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CURRENT STATUS OF SILICON SOLAR CELL TECHNOLOGY

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ABSTRACT

In quest of higher efficiency, major progress has occurred in solar cell technology during the last five years. In this period cell efficiency has climbed about 50 percent. Technical approaches leading to increased output include back surface fields (n^+-p-p^+ structures), shallow junctions, improved antireflection coatings, surface texturizing, and fine grid patterns on the cell surface. The status of current solar cell technology and its incorporation into cell production is discussed.

Research and development leading to improved performance and reduced cost are also described.

INTRODUCTION

During the last five years, the efficiency of silicon solar cells has increased dramatically. In 1970, the average outer space efficiency of silicon solar cells was 10.5%. In 1975, laboratory cells have reached efficiencies above 15% and production cells are in the 13% range. Most of the increased output has resulted from increased short-circuit current, with only minor increases in voltage being reported. It is appropriate to review the past accomplishments so that the future potential of the cell and the pertinent research problems can be clearly defined.

STATE OF PRESENT TECHNOLOGY

Short-Circuit Current

Short-circuit current can be increased in two ways. First, the amount of light entering the cell can be increased by reducing the surface area covered by the grid pattern and by reducing the reflectivity of the surface.

Grid Pattern: In 1970, the standard grid pattern on a 2x2 cm cell covered about 10% of the cell surface. By use of improved metal masks or photoresist technology, average coverage is now in the 5-7% range.

Antireflection Coatings: The conventional antireflection coating in 1970 was a quarter wavelength coating of SiO. However, when the cells were covered with adhesive and a coverslip, a loss in current of about 3% was obtained. Reoptimization of the antireflection coating to account for the cover glass required coatings with a higher refractive index such as TiO_x, Ta_2O_5 and Nb_2O_5. As shown in Table I, the use of these coatings led to an increase in current of about 5% on covering and an advantage over a glassed SiO cell of about 7%.

Texturizing: The most important advance in increasing the amount of light entering the cell came through surface texturizing. The use of the basis chemical etches such as KOH, NaOH or hydrazine in 100 silicon surfaces results in surfaces covered with a myriad of pyramids as shown in figure 1. This surface yields two benefits. One benefit arises from multiple reflections experienced by the incoming beam as shown in figure 2. This reduces bare surface reflectivity from 33% to about 11%. Addition of a Ta_2O_5 antireflection coating and a cover glass leads to a reflectivity of only 3% compared to about 10% average reflectivity for a smooth cell coated with SiO.

The second benefit arises because light is refracted as it enters the silicon and travels obliquely through the cell. Collection efficiency increases because light is absorbed closer to the junction. Also more infrared light is absorbed because the path length is greater than the silicon thickness and because the light is totally internally reflected from the smooth back surface. These factors also increase cell current.

Shallow Junctions: To reduce the effects of poor collection efficiency in the diffused region (due to anomalous phosphorus diffusion profiles and low lifetimes), shallow junctions have been used. Sheet resistances in the 150 to 500 $\Omega/\square$ range resulting from phosphorus diffusion in the 800° C temperature range yield junction depths on the order of 0.1 μm. These have led to substantial increases in the blue region of the cell spectral response.

Increased Minority Carrier Lifetime: The minority carrier lifetime measured in n^+-p solar cells ranges from 6 to 10 microseconds. Studies have shown that the front and back surface recombination velocities and the wafer thickness signitifantly influence the measured lifetime. For example, a

300 μm thick cell has an 8 μsec lifetime while a 100 μm thick n^+-p cell has a lifetime of only about 1 μsec. Use of a back surface p^+ field (n^+-p-p^+ structure) yields an essentially zero surface recombination velocity plane. Accordingly, the lifetime increases to about 30 μsec in 300 μm thick devices. This increase in lifetime yields an increase in short-circuit current of only a few percent but leads to a more important effect on cell open-circuit voltage.

Open-Circuit Voltage Efforts to increase the voltage have explored several areas. The inclusion of a back surface field in 10 Ω-cm cells produced an increase of about 50 mV in open-circuit voltage. However, almost no effect was observed for 1 Ω-cm material. It is believed now that the increased voltage results from the presence of the near zero surface recombination velocity p^+-p low-high junction coupled with the increased lifetime noted above.

Device Performance and Production Status

Increased device performance results from inclusion of the above technologies into the cell. However, transition from the laboratory to cost effective production is difficult and represents a significant barrier to rapid introduction of new, marketable solar cell devices. Table II summarizes the technologies used and the production status of current improved efficiency cells. Table III compares the performance of the 1970 cell with selected new technology cells, all with cover glasses. The 13% efficient Helios cell is in high volume production at Spectrolab. The violet cell nearing production by OCLI, was not included in Table III since it has the same features of the Helios cell but with a slightly higher voltage which leads to a 13.5% efficiency. The highest performance, 15.3%, is achieved by the CNR cell. This cell remains in laboratory production at the COMSAT laboratory.

From Table III it is clear that most of the improved output comes from increased short-circuit current. The increased voltage comes from use of the p^+ back surface field and lower resistivity material. Improved fill factor is the result of both improved grid geometry and junction processing procedures. A comparison of the spectral response of a CNR cell and a 1970 cell is shown in figure 3. The CNR cell has a quantum yield (electrons collected per incident photon) above 90% over most of the response region. Thus it appears that little further improvement in short-circuit current can be anticipated in the future.

FUTURE RESEARCH AND TECHNOLOGY TRENDS

Although developments to date have been significant and exciting, additional research and development opportunities exist. Efficiency increases can be expected and cost reductions by orders of magnitude can be predicted. Basic research and high technology will both play a significant role.

Open-Circuit Voltage

The last substantial barrier to achieving the maximum practical efficiency of about 19% is the open-circuit voltage. Although simple diode theory predicts an increasing voltage with decreasing resistivity, contrary results are obtained experimentally as shown in figure 4. The highest voltage reported for 0.1 Ω-cm material is 0.61 V instead of the 0.7 V calculated. Also the base region minority carrier lifetimes in the 0.1 and 0.01 Ω-cm cells are sufficiently great so as to yield much larger open-circuit voltages. Thus it appears that a low emitter efficiency of the diffused region is the cause of poor voltages. Several effects may act to reduce the voltage. These include band gap narrowing, increased interband transition rates and defect clustering. These mechanisms also influence bipolar transistor current gain and frequency response and hence are an area that should receive great attention. The kinship between solar cells and transistors is rather close at this time.

Technological approaches aimed at increasing cell voltage have examined alternate dopants, ion implantation and epitaxial structures. Of these, epitaxy seems to offer the most advantage at this time. By use of heavily doped substrates, and doping gradients within both the base and the emitter region, open-circuit voltages above 630 mV have been achieved. While this gain is modest, it may be the harbinger of things to come.

Short-Circuit Current

The one remaining research area related to current is determination and reduction of cell surface recombination velocity. Preliminary measurements of the surface recombination velocity on diffused solar cell surfaces yield values between 5 and 10×10^3 cm/sec, which is much lower than had previously been estimated. However, reduction to a value below 10^3 cm/sec is required before full short-circuit current can be achieved.

Wrapping the front contact around to the back of the cell eases interconnection of cells and may increase cell current and power by reducing front surface blockage. Simply wrapping the diffused junction around the cell edge has resulted in unacceptable leakage currents. Development of wraparound contacts for high efficiency cells warrants further study.

Low Cost Technology

The final barrier to widespread use of solar cells is cost. The ERDA National Photovoltaic Program is clearly focussed on this target. Both automated, high rate cell production and new technologies will be required to meet stringent cost requirements. Table IV summarizes some of the low cost, non-vacuum technologies that are currently being investigated for automated production. Cell costs have been reduced from $80/watt for space cells to under $10/watt for present terrestrial cells. The use of large circular wafers up to 10 cm diameter have aided this reduction. Automation is expected to reduce cell costs to $2/watt in the next few years. Additional major technological advances to reduce the cost of polycrystalline silicon and development of low cost single crystal silicon ribbon growth or wafer preparation together with further gains through automation are expected to yield 10-50¢/watt arrays by 1985.

SUMMARY

The progress made in improvement of the silicon solar cell has yielded a 50% increase in cell efficiency in the last five years. Current laboratory cells have reached an efficiency above 15% and continuing efforts are aiming at the 19% practical limit. The future holds research and development opportunities aimed at increased cell performance and ultra low cost production methods.

TABLE I. - EFFECT OF COVER GLASSING ON SHORT-CIRCUIT CURRENT OF SOLAR CELLS

	SHORT-CIRCUIT CURRENT	
	SiO	Ta_2O_5
COATED CELL ONLY	142 mA	140 mA
COATED CELL WITH COVER GLASS AND ADHESIVE	138 mA	147 mA

TABLE II. - SUMMARY OF PRESENT HIGH EFFICIENCY SOLAR CELLS

DESCRIPTION	STATUS
HELIOS CELL	
20 Ω-CM	
P^+ BACK	IN PRODUCTION BY SPECTROLAB
SHALLOW JUNCTION	
THIN GRID FINGERS	
Ta_2O_5 AR COATING	
VIOLET CELL	
2 Ω-CM	
P^+ BACK	
VERY SHALLOW JUNCTION	NEARING PRODUCTION BY OCLI
FINE GRID FINGERS	
Ta_2O_5 AR COATING	
COMSAT NON-REFLECTIVE CELL	
ETCHED, LOW REFLECTION SURFACE	LABORATORY, NOT OPTIMIZED
OTHERWISE LIKE VIOLET CELL	COMSAT CORP.

TABLE III. - PERFORMANCE COMPARISON OF SILICON SOLAR CELLS

	1970 PRODUCTION CELL	HELIOS CELL	CNR CELL
SHORT CIRCUIT CURRENT, I_{sc}	138 mA	157 mA	181 mA
OPEN-CIRCUIT VOLTAGE, V_{oc}	545 mV	585 mV	595 mV
MAXIMUM POWER, P_{max}	55 mW	70 mW	83 mW
FILL FACTOR*, FF	73%	76%	77%
EFFICIENCY (AMO), η	10.2%	13%	15.3%

$$*FF = \frac{P_{max}}{V_{oc} I_{sc}} \times 100$$

TABLE IV. - NEAR TERM SOLAR CELL COST REDUCTION APPROACHES

IMPROVE MATERIALS UTILIZATION

- USE LARGER DIAMETER SINGLE CRYSTAL INGOTS
- REDUCE SAWING LOSSES
  USE ROUND CELLS
  REDUCE KERF LOSS

AUTOMATE CELL MANUFACTURING PROCESSES

- ELIMINATE VACUUM PROCESSES
  USE SCREEN PRINTING FOR CONTACTS
  USE "SPIN ON" TECHNIQUES FOR ANTIREFLECTION COATINGS
- ELIMINATE GASEOUS DOPANT SOURCES
  USE "SPIN ON" TECHNIQUES
  USE ION IMPLANTATION

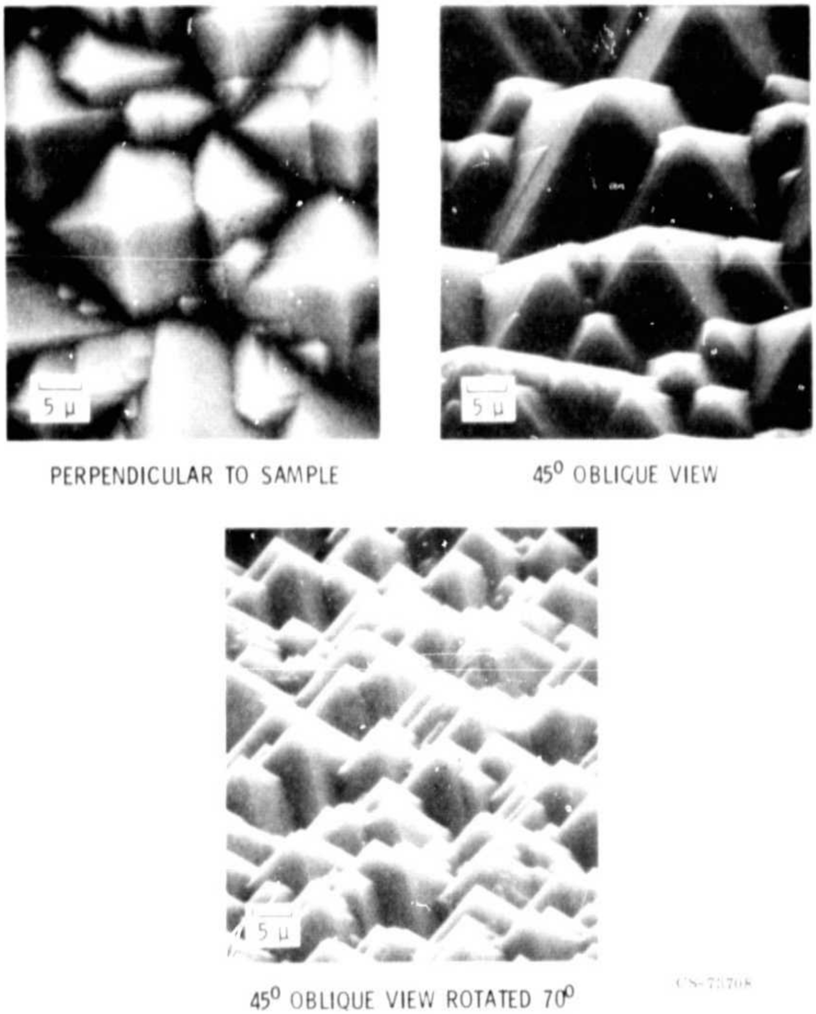

Figure 1. - Views of texturized surface.

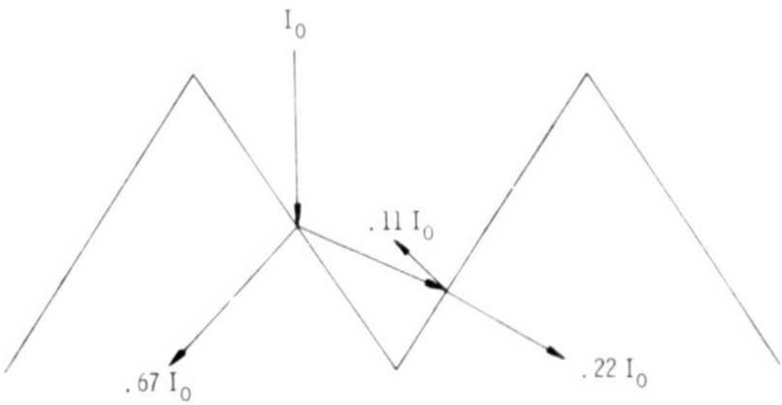

Figure 2. - Optical path diagram of tetrahedral texturized surface.

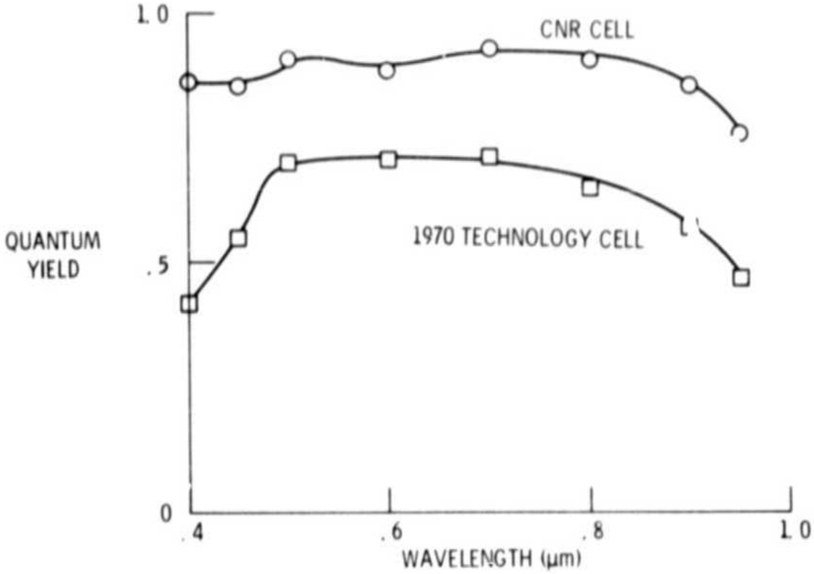

Figure 3. - Quantum yield comparison of solar cells.

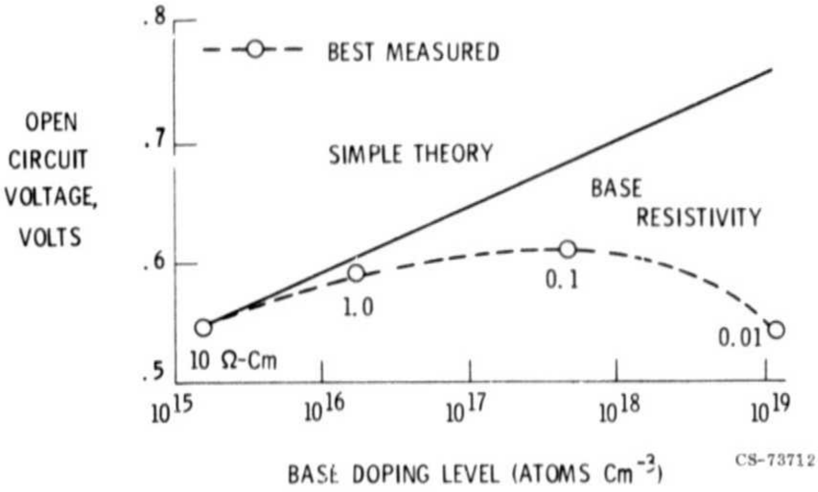

Figure 4. - Dependence of solar cell open circuit voltage on doping level.

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