GaP which rise more gradually. These differences are explainable in terms of the concept of direct or indirect gap semiconductors. Absorption curves of the type (a) described above are characteristic of direct gap semiconductors while those of type (b) are characteristic of indirect gap materials.

In general, type (a) absorption curves, i.e., direct gap semiconductors would be preferred for PV solar cells for the simple reason that the thickness of the material needed to absorb sunlight is smaller for such materials. This would mean that such materials could be used to make thin cells ( $\leq 10\mu$  thick) since virtually all the solar photons with energy in excess of  $E_g$  would be absorbed in a few micron thickness of these materials. Materials like Si which have type (b) absorption curves are not as suitable for thin film cells.

#### Charge Separation In the Photovoltaic Cell

Charge separation requires an electrostatic potential difference between two regions of the photovoltaic cell so that the excess carriers produced by absorption of ionizing radiation can be separated. Such an electrostatic potential difference can be produced by a metal-semiconductor junction or by a p-n junction.

Two types of p-n junctions can be distinguished: a) those in which there is a single semiconductor, one side of which is n-type and the other, p-type (homojunctions), and b) those in which the n-type side consists of one semiconductor and the p-side consists of a second semiconductor (heterojunctions). The number of semiconductors in which homojunctions can be made is limited mainly to the column IV (Ge, Si, C) semiconductors and column III-V semiconductors (GaAs, InP, AlSb, etc.). Among II-VI semiconductors (CdS, ZnS, CdSe, CdTe etc.) only CdTe can be prepared with both n- and p-type conductivity. The number of possible heterojunction type cells is limited only by the imagination. The Cu-Cd-S thin film cell is an example of the unexpected combinations which can be encountered. This cell is based on a heterojunction between p-  $\text{Cu}_y\text{S}_x$  (probable values are  $x = 2, y = 1$ ), and n-CdS. The Se cell is another case in point; it involves a heterojunction between the p-Se and n-CdSe.

In the case of metal-semiconductor junctions, a large electrostatic potential difference between the metal and semiconductor would require that the contact be of the depletion layer type. The height of the barrier is governed by the work function difference between the metal and semiconductor. Metal-semiconductor photovoltaic cells have not been explored very intensely since the invention of the silicon p-n junction photovoltaic cell. Recent advances in understanding of metal-semiconductor junctions associated with the development of MOS devices could be applicable to metal-semiconductor junction photovoltaic cells.

One obvious advantage of metal-semiconductor junctions is the ease with which they can be made. They should therefore be inexpensive, but of course it must first be established that some sort of metal semiconductor junction gives rise to an acceptable solar energy conversion efficiency, an efficiency in the vicinity of 10%.

#### Migration of Carriers to the Charge Separation Site

The carriers separated by absorption of ionizing radiation must remain separated long enough to travel to the charge separation site. The carriers may move toward this site under the influence of a concentration gradient (i.e. by

diffusion) or under the influence of a built in field (i.e. by drift).

The magnitude of the intrinsic minority carrier lifetime depends on whether the semi-conductor is a direct or indirect gap material. The intrinsic lifetime is short ( $<10^{-8}$  sec) in direct gap materials and it is therefore less affected by the presence of recombination centers. The intrinsic lifetime is long (up to  $10^{-3}$  sec in Si) in indirect gap materials and is therefore more likely controlled by imperfections acting as recombination centers. However, since the thickness of material needed to absorb most of the solar photons is smaller in the direct than in the indirect gap materials, the shorter lifetime in the direct gap materials is not an impediment to the fabrication of efficient solar cells from such material.

The lifetime of interest in the PVE is an effective lifetime; it is affected by both surface and bulk recombination. In the case of silicon, for example, analysis shows that attainment of a solar energy conversion efficiency close to 20% would require bulk diffusion lengths of about  $100\mu$  in material of bulk resistivity around 0.01 ohm cm and of surface recombination velocities of about 100 cm/sec on material of this resistivity<sup>2</sup>. Similar analyses would have to be made on other materials to determine what values the various parameters must have to obtain high efficiency PVE. Obviously direct gap materials would not require such long bulk diffusion length nor should they require such low values of surface recombination velocity.

#### Photovoltaic Effect Parameters

Four parameters are of interest in analyzing the performance of a photovoltaic cell. They are the short circuit current  $I_{sc}$ ; the open circuit voltage  $V_{oc}$ ; the current for matched load, i.e. current under maximum power transfer conditions  $I_{mp}$  and the corresponding voltage  $V_{mp}$ . Figure 2 shows the i-v curve of a PV cell in the dark and under

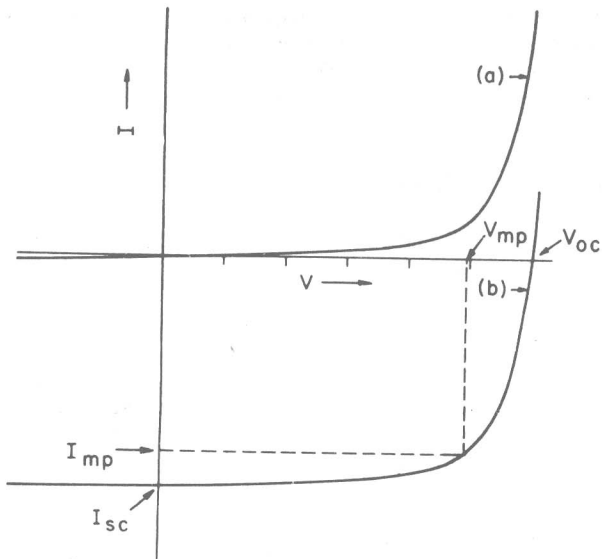


Figure 2. The current voltage curve of a p-n junction solar cell (a) in the dark and (b) under illumination. The important parameters are identified: short circuit current  $I_{sc}$ , open circuit voltage  $V_{oc}$ , current  $I_{mp}$  and voltage  $V_{mp}$  at maximum power.

illumination and identifies these four parameters. Note that a good PV cell has a nearly "rectangular" i-v curve so that  $I_{mp} \rightarrow I_{sc}$  and  $V_{mp} \rightarrow V_{oc}$  in such a cell.

a) Given the values of minority carrier lifetime, surface recombination velocity and the cell geometry, the short circuit current  $I_{sc}$  which flows across a short-circuited junction can be calculated from the relation

$$I_{sc} = q \int_{E_G}^{\infty} Q(h\nu) N_{ph}(h\nu) d(h\nu)$$

where  $q$  is the electronic charge;  $Q(h\nu)$ , the collection efficiency, is defined as the fraction of carriers generated by

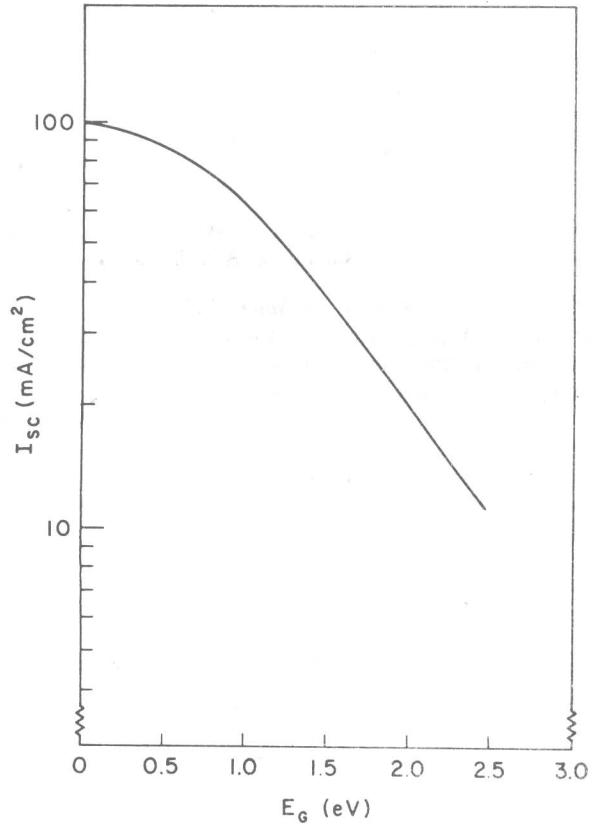


Figure 3. The maximum possible short circuit current  $I_{sc}$  for solar cells made from semiconductors with forbidden energy gaps  $E_g$  on the abscissa. Air Mass Zero (AMO) solar illumination.

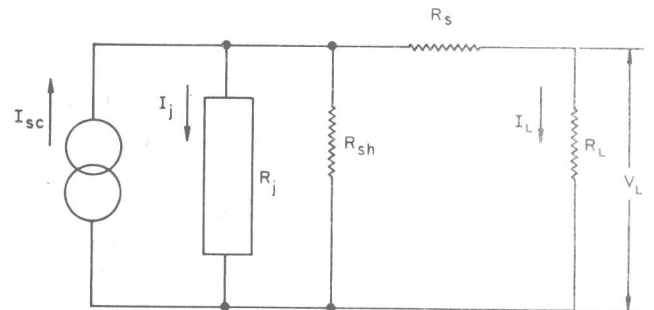


Figure 4. Lumped parameter equivalent circuit of an illuminated solar cell.

absorption of a photon of energy  $h\nu$  which actually contribute to  $I_{sc}$ ;  $N_{ph}(h\nu) d(h\nu)$  is the number of photons/cm<sup>2</sup> in the spectrum with energy  $h\nu$ .

Figure 3 is a plot of  $I_{sc}$  vs  $E_G$  for the solar spectrum calculated from Eq. (2) [ $Q(h\nu) = 0$  for  $h\nu < E_G$  and  $Q(h\nu) = 1$  for  $h\nu \geq E_G$ ].

b) Figure 4 shows a lumped parameter model of an illuminated photovoltaic cell including internal series and shunt resistances,  $R_s$  and  $R_{sh}$ , respectively and load resistor  $R_L$ . The non-linear junction impedance is denoted by  $R_j$  and the current through the junction is  $I_j$ . If we assume that  $R_{sh}$  is large and  $R_s$  small, the load current is given by the relation

$$I_L = I_0 [\exp(qV/AkT) - 1] - I_{sc}$$

from which  $V_{oc}$  is given by

$$V_{oc} = \frac{AkT}{q} \ln \left( \frac{I_{sc}}{I_0} + 1 \right)$$

Now  $I_0$  is a strong function of  $E_G$

$$I_0 \propto \exp(-E_G/BkT)$$

Usually  $A = B$ ; in Si PV cells  $A = B \sim 2$ ; in an "ideal" p-n junction, their values should be  $A = B = 1$ .

#### Selection of Semiconductors for Solar Cells

If  $I_{mp}$  and  $V_{mp}$  are evaluated for various semiconductors, it is found that the energy gap plays a central role in determining the maximum efficiency attainable in a PV cell. From Eq. (2) and Fig. 3, we note that for solar illumination  $I_{sc}$  decreases with  $E_G$ . From Eqs. (4) and (5) combined with  $I_{sc}$  from Eq. (2), we find that  $V_{oc}$  increases with increasing  $E_G$ . This means that their product, i.e. the output electrical power, passes through a maximum as shown in Fig. 5, which shows the maximum efficiency vs  $E_G$  at 300°K.

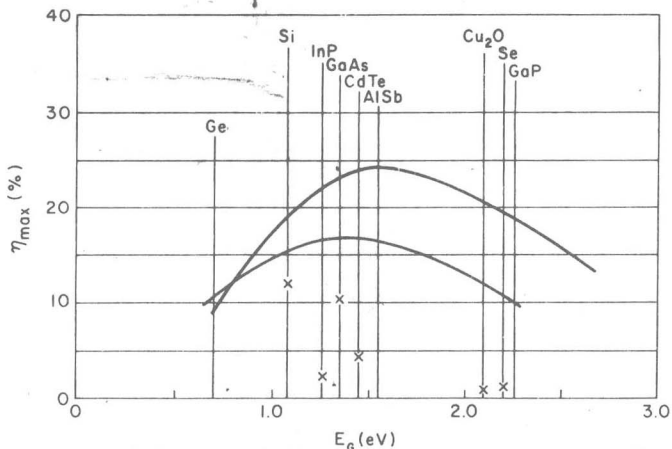


Figure 5. Maximum attainable efficiency for matched load conditions  $\eta_{max}$  as a function of energy gap  $E_G$ . Curve (1)  $A = B = 1$  and curve (2)  $A = B = 2$ .  $A$  and  $B$  are defined in Eqs. (3) and (5). Temperature 300°K.

The upper of these lines corresponds to  $A = B = 1$  and the lower to  $A = B = 2$ . Figure 6 shows  $\eta_{max}$  vs  $E_G$  with  $A = B = 1$  for a series of temperatures above room temperature (298°K)<sup>3</sup>. These curves show that the highest attainable solar energy conversion efficiency is about 25%

for a homojunction PV cell. The maximum efficiency for silicon is about 20% for  $A = B = 1$  and about 15% for  $A = B = 2$ .

Figure 6 shows that  $\eta_{max}$  is a strong function of temperature. Both figures indicate that for room temperature

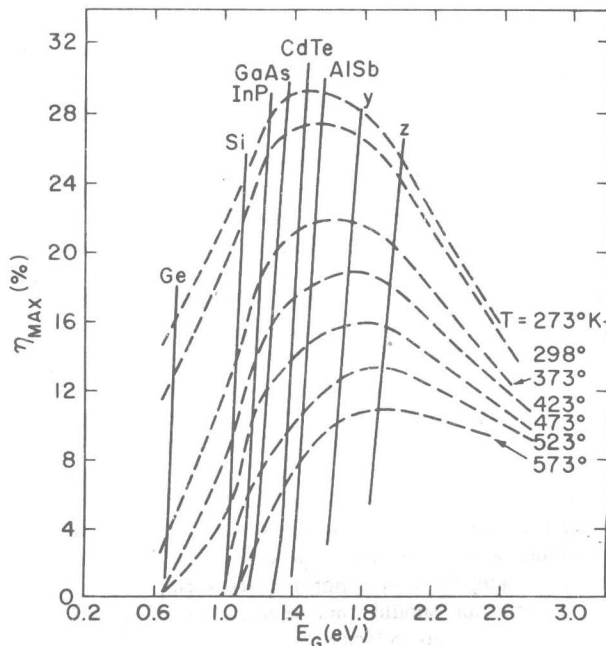


Figure 6. Maximum efficiency  $\eta_{max}$  as a function of energy gap  $E_G$  for various temperatures.

operation, materials with energy gaps in the vicinity of 1.5 eV promise to have the highest possible efficiency. The crosses in Fig. 5 show the highest reported AMO efficiencies for the selected materials.

It should also be noted that the solar spectrum on the earth's surface differs substantially from that in space (AMO) and that it varies with time of day, season, etc. because it depends on the solar azimuth. The main result is that the spectrum received on the earth's surface has a reduced blue response which results in a higher efficiency for a Si cell than the same cell has for AMO illumination.

#### Summary and Conclusions

The theory of the photovoltaic effect in p-n homojunctions is quite well understood. It can be used to predict optimum performance of solar cells.

No semiconductor has reached its predicted maximum efficiency. In the case of silicon, this failure to attain its predicted  $\eta_{max}$  is attributed to inadequate quality of the semiconductor material comprising the cell.

The efficiency of solar cells is a strong function of temperature; it decreases as temperature increases. This must always be taken into account especially if the cells will be used with concentrators.

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## POTENTIAL IMPROVEMENTS IN EFFICIENCY AND COST OF SOLAR CELLS

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### Introduction

Twenty years have passed since the development and production of "solar cells" has begun as devices which are specifically designed to convert solar radiative energy into useful electrical power. Although the work was, at the beginning, oriented towards terrestrial applications, the vast majority of the devices produced so far has found application in power systems for space craft. While this application has been of particular usefulness for the space program, the increasing shortage of the most commonly used fossil fuels, petroleum and natural gas, has re-awakened the interest for the application of solar cells for large scale terrestrial applications.

While efficiency is of primary importance in space applications, cost is the more important parameter in large scale terrestrial applications. Nevertheless, efficiency plays an important role here also since significant cost components of the system are directly related to the area covered by the collectors. Since delivery of a given amount of power is always the end goal, and since the input power is a limited quantity in a given geographic location, the collection area is an inverse function of efficiency. Consequently, solar cells of higher efficiency can demand a higher price for comparable cost of the delivered energy.

### Potential Efficiency Improvements

At the beginning of the solar cell epoch, efficiencies of 3 to 6% were obtained in devices prepared from silicon and from cadmium sulfide. Within three years, production silicon solar cells attained 10% efficiency in terrestrial sunlight, while those made from single crystal cadmium sulfide with copper sulfide barrier layer achieved over 8%. Two years later, terrestrial sunlight efficiencies in silicon solar cells rose to 14%, while cells prepared from gallium arsenide, reached approximately 10%, although they should have attained slightly higher efficiencies than silicon cells, based on theoretical considerations of energy gap-width and configuration. Their actual performance was limited primarily by process problems. Efficiency-wise, the field stayed rather stationary until the National Academy of Sciences convened a panel to study the potential for future efficiency improvement (Ref. 1). This panel concluded that the best hope for early further improvements in efficiency would lie with the silicon device, since far greater amounts of materials and process technology development had been carried out on silicon than on any other material.

Several areas for potential improvement in silicon solar cells were identified, based on an accounting for the various losses occurring in the conversion of

solar photon energy to electrical power available at the terminals of the solar cell. This is illustrated in the bar graph of Fig. 1. Some of the losses are determined by basic physical phenomena and are fixed as soon as the energy gap of the material has been selected. These basic losses are represented by the upper three blocks in the left bar of Fig. 1. For silicon, they amount to 62% of the available solar energy for air mass zero. For gallium arsenide, this number would be slightly lower. Below the horizontal line, in Fig. 1, two separate bars are shown for those loss factors which are predominantly determined by technology effects, and which are therefore subject to potential improvement. The left bar indicates the losses in the current cells with 10.6% efficiency, while the right bar shows the reduced losses leading to 22% efficiency (Ref. 2).

Figure 2 illustrates two of these improvements, which are connected with the collection efficiency. Curve 1 is representative of the spectral collection efficiency of recent production solar cells. In contrast, curve 3 indicates a significant improvement in the short wavelength range, to be achieved through a reduction of the "effective surface recombination velocity". It has been shown earlier (Ref. 3,4), that layers of poor electronic quality or of an inverse impurity gradient might exist near the light exposed surface and affect the spectral response from the diffused region in a similar way as a high surface recombination velocity would. It was shown, that an improvement of 17% in collection efficiency was available through elimination of the high effective surface recombination velocity in combination with a reduction of the thickness of the diffused layer. An additional 6% gain in collection efficiency was shown to be obtainable by improving the long wavelength response through increased minority carrier lifetime (Curve 4 of Fig. 2).

A second major improvement can be made on the current-voltage characteristic. While at present silicon of a base resistivity of 2 to 10  $\Omega\text{cm}$  is commonly used, yielding open circuit voltages in the range of 0.55 to 0.59 V, use of a base resistivity of 0.01  $\Omega\text{cm}$  could potentially yield an open circuit voltage of 0.79 V (Fig. 3). A precondition for this achievement is, that minority carrier lifetimes in the low resistivity material could be obtained as predicted by the Shockley-Read theory (Ref. 5). Attainment of this improvement is expected to require a considerable amount of materials work. An increased "sharpness of the knee" of the current voltage characteristic would be obtained simultaneously with the increased open circuit voltage, so that the "curve factor" (C.F.) would increase from 0.82 to 0.86.

Finally, current-voltage characteristics as shown

in Fig. 3, are generally not obtained, but rather those indicated by the dots in Fig. 4. The experimental data points deviate at the high voltages from the theoretical exponential characteristic (straight line on the semilogarithmic plot) due to series resistance, and at the low voltages such that they can be expressed by a second exponential term, which is characterized by a saturation current  $I_{02}$  and a factor  $A_2$  in the exponent:

$$I = I_{01} \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right] + I_{02} \left[ \exp \left( \frac{qV}{A_2 kT} \right) - 1 \right] - I_L ;$$

While, at room temperature and normal illumination levels, the open circuit voltage falls into the range of the first exponential which obeys Shockley's theory for pn-junction behavior based on diffusion of minority carriers, the maximum power point falls into the transition region between the two exponential terms. This results in a "softening of the knee", which leads to a reduction of the available maximum power by approximately 9% compared to that which would be obtained from a device having its current-voltage characteristic described by the first exponential term only. The origin of the second exponential is not fully understood at this time—recombination and generation of minority carriers in the depletion region as described by Sah, Noyce, and Shockley (Ref. 6) may be a cause, surface conduction effects may be another. Nevertheless, characteristics have been seen both in a few commercial solar cells and in cells resulting from developmental efforts, (the so called "violet cell" of Comsat Laboratories (Ref. 7), which do not contain the second exponential term.

In total, an efficiency improvement from the level of 10.6% (air mass 0) of the current commercial cells to 22% in silicon solar cells (or slightly higher in gallium arsenide solar cells) was predicted. In both devices, significant advances have been made during the three year period since the review by the National Academy of Sciences panel. In both cases, the primary improvement was obtained by reducing the "effective surface recombination velocity" through improvements of the characteristics of the diffused region. In silicon, they consisted in a narrowing of the diffused region thickness and elimination of a layer of inadequate electron transport properties while, in the gallium arsenide device, a corresponding effect was achieved by application of a window of wide band gap material, which effectively removes the surface from the diffused region. A tabulation of the expected improvements together with those attained in the "violet cell" of Comsat Laboratories (derived from data contained in Ref. 7) is provided in Table I. These data show that the improvement in silicon solar cell performance achieved recently, amounts to about one third of the total predicted improvement. The work has to shift now particularly to the material improvement which has been expected to lead to increased open circuit voltage and improved curve factor. With the present improvements, the silicon cell has achieved confirmed air mass 0 efficiency of 14%, the gallium cell of over 12%. In terrestrial sunlight, efficiencies of 16 to 18% have been reported for both types of cells.

### Potential Cost Improvements

At present, two prime contenders for the expected large scale terrestrial solar cell market are in existence: the silicon solar cell and the thin film copper sulfide/cadmium sulfide device. The silicon device is currently produced at a rate of approximately 70 kW peak power output per year, primarily for the space program, and at a cost of approximately \$7,000 per  $m^2$  of space quality cells. For the terrestrial market, they are now offered at the price level of \$1,000 to \$1,500 per  $m^2$ , although their production rate is still small compared to that for the space market. The copper sulfide/cadmium sulfide thin film cells are in pilot line production and are offered at comparable prices per unit peak power. While the production processes for the copper sulfide/cadmium sulfide thin film solar cell hold more immediate promise for a low cost operation, questions of production yield, lower efficiency (about 5% regularly achieved in pilot production lines, 8% in the laboratory) and a stability problem on which significant recent progress has been made in France (Ref. 8), are still problem areas. For the silicon cell, the question of cost reduction is the prime problem, with high production yields, high efficiency and long life being established facts.

Since it is practically impossible to predict the course of future cost reductions through process improvements, it is more feasible, at this point in time, to establish a set of cost goals and to examine all known facts which might possibly prevent the attainment of these goals. The computation of these cost goals has to be based on the potential production of electric energy by the device in its intended application, on the cost of electric energy from other sources which would be replaced by the solar cell application, and by the cost of capital. Since future trends in costs of energy and costs of capital are nearly impossible to predict, it is best to base the computation on current costs of energy and capital. It is easy to adjust these goals, once future cost trends become known.

Table II shows a comparison of the present costs of silicon solar arrays with the cost goals for large scale terrestrial applications. Three different potential applications are included in this comparison (Ref. 9): the two right hand columns provide the approximate allowable costs for arrays for a solar energy conversion station in synchronous orbit, or for a residential combination system in the north-eastern United States, providing electric power and thermal energy for space conditioning, assuming a subsidy of capital cost in the latter case. The central two columns under terrestrial applications apply to the same system without subsidy, and the two left hand columns apply to a ground based central power station in Arizona, with credit for delivered power on an "intermediate power" cost basis. It is considered improbable that the latter cost goals can be met. However, the cost range of \$16 to \$46 per  $m^2$  included in the central and right hand columns is considered a realistic goal. Although the considerations of Ref. 9 as well as others following in this discussion are oriented toward silicon solar arrays, many of them apply in analogy to the copper sulfide/cadmium sulfide device, which may be equally feasible for residential and other end user purposes.



A point to be noted examining Table II is, that the purified silicon compound (predominantly  $\text{SiHCl}_3$ ) is already of adequately low price in the central and right hand columns (wafer thickness of 0.1mm assumed with negligible Si losses). However, the purified silicon price (polycrystalline, solar grade) of \$ 70.-/kg is distinctly too high for either of the two columns. The allowable, but unused cost portion of a particular line, as experienced with purified silicon compound, has been carried forward to the next higher line.

Table III shows the accumulation of costs through the present front-end processes leading to polycrystalline silicon. Ferrosilicon is produced at a rate of approximately 100,000 tons per year at a cost which is fully acceptable for large scale terrestrial solar cell production. It is also seen that the processes for generation of purified silicon compound and the reduction to polycrystalline silicon each increase the price by approximately an order of magnitude. Similar cost increases continue through the subsequent process steps.

In order to analyze the potential for future cost reductions and the type of processes to be applied, it is of first importance to determine the magnitude of the anticipated production rates. Such determinations can be made by two methods. The first method consists in estimating potential introduction rates, using existing economic forecasts such as that for the construction rates for dwelling units (Ref. 10), augmenting this with an allowance for commercial and industrial construction, and adding the launch of solar power stations in space (Table IV), (Ref. 11). The total amounts to an introduction rate of approximately  $5 \cdot 10^8 \text{ m}^2$  annually.

In the second approach, introduction rates are calculated as would be required to achieve a significant impact on the total electric power generation within a certain time period (Table V). This is the only valid objective to justify government support. The impact goal assumed here equals 65% of the 1970 electric power generation, but only 5.5% of that predicted for the year 2020 (Ref. 10). Using a time-invariant introduction rate for twenty years to reach the target capacity, a rate is obtained which is comparable to that derived from the construction rates. It may be noted that the twenty year introduction period is equal to the presently assumed life for the photovoltaic solar conversion systems, so that replacement production would continue at the same rate, that is  $5 \cdot 10^8 \text{ m}^2/\text{year}$ .

The potential rates of silicon solar array production for terrestrial applications have thus been found to exceed the present production rate by six orders of magnitude. The areas considered here for photovoltaic conversion are of the same general magnitude, although somewhat more conservative, than those contained in the report to OST (Ref. 12). It may be noted that use of the solar arrays is envisioned to occur predominantly on buildings (Table IV), thus reducing the land use problem. A comparison with the magnitudes of certain current land uses are nevertheless interesting (Table VI).

The question of future costs can now be attacked. At least two different methods are available: a statistical method, and a more detailed analytical method. The

statistical method is based on experience factors of the electronics industry, and particularly the semiconductor components industry. Here the costs per unit have been related to the total cumulative production which if plotted on a doubly logarithmic graph, form more or less straight lines called "learning curves" (Fig. 5) (Ref. 13). Learning curves with a slope of 70 to 80% have generally been experienced. Plotting such a learning curve for silicon solar cells (Fig. 6), and indicating the slopes to future large scale production, it is seen that the 70 to 80% slopes lead to cost levels in the range of the goals for a cumulative production of only a few times the predicted annual rate. Also, extrapolating by use of the learning curve, price predictions at the 25, 50, 75% probability levels have been made for purposes of the "Space Solar Power Station" (SSPS) prototype study (20  $\text{km}^2$  points in Fig. 6) (Ref. 14, 15).

Figure 6 includes a few interesting details. The first is a point indicating the production in 1967-68 for the Skylab project of a significant number of cells of 2 x 6 cm size (rather than the usual 2 x 2 cm) at a considerably lower than average cost. The cost advantage was gained from reduced handling costs due to the larger cell size (Ref. 15). The impact of these cells on overall production costs has remained small, however, since orders for the large cells constitute only a minor fraction of the total cells produced. A second point, in 1971, indicates the offering for sale of a still larger, round cell for terrestrial applications, fabricated with a simplified process (Ref. 15). These points could indicate a curve much steeper than the 70% slope, since they represent potential cost reductions which have, however, not been exploited in increased orders.

Since the statistical method has indicated a realistic potential for achievement of the cost goals, a few more details should be analyzed. First, a further look at the impacts of the large scale production rates is indicated. Table VII indicates that the volume of silicon production for solar arrays would be over 120,000 t per year, making allowance for yield. This is two orders of magnitude greater than the present world semiconductor-grade silicon production, but of the same magnitude as the 1969 metallurgical grade silicon production in the U.S.A. alone (93,000 t, Ref. 16). A particular conclusion is, that the metallurgical grade silicon production would not be greatly perturbed by the advent of large scale silicon solar array production (that is, potentially doubled), and that therefore the price of metallurgical grade silicon cannot be expected to decrease significantly. As has been discussed, this price is fully acceptable for the large scale terrestrial solar cell production. This leads to the somewhat gratifying conclusion that all the cost improvements have to be made in the subsequent purification and device processing steps which are currently carried out on a much smaller scale and are therefore more readily amenable to improvement.

The strip production rate would be  $17 \text{ m/s}^{-1}$  (50ft per second, and the annual dollar volume of solar arrays more than seven times that of the U.S. semiconductor device industry in 1972 (Table VII). Although this would require a sizable new industry, it



would be considerably smaller than the present automobile industry.

It is clear that the required large scale cost reductions can be achieved only by an all new approach to production processing. This approach will have to be an integrated one from the reduction of the ore (quartzsand) to the finished array. All process steps along this route have to be compatible with each other. Although the present ferrosilicon has been found to be of adequately low price, and even the purified  $\text{SiHCl}_3$  to be of acceptable cost, a new process of reduction and purification could lend itself much more favorably to a simplified overall process sequence. A fresh look at every facet of the production sequence is therefore indicated.

It is possible to list the measures which have to be undertaken to achieve the required degree of cost reduction (Table VIII). Although it may not be possible to fully implement all of these measures and still produce a high efficiency device, as many of these process improvements as possible will have to be realized. In particular, it will be necessary to eliminate all relatively high cost processes such as photoresist masking or more generally to avoid two dimensional pattern generation processes. A continuous flow process is most readily attained, if all patterns are of linear geometry. Of particular concern has to be the controllability of the processes and their yield. It is well known in the semiconductor industry, that low costs in mass production can be obtained only with high yield processes. Also, to eliminate the costs of array assembly and cell interconnection, the production should be based on that of integrated arrays rather than of individual cells. An early form of such integrated arrays, using the copper sulfide/cadmium sulfide structure on plastic film, has been under development at RCA already 6 years ago (Fig. 7). A corresponding structure suitable for single crystal silicon sheet is suggested in Fig. 8. About the last point concerning energy consumption, more will be said later.

It is clear that such a large scale production will have to be carried out in a fully automated continuous flow process. A preliminary analysis of a production "machine" has been carried out on the assumption that the entire production would be handled by 3,000 such machines. This leads to a production rate of  $20\text{m}^2/\text{h}$  for each machine (Table IX). This production rate is compatible with most processes used in solar cell production, and it permits reasonable sizes of the individual machine elements (Table X). Some other process which might be applied in large scale solar array manufacture, such as material deposition by spraying or off-set printing, heat treating in a tunnel oven for relatively short time periods, etc., are equally compatible with this speed of work piece movement. Heat treatments for long time periods, however, would require a chamber oven with work piece stacking, but are compatible with the requirement of simplicity for slow process steps.

Another point to consider is the cost for such a production machine. An upper cost limit for the production machine can be determined, using the cost goal for the product and the expected annual output

from the machine. Applying the rule of thumb for the machine value (including building) of one to two times the value of annual production (cost of capital about one third of cost of sales; annual cost of capital approximately 17 to 33% of capital), the original equipment cost is found to be in the \$3.5 to 7 million range. Considering the fact that a significant number of such production units will ultimately be built, and that part of the original development costs are expected to be subsidized by the government, the cost appears to represent a reachable goal.

A third point to be considered is concerned with the energy consumption for the production of solar arrays. At present, the energy consumed in the production of metallurgical grade silicon, its purification, the fabrication of solar cells, and the array assembly, including plant lighting and air conditioning, amounts to about 40 years' worth of electricity generation from the resultant solar array in terrestrial applications in the northeastern part of the United States (Ref. 9). At today's low energy prices, the cost of this energy consumption represents only a fraction of one percent of the current cost of completed arrays. Therefore, no effort has been made towards reducing this energy consumption. Such a large energy use is clearly not permissible in future processes. Fortunately, the basic processes required for the reduction of silicon dioxide, purification, melting for crystal growing, and repeated heat treatments require only a negligible fraction of the present energy consumption (Table XI). Thus, through use of energy conservation methods, including better insulation of furnaces, heat recovery, etc., a reduction of the energy consumption for production of silicon solar arrays by a factor of ten to twenty from the present value can reasonably be expected. This level of energy consumption for production can then be recovered by the solar array within ten to twenty percent of its expected lifetime (20 years). Based on this permitted energy consumption, the total installed power of the single production unit should not exceed 3 MW, a number which also appears reasonable.

Both the statistical approach and a more detailed analysis, of which a few samples have been presented, thus indicate that the expectation of achievement of the cost goals for competitive energy production in large scale terrestrial application of photovoltaic solar energy conversion is not unreasonable.

### Conclusion

The preceding discussions have shown that the efficiency of solar cells which can be expected to be increased from the present level of 16 to 18% in terrestrial sunlight, achieved in developmental units, to well over 20%, will be very competitive with the efficiencies expected to be reached in solar thermal electric power plants. To achieve this additional efficiency increase, a considerable effort towards the improvement of the electronic properties of low resistivity semiconducting materials is expected to be required.

A still larger effort will be needed to reduce the cost of photovoltaic solar energy conversion arrays by a sufficient amount to make the electric energy

thus generated competitive with that obtainable from other energy sources. Prime candidates for this are the copper sulfide/cadmium sulfide thin film system which can expect to attain efficiencies of 8 to 10%, and silicon arrays with efficiencies of 16 to over 20%, probably based on single crystal ribbon or sheet technology. Proof of commercial feasibility of large scale terrestrial application which includes meeting the cost goals, may be achievable within 5 years with the copper sulfide/cadmium sulfide thin film system, but should require, with expenditures of significant efforts, approximately 10 years for the silicon system. Other semiconductor systems will require a greater development effort, and some may achieve results comparable to those obtainable with silicon, after a longer time period.

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