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AUTOMATED ARRAY ASSEMBLY TASK

IN-DEPTH STUDY OF SILICON WAFER SURFACE TEXTURIZING

QUARTERLY TECHNICAL REPORT NO. 1

March 1979

Gregory T. Jones, Sanjeev Chitre

Sang S. Rhee, Kimberly L. Allison

JPL CONTRACT NO. 955266

Sensor Technology, Incorporated
21012 Lassen Street
Chatsworth, California 91311

"The JPL Low-Cost Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE".

PREFACE

The information presented in this report on silicon wafer surface texturizing represents the work performed from December 14, 1978 through March 31, 1979 by Sensor Technology, Inc., in Chatsworth, California. The program is directed by Sang S. Rhee. The principle contributors include Gregory T. Jones, Sanjeev R. Chitre, and Kimberly L. Allison.

The JPL Technical Program Manager is David Moffett.

ABSTRACT

Work on an "In-depth Study of Silicon Wafer Surface Texturizing", part of the JPL Automated Array Assembly Task, a Low-Cost Solar Array Project, was conducted during this quarter. This project covers the period from December 14, 1978 to March 31, 1979.

Four tasks were investigated in this program. Identification of Freon recycling as a low-cost wafer cleaning method was made. An ultrasonic vapor degreaser that utilizes the Freon recyling technique was ordered. Equipment was acquired to produce clean dry air. It was concluded that the low cost clean dry air system can replace the high cost dry nitrogen system without any adverse effects in the solar cell electrical performance. The texturizing process time in large scale production was found to be variable when chemical concentrations and temperatures in the two stage texturizing process were held constant.

The introduction of a low temperature intermediate gettering step in combination with a two stage texturizing process sequence was shown to produce a large improvement in solar cell efficiencies. Gettering improved the quality of silicon wafer material. Experimental results also showed that gettering improved the electrical performance of spray-on doped solar cells. Sensor Technology's standard production process utilizing the gettering treatment produced an average batch efficiency of 13.3 percent. The highest solar cell efficiency obtained from this batch was 14.3 percent.

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INTRODUCTION

The objectives of this program are to develop a low-cost wafer surface texturizing process which includes the cleaning and drying operations of silicon wafers as received from the silicon suppliers and a two stage texturizing process with gettering to enhance solar cell efficiency.

The specific tasks include: (1) low cost wafer cleaning, (2) low-cost wafer drying, (3) two stage wafer texturizing and (4) gettering process. Task (1) consists of an investigation of low-cost cleaning operations to clean residual wax and organics from the surface of silicon wafers as received from the silicon suppliers. Task (2) consists of an investigation of the feasibility of replacing dry nitrogen with clean dry air for drying silicon wafers. Task (3) involves a study of the two stage texturizing process for the purpose of characterizing relevant parameters in large volume applications. Task (4) consists of a study of the effect of gettering solar cells on photovoltaic energy conversion efficiency. The gettering method used involved the removal of unwanted impurities by thermal treatment in $POCl_3$ and subsequent removal of the phosphosilicate glass.

TECHNICAL DISCUSSION

TASK (1) LOW COST WAFER CLEANING

Silicon wafers initially received from the silicon manufacturer contain various amounts of organic surface contaminants. This nonuniformity of wafer surface cleanliness has been found to necessitate texturization process times in excess of five minutes in order to develop uniformly texturized surfaces. Consequently, it is essential that incoming silicon wafers be consistently cleaned prior to texturization in order to maintain a five minute texturization process cycle.

The wafer surface cleaning technique presently utilized by Sensor Technology, Inc., involves the use of trichloroethylene and methanol, which are expensive chemicals. In an effort to reduce the cost of the cleaning process without compromising wafer cleanliness, an alternative cleaning technique involving recycled Freon is being pursued. A Model DS-10R-3, Ultrasonic Vapor Degreaser, manufactured by Delta Sonics in Long Beach, California, has been placed on order. Delivery of this system is expected in the first week of June.

TASK (2) LOW COST WAFER DRYING

A clean air drying method is being investigated in an effort to reduce the wafer drying cost, which in the past has utilized dry nitrogen, an expensive inert gas. The wafer drying equipment to be utilized in this task consists of two components. The first component is an air cleaning unit that will reduce the moisture content of the air and remove oil and dust particles. The second component is an experimental wafer drying system which drys wafers by means of a clean air jet.

A refrigerated air dryer and air line filter manufactured by Arrow Pneumatics, Inc., Mundelein, Illinois were selected for supplying clean compressed air to the wafer drying system. The detailed specifications of this equipment are listed below:

Dryer: Model No. A-50
Capacity:50 SCFM
Refrigerant R-12
Charge:3 lbs.
Hp: ½ Volt:115/1/60
RLA 9.5 LRA 47.07
Refrigerant test pressure:High-250 psi
Low - 150 psi
Maximum working pressure air side:175 psi
Current setting of refrigerant:35 psi

Filter: Model No. Oilescer No. 3308
Particle size limit: 0.01 micron
Retention Efficiency: 99.95 $\pm$ .05%
Pressure drop at 50 CFM: 2 psi

A special feature of the Arrow system is a patented tube in the main heater exchanger tube, which contains an inner finned tubing to create turbulence for heat transfer and self cleaning action. The use of the Arrow Refrigerated Air Dryer prior to the use of the Arrow Filter, maximizes the performance and lifetime of the filter element. The primary function of the Arrow Air Filter is to remove harmful contaminants such as condensed moisture, pipe scale, dirt and rust from the incident air stream.

The complete Arrow Air Dry and Filter System was purchased and installed at Sensor Technology, Inc. Wafers were processed to check the clean air system performance capability. It was demonstrated that the low-cost clean dry air system can replace the high cost dry nitrogen system without any adverse effects on the solar cell electrical performance.

Sensor Technology's in-house spray-on equipment is being investigated to simulate a wafer drying system. This equipment contains a spray nozzle, conveyor, and I.R. oven.

An initial wafer drying test was performed. In this test, air was utilized at room temperature, with a pressure of 40 psi, a reciprocator speed of 90 cycles per minute, and a nozzle height of 2" from the wafer jig. The wafers emerging from the spray-on system under these test conditions were not consistently dried. In an effort to improve the consistency of the drying process, the existing spray-on system is being modified to accommodate a heating mechanism capable of supplying hot air.

TASK (3) TWO-STAGE TEXTURIZING PROCESS

Wafer surface texturizing involves the use of orientation dependent etches that reduce front surface solar cell reflection losses. The surface macrostructures produced by anisotropic sodium hydroxide etching have been found to significantly improve solar cell photovoltaic energy conversion efficiency. [1], [2], [3]

A two-stage texturizing process was developed which utilizes two NaOH and D.I. water etching solutions consisting of 10% NaOH by weight to D.I. water and 1% NaOH by weight to D.I. water, respectively. [1], [2] When the two-step texturizing process was applied in large scale production, the texturizing process time was found to be variable when chemical concentrations (10% and 1% NaOH solutions) and temperatures were held constant. Extensive experimentation yielded the result that consistent texturization process times strongly depend upon the initial wafer cleanliness. In these experiments, trichloroethylene and methanol were utilized to clean the silicon wafers. The texturization processing time was found to lie within an interval of 5 to 10 minutes depending on the cleanliness of the wafers. Consequently, the optimization of the texturizing process can be achieved if incoming wafer cleanliness is consistently maintained. To this end, the successful completion of Task 1 (lower cost wafer cleaning study) should lead to the optimization of the texturizing process time.

TASK (4) GETTERING PROCESS

The gettering method used in this task consisted of heating silicon wafers in the presence of $POCl_3$ to grow a phosphosilicate glass layer on the silicon surface followed by etching, or removal of the glass layer. Phosphosilicate glass gettering has been used for some time to remove unwanted electrically active impurities from silicon wafers.[4] It is the purpose of this study to determine whether phosphosilicate glass gettering during solar cell fabrication will serve to improve solar cell efficiencies.

The gettering process as described above, is ideally suited to be performed in conjunction with Sensor Technology's two stage texturization process (see Task 3), since either the one percent or ten percent NaOH etching steps performed in this process sequence would remove the gettered surface. Consequently, a series of experiments were carried out to study the gettering effect in conjunction with the two stage texturizing process on silicon solar cell electrical performance.

The overall program plan for the gettering task has three main objectives, which are: (1) to increase the average gettered solar cell efficiency with respect to the average efficiency of a controlled batch of ungettered solar cells, (2) to minimize the I-V curve dispersion for any batch of solar cells, and (3) to develop a reproducible gettering process.

The experimental approach in this quarter was directed toward analysis of four parameters, which are: (1) gettering step placement with respect to the two stage texturizing process, (2) gettering temperature, (3) silicon wafer material quality, and (4) silicon wafer size.

a) Preliminary Experiments "Series P"

Preliminary experiments were performed to investigate the gettering temperature and placement in the solar cell process. Four sample batches, which are designated "Series P," each consisting of twenty-five 3.35 inch (85mm)diameter silicon wafers were processed. The solar cells were processed with Sensor Technology's standard two stage (10%/1% NaOH) texturizing process sequence, $POCl_3$ diffusion step, electroless nickel plating step, aluminum back surface, solder and no A.R. coating. All solar cells have identical parallel track grid patterns. The solar cells were tested under a tungsten light source (G.E. Quartzline Lamp DWY, 2800°K) calibrated at $100mW/cm^2$ at 28°C).

Electrical performance data for Batches P-1 through P-4 were determined from the corresponding experimental I-V curves presented in Figures 1 through 4 respectively, and are summarized in Table 1.

Batch P-1 was not gettered and is designated as the control batch. From Figure 1 it is clear that Batch P-1 has a very large efficiency and fill factor dispersion which are designated in Table 1 by $\Delta\eta/\eta$(%) and $\Delta FF/FF$ (%). The lowest solar cell I-V curve in Figure 1 was not included in the calculations.

Batch P-2 underwent a high temperature (1000 C,35min) intermediate gettering step (gettering between the 10% NaOH and 1% NaOH steps in the two stage texturizing process sequence). Figure 2 clearly shows that Batch P-2 also has a very large

efficiency and fill factor dispersion. However, the average efficiency (a weighted average efficiency) of Batch P-2 is higher than the nongettered Batch P-1.

Batch P-3 was pregettered (gettered prior to the two stage texturizing process) at 875°C, 35 minutes. The I-V curves for the pregettered solar cells are shown in Figure 3. The average efficiency is higher and the efficiency and fill factor dispersion is smaller than the nongettered control Batch P-1. The pregettered batch is also characterized by two very low I-V curves which were not included in the dispersion calculations.

Figure 4 shows the I-V curves from Batch P-4. The solar cells have undergone an intermediate gettering step at 875°C, 35 minutes. The low temperature intermediate gettered solar cells have a significantly higher average efficiency and smaller average efficiency and fill factor dispersion than the nongettered control Batch P-1, the high temperature intermediate gettered Batch P-2, or the low temperature pregettered Batch P-3. The low temperature intermediate gettered solar cells are characterized by very well defined I-V curves and no low efficiency solar cells.

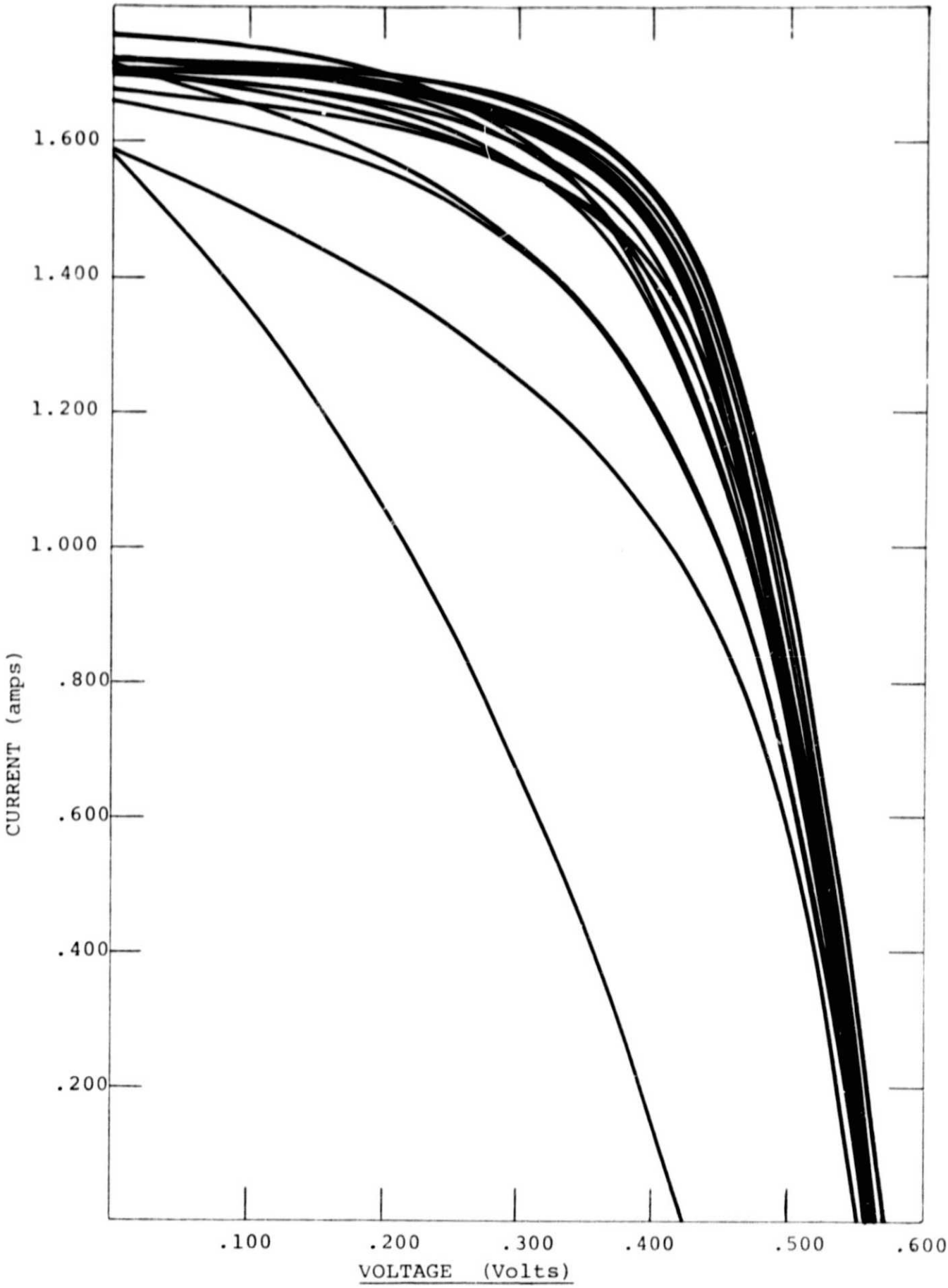


Figure 1. Electrical performance of 3.35 inch (85mm) diameter solar cells. The cells were texturized with a two-step process (10%/1% NaOH), $POCl_3$ diffused, and nickel plated with an Aluminum back.

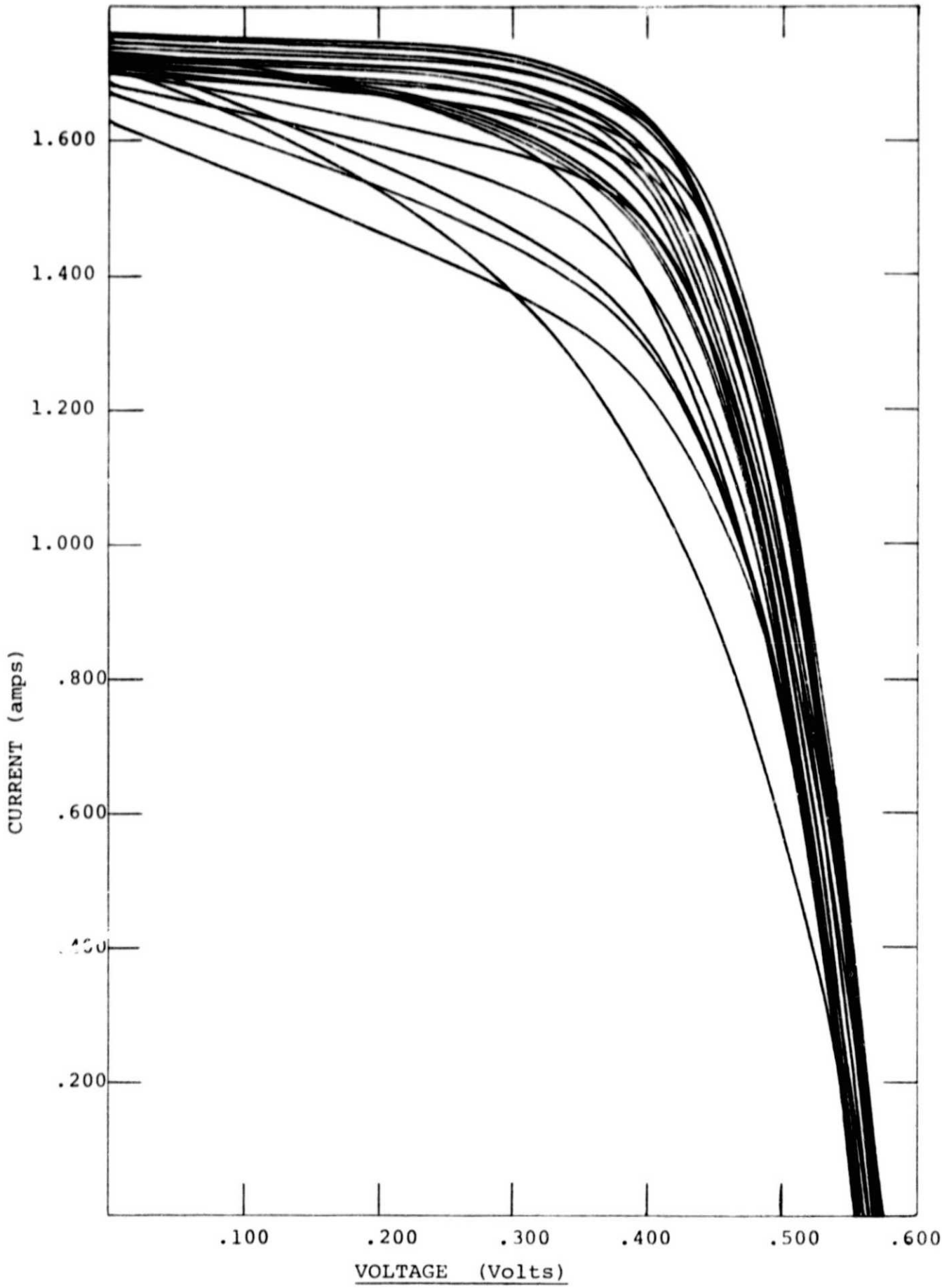


Figure 2. Electrical performance of 3.35 inch (85mm) diameter solar cells. The cells were texturized (10% NaOH), gettered (1000°C, 35 min), texturized (1% NaOH), $POCl_3$ diffused, and nickel plated with an Aluminum back.

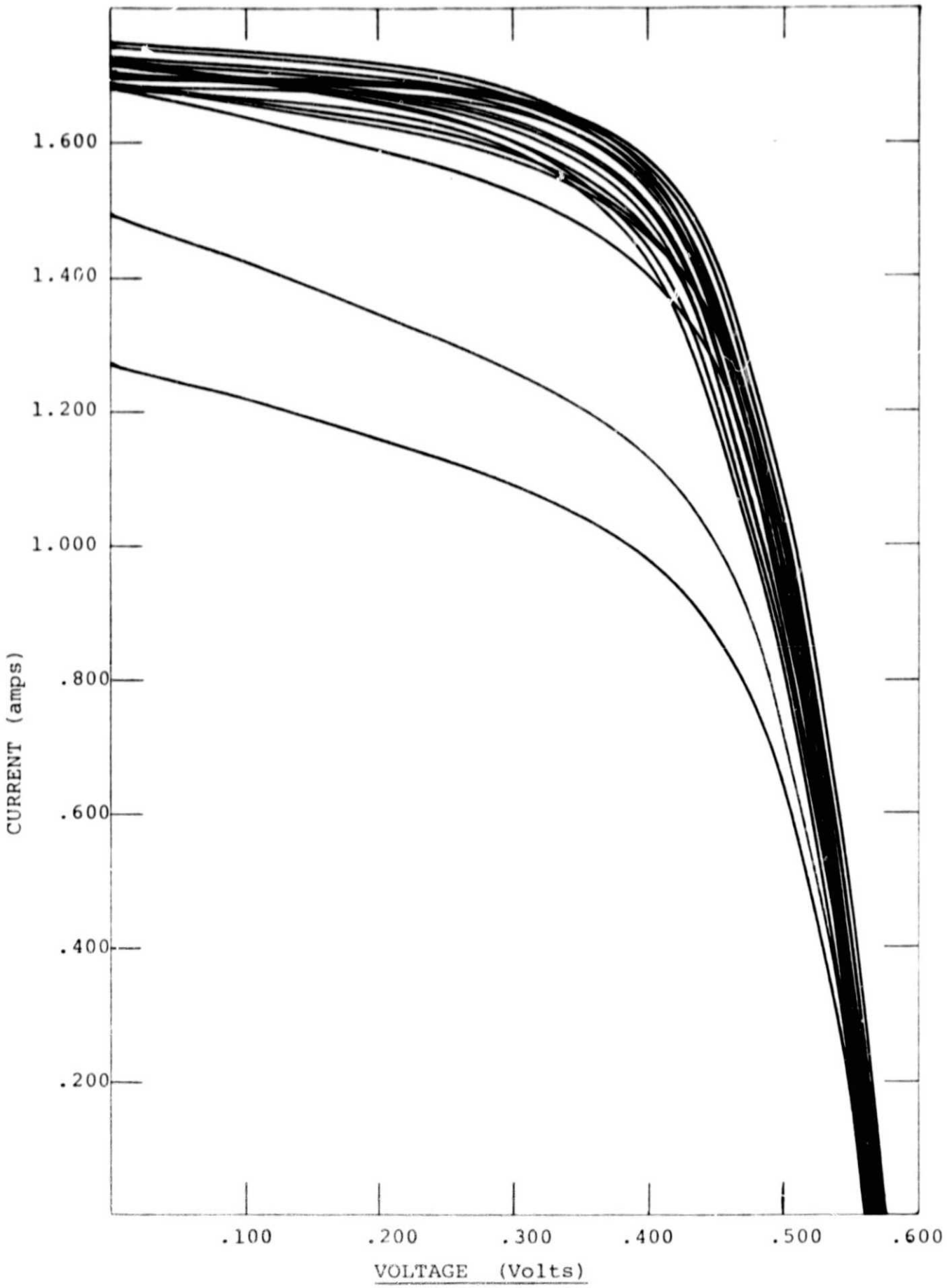


Figure 3. Electrical performance of 3.35 inch (85mm) diameter solar cells. The cells were pregettered (875°C, 35 min), texturized (10% NaOH/1%NaOH), $POCl_3$ diffused, and nickel plated with an Aluminum back.

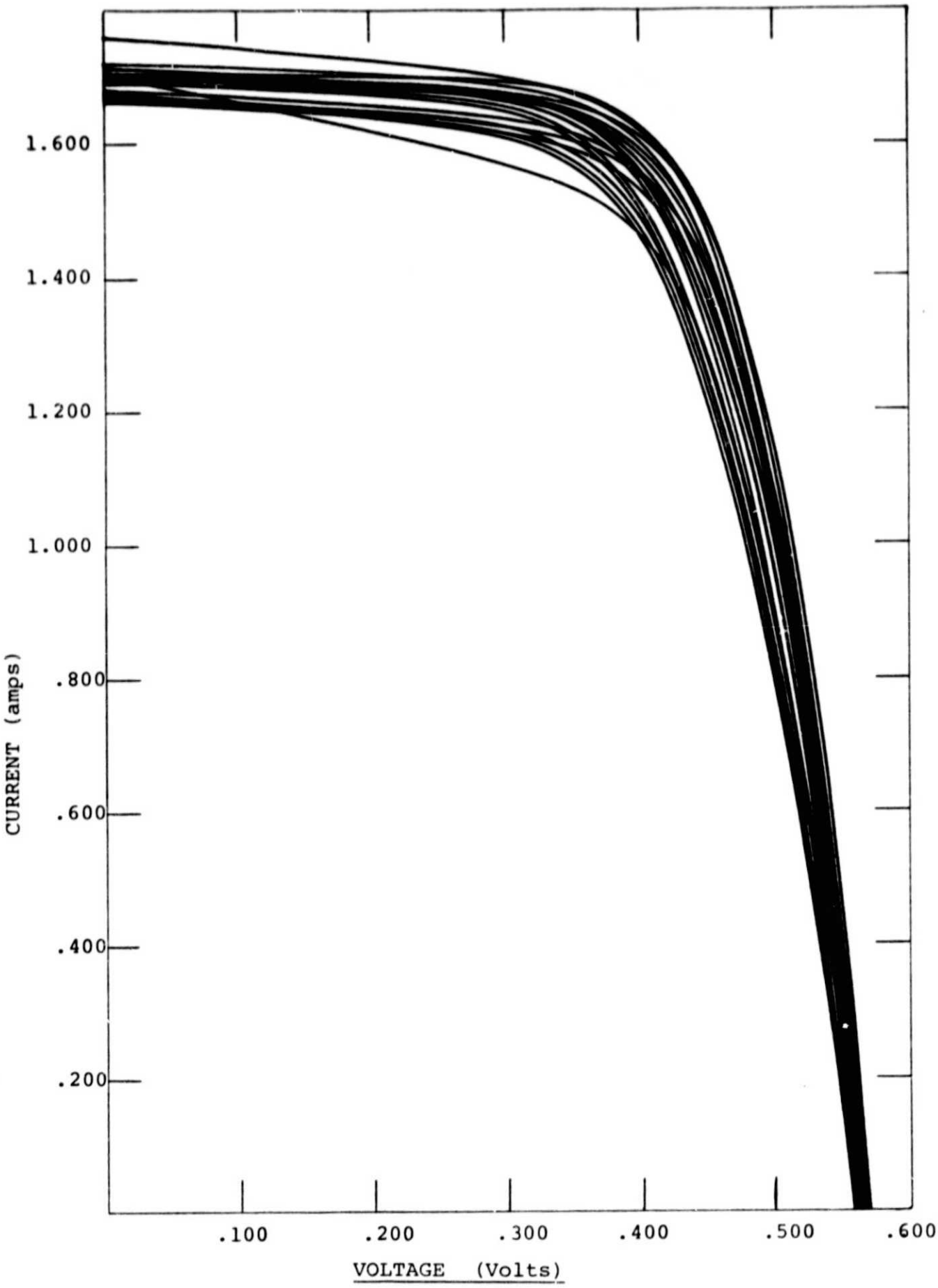


Figure 4. Electrical performance of 3.35 inch (85mm) diameter solar cells. The cells were texturized (10% NaOH), gettered (875°C, 35 min), texturized (1% NaOH), $POCl_3$ diffused, and nickel plated with an Aluminum back. -12-

TABLE 1. SOLAR CELL ELECTRICAL PERFORMANCE RESULTS SHOWING THE EFFECTS OF TEXTURIZING AND GETTERING 3.35 INCH (85MM) DIAMETER SILICON MATERIAL

Batch	I_{sc}(a)	V_{oc}(v)	I_{pp}(a)	V_{pp}(v)	η(%)	FF	$\frac{\Delta\eta}{\eta}$(%)	$\frac{\Delta FF}{FF}$(%)
P-1	Controlled cell, std. two step. tex., std. $POCl_3$ diff., nickel plated with an Aluminum back and no A.R. coating.							
High	1.72	.570	1.46	.415	11.02	.618	10.87	6.73
Low	1.59	.560	1.04	.400	7.56	.467	-23.94	-19.34
Wt. Ave.	1.67	.565	1.35	.405	9.94	.579		
P-2	Intermediate Gettering (1000°C, 35 min).							
High	1.76	.570	1.59	.420	12.14	.666	10.66	6.05
Low	1.70	.560	1.08	.400	7.85	.454	-28.44	-27.71
Wt. Ave.	1.70	.565	1.42	.425	10.97	.628		
P-3	Pre-gettering (875°C, 35 min).							
High	1.73	.580	1.54	.420	11.76	.645	7.69	5.05
Low	1.68	.570	1.36	.420	10.39	.596	- 4.85	- 2.93
Wt. Ave.	1.70	.575	1.43	.420	10.92	.614		
P-4	Intermediate gettering (875°C, 35 min).							
High	1.72	.575	1.55	.435	12.26	.682	5.78	3.65
Low	1.67	.565	1.39	.425	10.74	.626	-7.33	- 4.86
Wt. Ave.	1.70	.570	1.50	.425	11.59	.658		

The trends depicted in Table 1 suggest the following preliminary conclusions:

(1) Gettering improves average solar cell efficiencies.

(2) The best solar cell electrical performance takes place with an intermediate gettering step at a temperature of 875^{0}C for 35 min.

(3) Low temperature intermediate gettering produces solar cells with very small efficiency and fill factor dispersion. It therefore, appears that low temperature intermediate gettering will lead to batch to batch reproducibility.

b) Quality of Silicon Wafer Material

Additional gettering experiments were performed to evaluate the preliminary conclusions made in the previous section. Low and fair quality silicon wafer material was used in the analysis. In the context of this study, the quality of the silicon material will be defined in terms of the electrical performance or characteristic I-V curves for a batch of solar cells. A batch of solar cells is a group of solar cells processed together under (nearly) identical conditions.

Low quality silicon wafer material is characterized by a very large dispersion in short circuit current. The batch of solar cells is also characterized by a large dispersion in solar cell efficiencies and may be (but not necessarily be) characterized by a large dispersion in fill factor and a moderately large dispersion in open circuit voltage.

Fair quality silicon wafer material is characterized by a moderate dispersion in short circuit current. The batch of solar cells is also characterized by a moderately large dispersion in solar cell efficiencies and may be (but not necessarily be) characterized by a moderately large dispersion in fill factor and a small dispersion in open circuit voltage.

In the following discussion, low quality silicon wafer material will be designated as "Series A" and the fair quality silicon wafer material will be designated as "Series B". Also, the silicon wafer material designated as "Series P" and "Series C" is fair quality material.

c) Low Quality Silicon Wafers "Series A"

A gettering study was made on low quality, Czochralski, as cut silicon wafers. Four batches, which are designated "Series A", each consisting of twenty-five 1.406 (35.7mm) square silicon wafers were processed with Sensor Technology's two stage (10%/1% NaOH) texturizing process sequence, spray-on dopant junction formation (n+ front surface and p+ back surface), electroless nickel plating step, aluminum back surface, solder coating step, and no A.R. coating. These silicon wafers were cut (scribed then manually broken) by laserscribe from 2.25 inch (64mm) diameter round silicon wafers. The parallel track gridline pattern for the square solar cells was not optimized.

Electrical performance data for Batches A-1 through A-4 were determined from the corresponding experimental I-V curves presented in Figures 5 through 8 respectively, and are summarized in Table 2. The batches are differentiated on the basis of the location of the gettering step with respect to the two step texturizing process. Batch A-1 was not gettered and is delineated as the control batch.

The I-V curves from the control batch A-1, Figure 5, are presented along side of the I-V curves of the other three batches (Figure 6, 7, and 8) inorder to accentuate the effect of the gettering step.

Figures 5 and 6 compare the I-V curves of the control batch A-1 with batch A-2, Figure 6, which was not gettered but underwent SiO_2 removal. Batch A-2 shows a

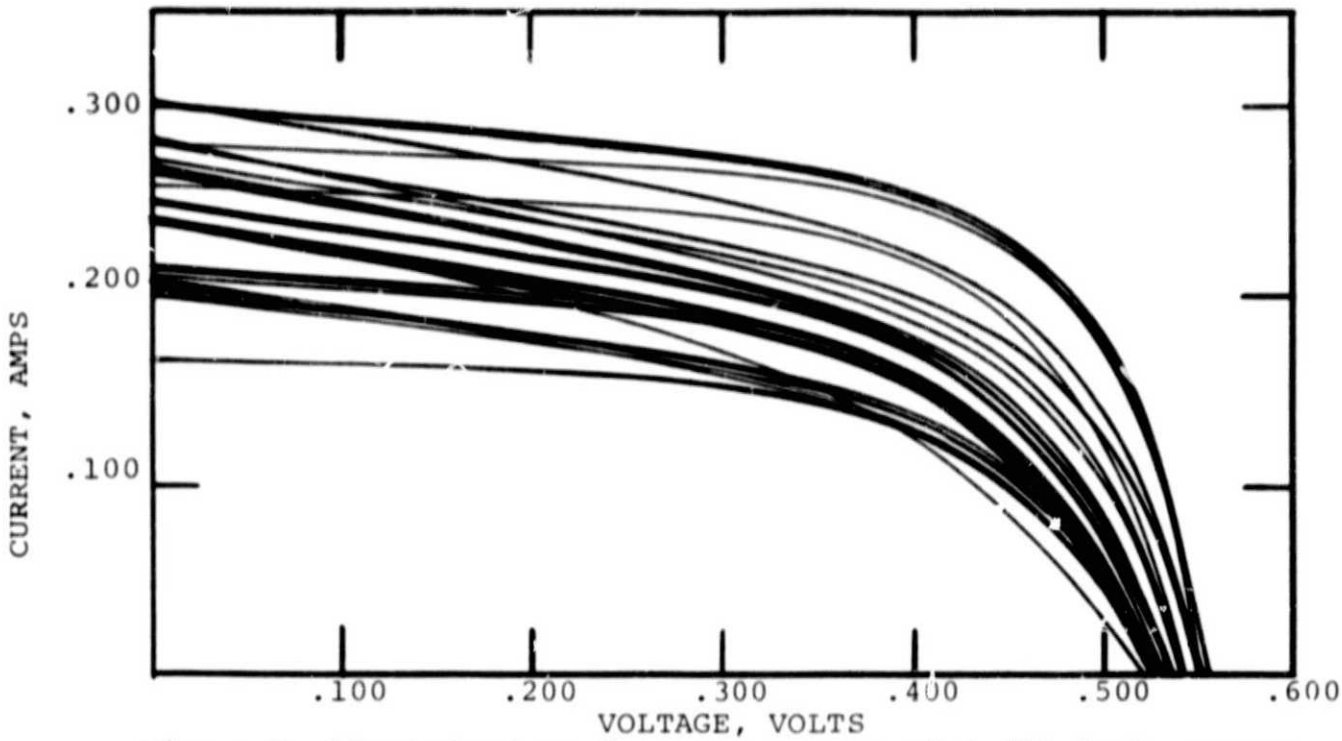


Figure 5. Electrical performance curves of 1.406 inch, square solar cells. The solar cells were texturized with a two step process (10%/1% NaOH), spray-on doped (both surfaces), nickel plated with no A.R.coating. They were tested at 100 mw/cm^2 and at 28^{o}C.

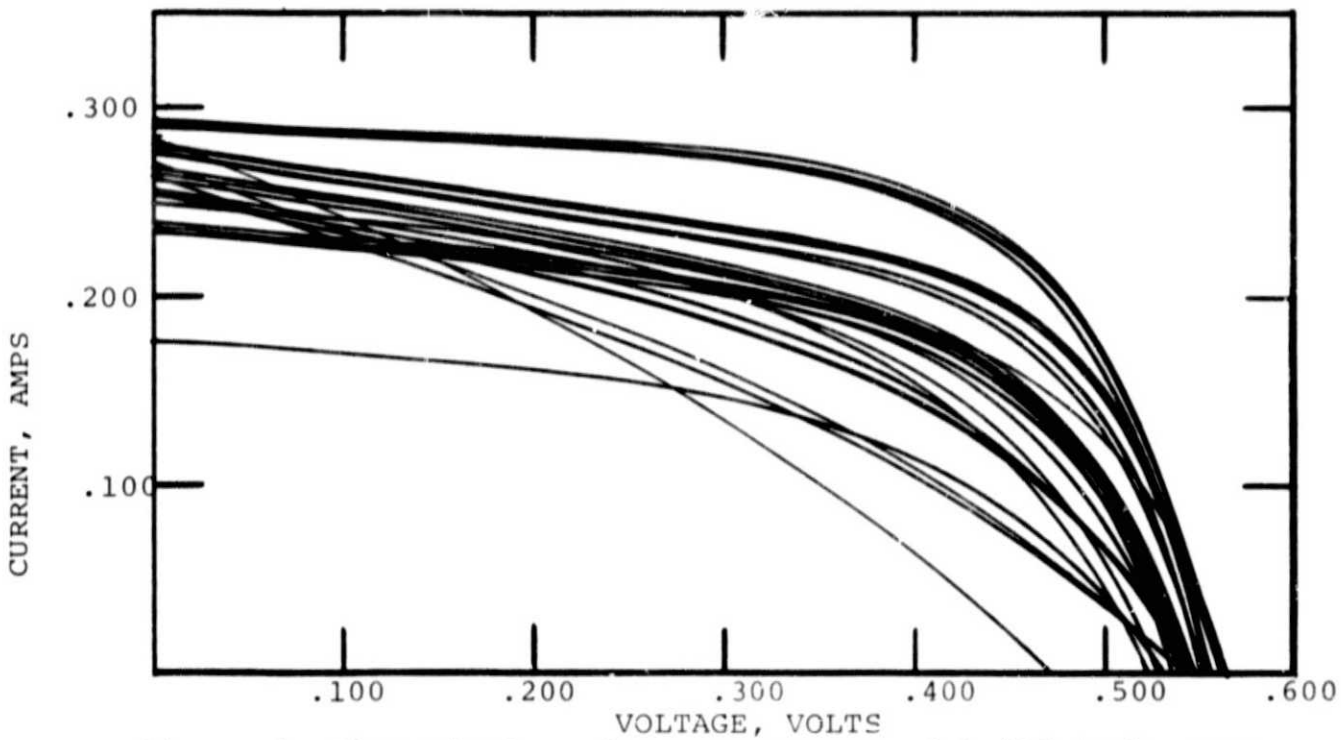


Figure 6. Electrical performance curves of 1.406 inch, square solar cells. The solar cells were texturized with a two step process (10%/1% NaOH), spray-on doped (both surfaces), nickel plated with SiO_2 glass removed. They were tested at 100mw/cm^2.

slight improvement in average photovoltaic energy conversion efficiency relative to the control batch. Batch A-2 has a large efficiency and fill factor dispersion.

Figures 5 and 7 compare the I-V curves of the control batch with batch A-3, Figure 7, which was gettered (875^0C, 35 min) prior to texturization. Batch A-3 shows a decrease in efficiency and fill factor dispersion relative to the control batch, as well as a relative improvement in average photovoltaic energy conversion efficiency.

Figures 5 and 8 compare the I-V curves of the control batch with batch A-4, Figure 8, which underwent intermediate gettering (875^oC, 35 min). Batch A-4 displays, by far, the narrowest efficiency and fill factor dispersion of all four batches, as well as the highest average efficiency.

The effect of SiO anti-reflective coating in conjuction with intermediate gettering is shown in Figure 9 and in Table 3. The lower set of curves in the figure correspond to Batch A-4 which had undergone an intermediate gettering step at 875^oC but no A.R. coating. The upper set of curves in the figure correspond to Batch A-5 which had undergone an intermediate gettering step at 875^oC for 35 minutes and SiO A.R. coating. Although both batches display a narrow efficiency and fill factor dispersion, the average efficiency of Batch A-5 with SiO A.R. coating is 21.46% higher than Batch A-4 without an A.R. coating.

A batch of solar cells, which underwent a $POCl_3$ diffusion step instead of spray-on dopant junction formation, was processed and tested for comparison with the spray-on

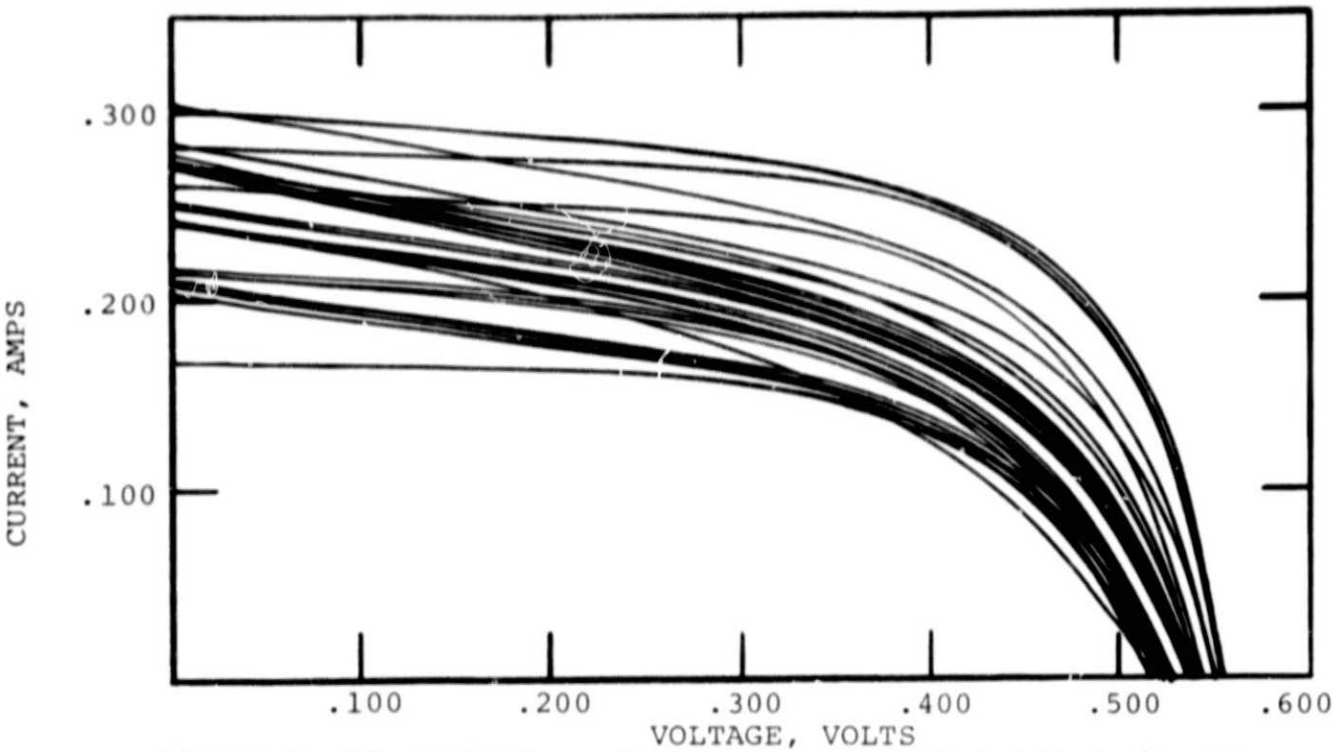


Figure 5. Electrical performance curves of 1.406 inch, square solar cells. The solar cells were texturized with a two step process(10%/1% NaOH), spray-on doped (both surfaces), nickel plated with no A.R.coating. They were tested at 100 mW/cm^2 and at 28°C.

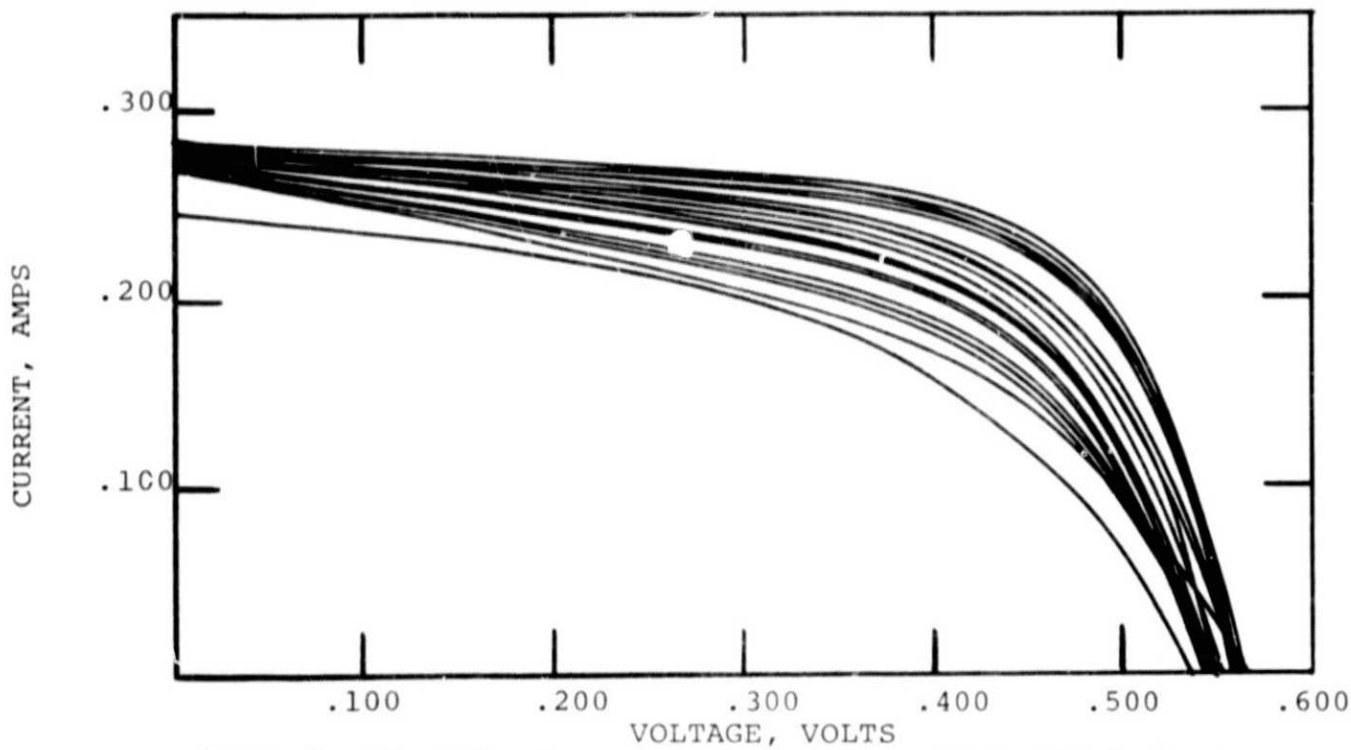


Figure 7. Electrical performance curves of 1.406 inch, square solar cells. The solar cells were gettered, texturized (10% NaOH), texturized (1% NaOH), spray-on doped (both sides), nickel plated, with no A.R.coating. They were tested at 100 mw/cm^2 and at 28°C.

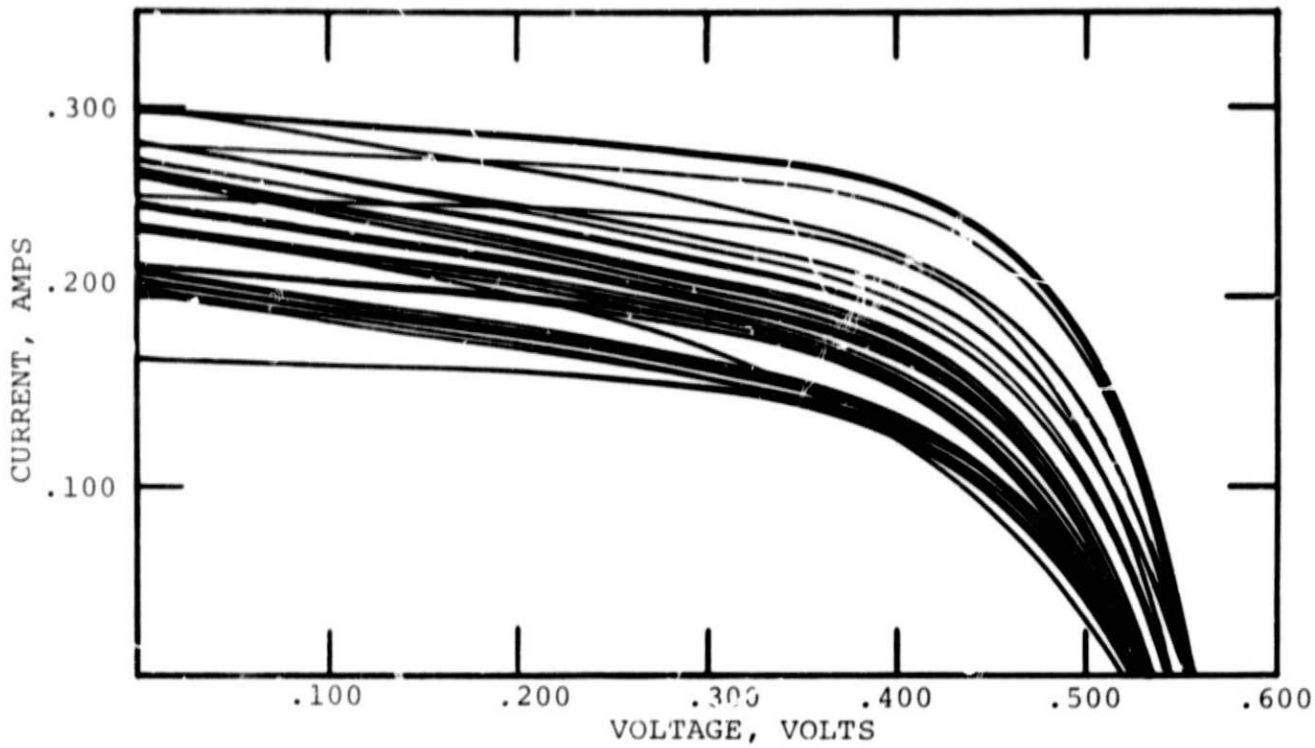


Figure 5. Electrical performance curves of 1.406 inch, square solar cells. The solar cells were texturized with a two step process (10%/1% NaOH), spray-on doped (both surfaces), nickel plated with no A.R.coating. They were tested at 100mW/cm^2

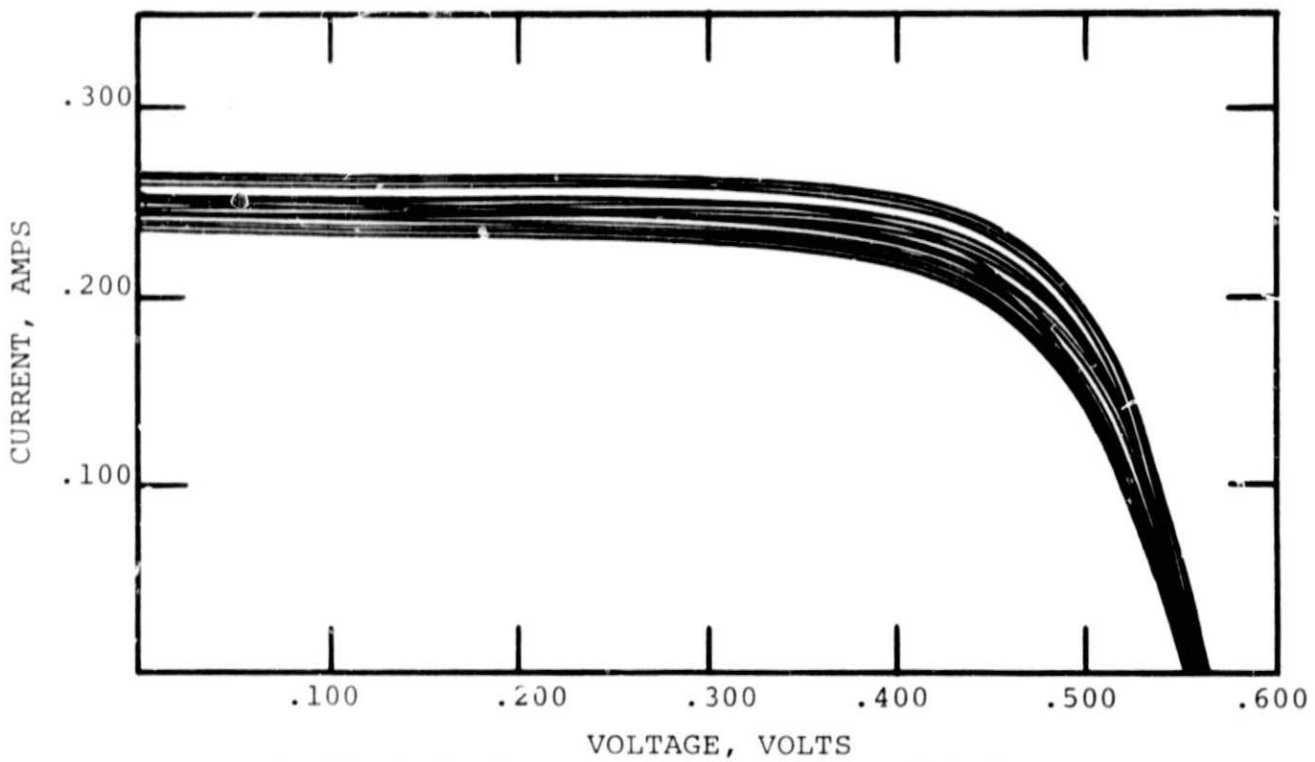


Figure 8. Electrical performance curves of 1.406 inch, square solar cells. The solar cells were texturized (10% NaOH), gettered, texturized (1% NaOH), spray-on doped (both sides), nickel plated, with no A.R.coating. They were tested at 100mW/cm^2 and at 28^{o}C.

Table 2. Solar cell electrical performance results on the effect of gettering and texturizing on low quality 1.406 inch, square silicon material.

BATCH	I_{sc} (a)	V_{oc} (v)	I_{pp} (a)	V_{pp} (v)	η (%)	FF	$\frac{\Delta\eta}{\eta}$ (%)	$\frac{\Delta FF}{FF}$ (%)
A-1 Solar Cells: 1.406 inch square, texturized (10%, NaOH), texturized (1% NaOH), spray-on doped (both sides), nickel plated, no A.R. coating.								
High	.300	.550	.235	.45	8.30	.64	+47.2	+16.4
Low	.200	.520	.105	.45	3.70	.45	-34.4	-18.2
Wt.Ave.	.245	.535	.160	.45	5.64	.55	--	--
A-2 Solar Cells: 1.406 inch square, texturized (10% NaOH) texturized (1% NaOH) spray-on doped (both sides, nickel plated, SiO_2 glass removed								
High	.290	.550	.28	.45	9.87	.79	+74.4	+41.1
Low	.235	.515	.10	.40	3.14	.33	-44.5	-41.1
Wt.Ave.	.240	.535	.17	.425	5.66	.56	--	--
A-3 Solar Cells: 1.406 inch square, gettered, texturized (10% NaOH), texturized (1% NaOH), spray-on doped (both sides) Nickel plated, no A.R.coating.								
High	.285	.560	.235	.455	8.38	.67	+18.9	+13.6
Low	.267	.535	.155	.40	4.85	.43	-31.2	-27.1
Wt.Ave.	.280	.545	.20	.45	7.05	.59	--	--
A-4 Solar Cells: 1.406 inch square, texturized (10% NaOH), gettered, texturized (1% NaOH), spray-on doped (both sides), nickel plated, no A.R.coating.								
High	.260	.565	.23	.465	8.38	.73	+8.0	+2.8
Low	.235	.555	.195	.45	6.90	.68	-11.1	- 4.2
Wt.Ave.	.250	.560	.22	.45	7.76	.71	--	--

doped solar cells. Batch A-6 consisting of twenty-five 1.406 (35.7mm) square silicon wafers was processed with Sensor Technology's two stage texturizing process sequence with no gettering step, $POCl_3$ diffusion step with no p+ back surface field, electroless nickel plating, aluminum back surface, solder and SiO A.R. coating. The electrical performance of Batch A-6 is shown in Figure 10 and is summarized in Table 3. The batch displays low average efficiency with high efficiency and fill factor dispersion.

From the preceeding discussion, it is clear that low temperature intermediate gettering in conjunction with an A.R. coating will lead to higher average solar cell efficiency and lower fill factor dispersion than ungettered or pregettered solar cells. A large improvement in average solar cell efficiency can be achieved using low temperature intermediate gettering for low quality silicon. The electrical performance of solar cells, which have been texturized and spray-on doped but not gettered, is very similar to the electrical performance of solar cells which have been texturized and $POCl_3$ diffused but not gettered. Spray-on doped solar cells, which are processed with a low temperature intermediate gettering step, have significantly higher efficiency and fill factor dispersion than diffused solar cells which are processed without a gettering step.

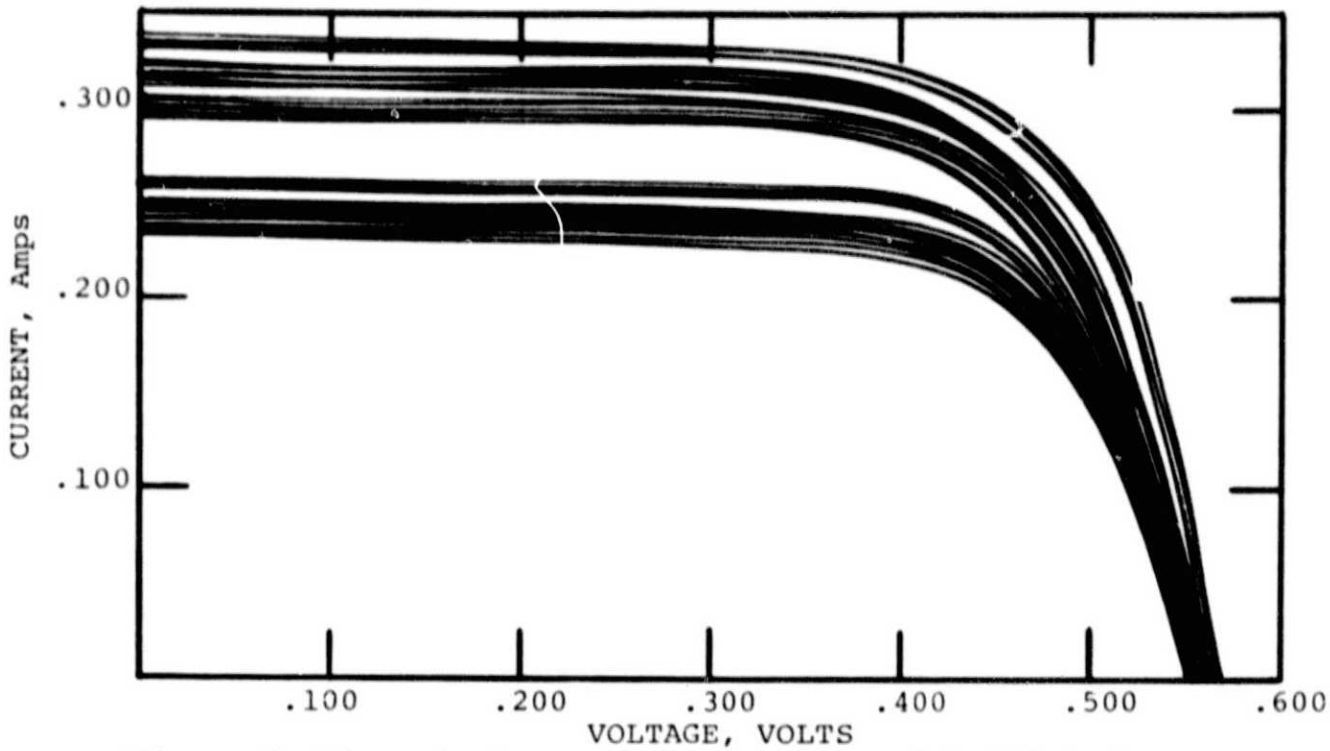


Figure 9. Electrical performance curves of 1.406 inch, square solar cells with and without SiO anti-reflective coating. The solar cells were texturized (10% NaOH), gettered, texturized (1% NaOH), sprayed-on (both surfaces), and nickel plated. They were tested at 100 mW/cm^2 and at 28^{o}C.

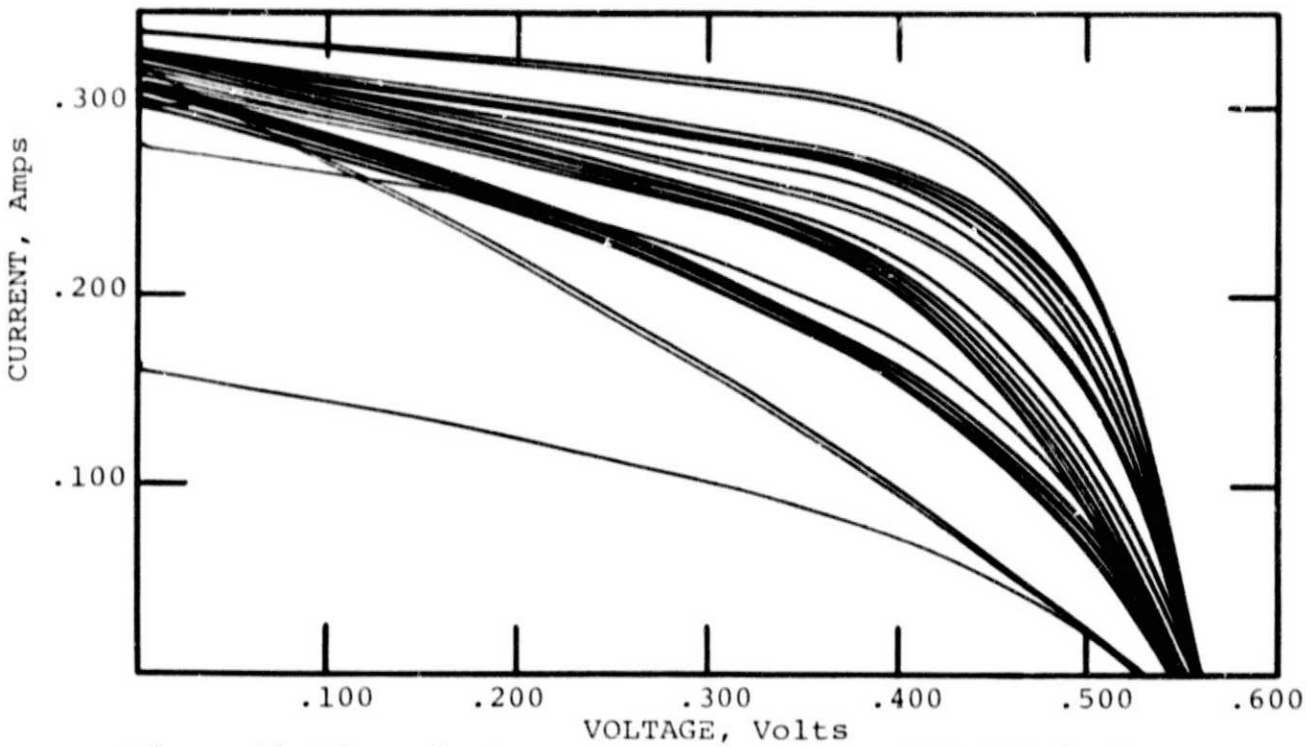


Figure 10. Electrical performance curves of 1.406 inch, square solar cells with $POCl_3$ diffusion and SiO anti-reflective coating. The solar cells were texturized with a two step process (10%/1% NaOH), aluminum back and nickel plated. They were tested at 100 mw/cm^2 and at 28^{o}C.

Table 3. Solar cell electrical performance results on the effect of gettering, texturizing and A.R.Coating on low quality 1.406 inch, square silicon material.

BATCH	I_{SC}(a)	V_{OC}(v)	I_{pp}(a)	V_{pp}(v)	η(%)	FF	$\frac{\Delta\eta}{\eta}$(%)	$\frac{\Delta FF}{FF}$(%)
A - 4 Intermediate gettering, spray-on doped (both sides)								
High	.260	.565	.23	.465	8.38	.73	+ 8.0	+ 2.8
Low	.235	.555	.195	.45	6.90	.68	-11.1	- 4.2
Wt.Ave.	.250	.560	.22	.45	7.76	.71		
A - 5 Intermediate gettering, spray-on doped (both sides), SiO.A.R. coating								
High	.330	.570	.300	.450	10.58	.72	+ 7.1	+ 1.4
Low	.295	.555	.255	.450	8.99	.70	- 9.0	- 1.4
Wt. Ave.	.315	.563	.280	.450	9.88	.71		
A - 6 No gettering, $POCl_3$ diffusion, SiO A.R.coating								
High	.335	.565	.265	.460	9.55	.64	+50.6	+39.1
Low	.160	.520	.075	.400	2.35	.36	-62.9	-21.7
Wt.Ave.	.320	.545	.180	.450	6.34	.46		

d) Fair Quality Silicon Wafers "Series B"

A gettering study was made on fair quality, Czochralski , as cut silicon wafers. Four batches, which are designated "Series B", each consisting of twenty-five three inch (76mm) diameter round silicon wafers were processed with Sensor Technology's two stage (10%/1% NaOH) texturizing process sequence, $POCl_3$ diffusion step, electroless nickel plating step, aluminum back surface, and solder coating step.

Electrical performance data for Batches B-1 through B-4 were determined from the corresponding experimental I-V curves presented in Figures 11 through 14 respectively, and are summarized in Table 4. The batches are differentiated on the basis of the location of the gettering step with respect to the two step texturizing process.

Batch B-1 was not gettered and is delineated as the control batch. From Figure 11 it is clear that Batch B-1 has a large efficiency dispersion.

Figure 12 shows the I-V curves from Batch B-2. The solar cells have undergone an intermediate gettering step at 875°C for 35 minutes. Batch B-2 has a significantly higher average efficiency and smaller efficiency and fill factor dispersion than the control Batch B-1.

Figure 13 shows the I-V curves from Batch B-3 which was pregettered at 875°C for 35 minutes. The average efficiency is higher and the efficiency and fill factor dispersion is smaller than the nongettered control Batch B-1. The average

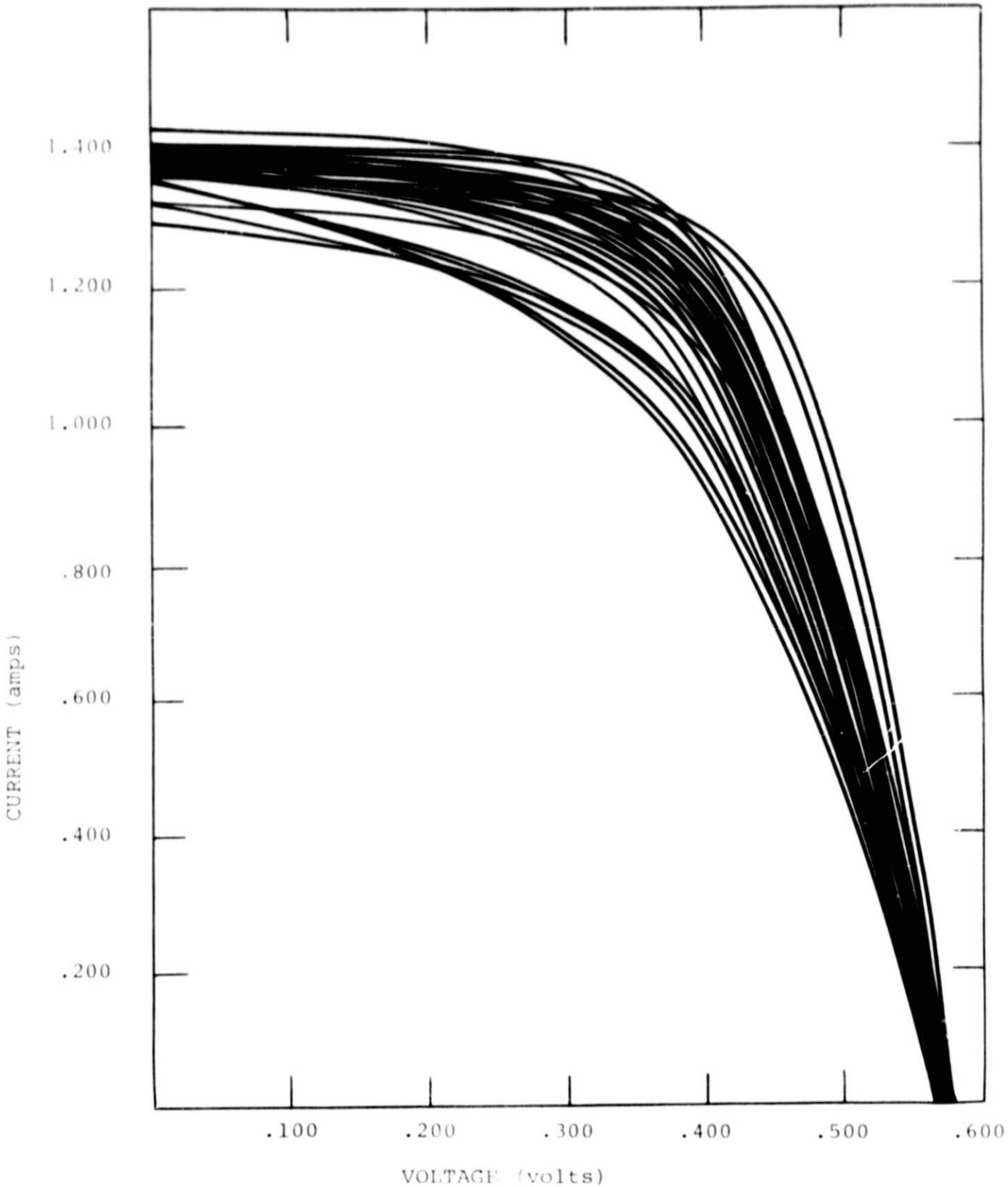


Figure 11. Electrical performance of 3 inch (76mm) nominal diameter solar cells. The cells were texturized with a two step process (10%/1%

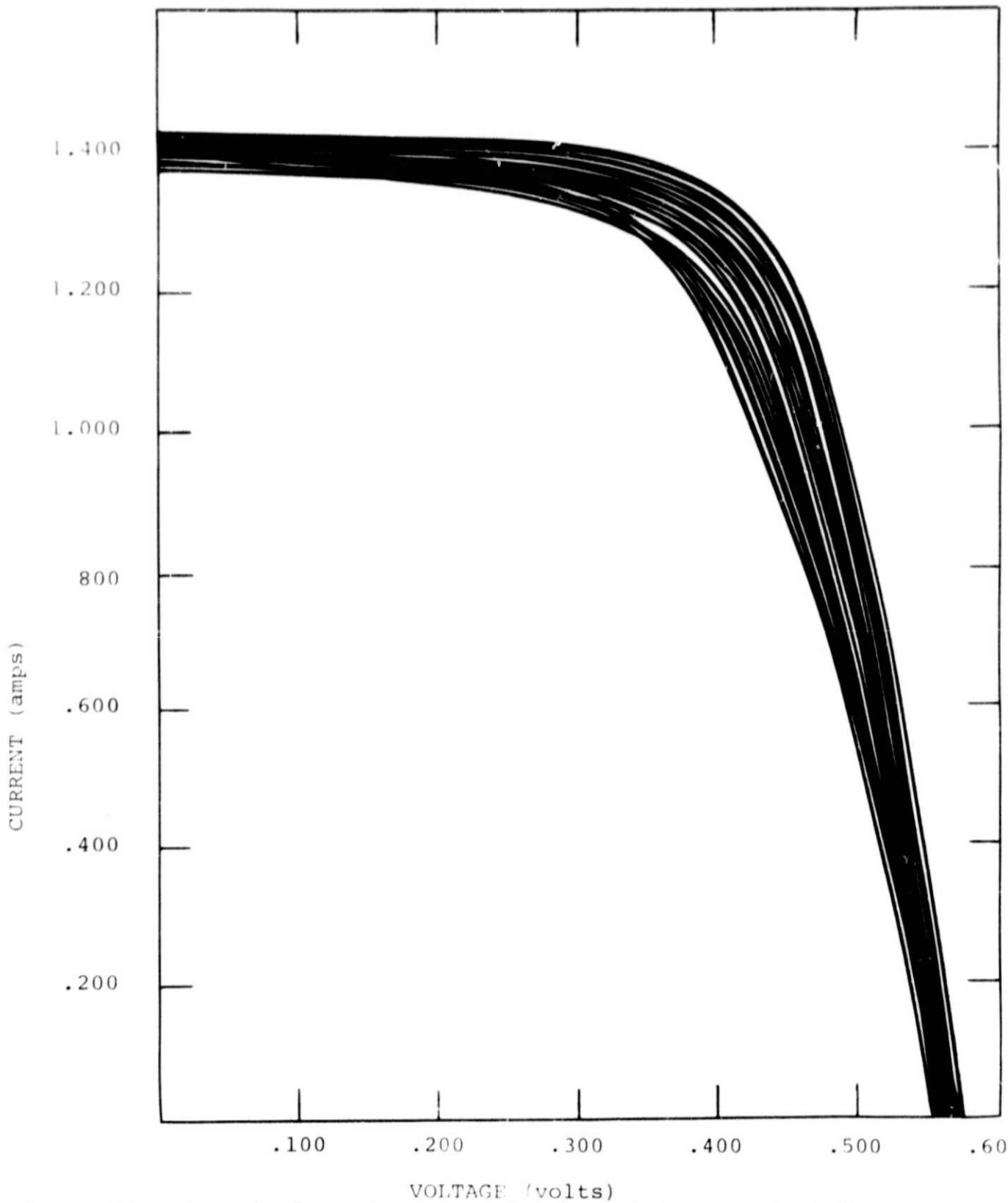


Figure 12. Electrical performance of 3 inch (76mm) nominal diameter solar cells. The cells were texturized (10% NaOH), gettered (875°C, 35 min), texturized (1% NaOH), $POCl_3$ diffused, nickel plated with an Al back, and were tested at 100mw/cm^2, 28°C.

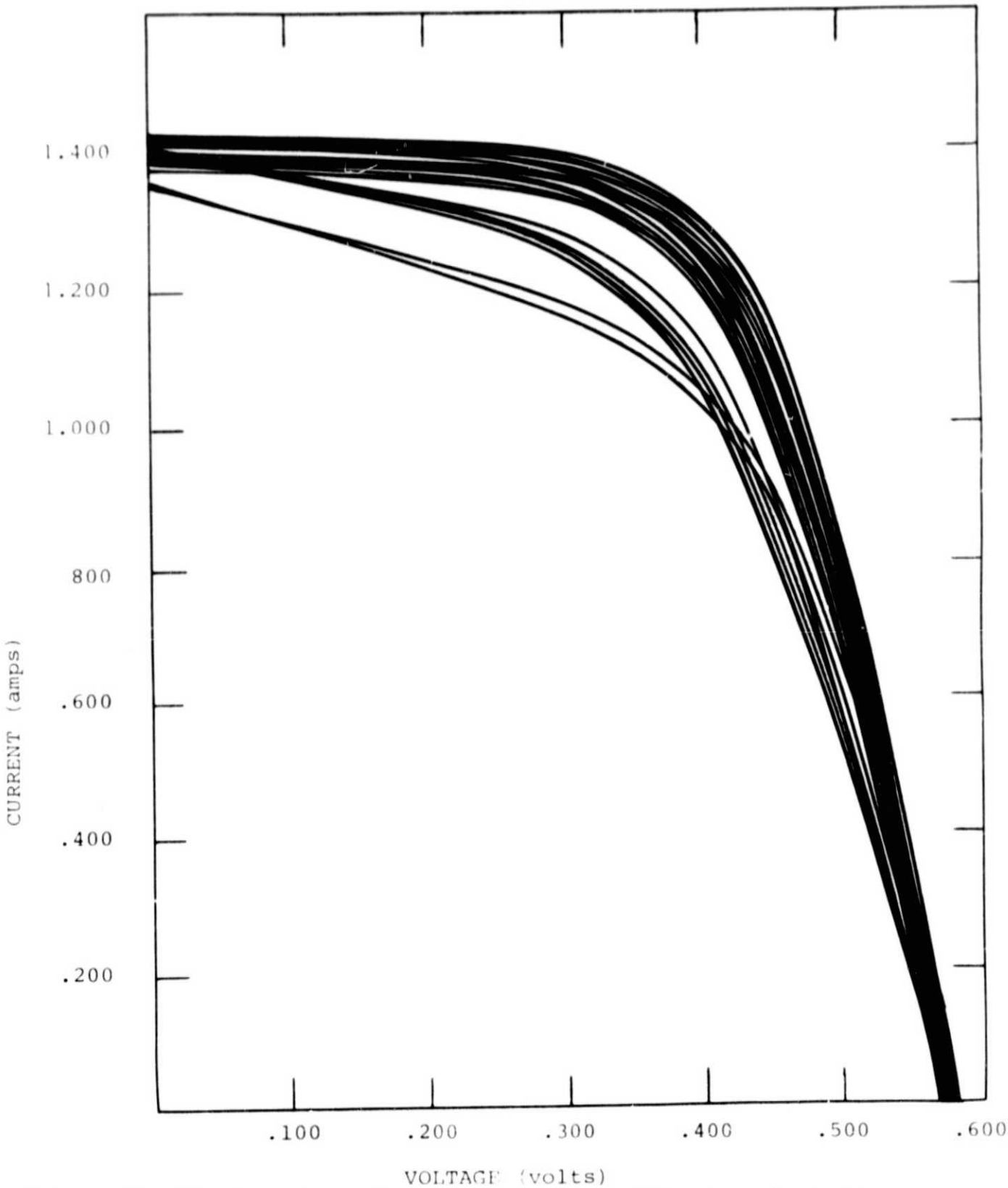


Figure 13. Electrical performance of 3 inch (76mm) nominal diameter solar cells. The cells were pregettered (875°C, 35 min), texturized (10% NaOH/1% NaOH), $POCl_3$ diffused, nickel plated with an Al back, and were tested at 100mw/cm^2, 28°C.

efficiency is lower and the efficiency and fill factor dispersion is slightly larger than the intermediate gettered Batch B-2.

The effect of SiO anti-reflective coating in conjunction with intermediate gettering is shown in Figure 14 and in Table 4. Batch B-4 has the highest average efficiency and the smallest efficiency and fill factor dispersions of all four batches. Batch B-4 solar cells with SiO A.R. coating had an increase in average efficiency of 8.0 percent over Batch B-2 solar cells without an A.R. coating (but with an SiO_2 glass surface). The highest efficiency obtained was 14.29 percent. The average solar cell efficiency for Batch B-4 was 13.28 percent.

From the preceeding discussion, it is clear that low temperature intermediate gettering in conjunction with an A.R. coating will lead to higher average solar cell efficiency and smaller efficiency and fill factor dispersion than ungettered or pregettered solar cells. A large improvement in average solar cell efficiency can be achieved using low temperature intermediate gettering for fair quality silicon.

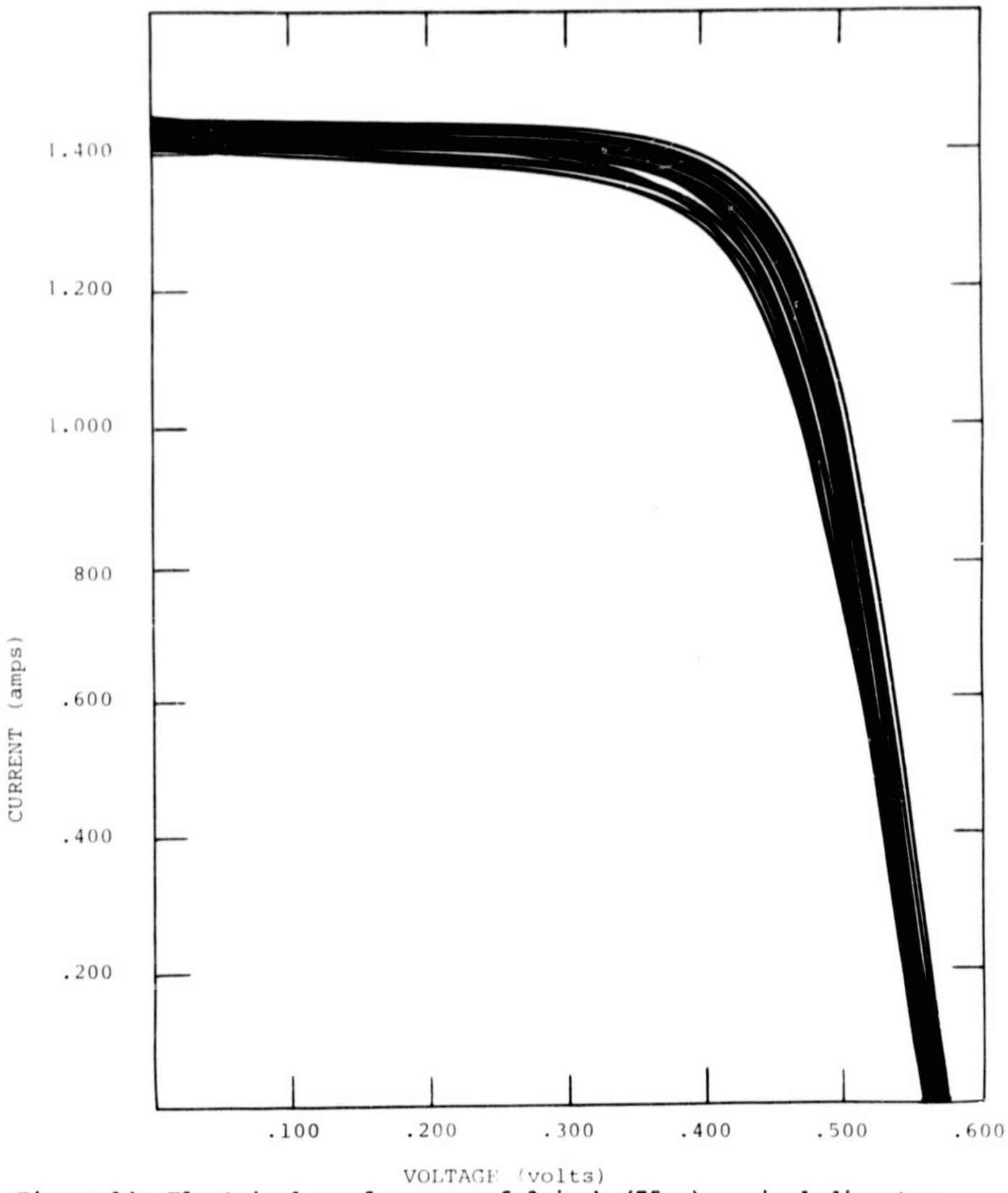


Figure 14. Electrical performance of 3 inch (75mm) nominal diameter solar cells. The cells were texturized (10% NaOH), gettered (875°C, 35 min), texturized (1% NaOH), $POCl_3$ diffused, nickel plated with an Al back, SiO A.R. coating and were tested at 100mw/cm^2, 28°C.

Table 4. Solar cell electrical performance results on the effects of gettering and texturizing on good quality 3 inch diameter round silicon material.

Batch	Isc (A)	Voc (V)	Ipp (a)	Vpp (v)	η (%)	FF	$\frac{\Delta\eta}{\eta}$ (%)	$\frac{\Delta FF}{FF}$ (%)
B-1. Controlled Cell, Std. Two Step Tex., Std. $POCl_3$ Diff. with Al Back								
High	1.40	0.580	1.22	0.435	12.82	0.654	16.55	15.14
Low	1.30	0.565	0.99	0.365	8.73	0.492	-20.64	-13.38
Wt.Ave.	1.38	0.580	1.20	0.38	11.00	0.568	--	--
B-2. Intermediate Gettering (with SiO_2 glass on surface)								
High	1.43	0.575	1.26	0.44	13.40	0.680	8.94	5.43
Low	1.40	0.555	1.20	0.37	10.71	0.559	-12.93	-13.33
Wt.Ave.	1.40	0.565	1.24	0.41	12.30	0.645	--	--
B-3. Pre-Gettering (with SiO_2 glass on surface)								
High	1.42	0.575	1.25	0.420	12.68	0.643	8.10	4.72
Low	1.37	0.560	1.10	0.370	9.83	0.531	-16.20	-13.52
Wt.Ave.	1.40	0.565	1.20	0.405	11.73	0.614	--	--
B-4. Intermediate Gettering with SiO AR Coating								
High	1.46	0.573	1.30	0.455	14.29	0.712	7.61	3.79
Low	1.40	0.555	1.20	0.43	12.46	0.664	-6.17	-3.21
Wt.Ave.	1.43	0.565	1.28	0.43	13.28	0.686	--	--

e) Gettering Temperature Effects "Series C"

Experiments were performed to study the effect of gettering temperature on solar cell electrical performance. Three batches, which are designated "Series C," each consisting of thirty three inch (76mm) diameter silicon wafers were processed with Sensor Technology's two stage (10%/1%) NaOH texturizing process sequence, intermediate gettering for 35 minutes, $POCl_3$ diffusion step, electroless nickel plating step, aluminum back surface, and solder coating step.

Electrical performance data for Batch C-1 through C-3 were determined from the corresponding I-V curves presented in Figures 15 through 17 respectively, and are summarized in Table 5. The batches are differentiated on the basis of the gettering temperature.

Batch C-1 was gettered at 1050^0C. From Figure 15 it is clear that Batch C-1 has very large efficiency and fill factor dispersions. The electrical performance of many solar cells were severely impaired at this gettering temperature.

Batch C-2 was gettered at 975^oC. Figure 16 clearly shows that Batch C-2 has a very large efficiency and fill factor dispersion. However, the average efficiency of Batch C-2 is higher than Batch C-1.

Batch C-3, was gettered at 900^oC. Figure 17 shows a well defined set of I-V curves. However, one I-V curve was low and was not included in the analysis shown in Table 5. Batch C-3 has significantly higher average efficiency and smaller efficiency and fill factor dispersions that Batch C-1 or C-2.

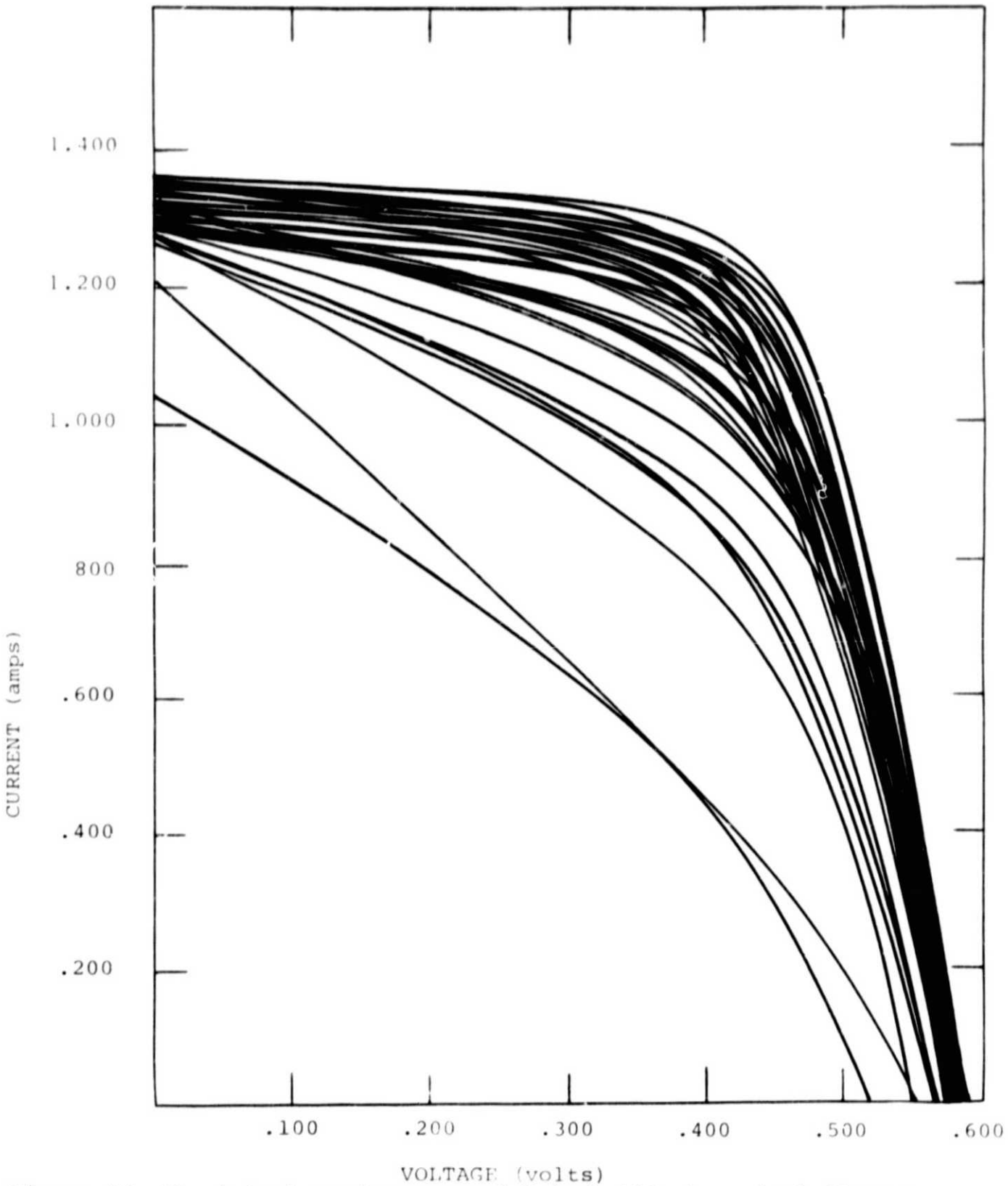


Figure 15. Electrical performance of 3 inch (76mm) nominal diameter solar cells. The cells were texturized (10% NaOH), gettered (1050^0C, 35 min), texturized (1% NaOH), $POCl_3$ diffused, nickel plated with an Al back and were tested at $100mw/cm^2$, 28^oC.

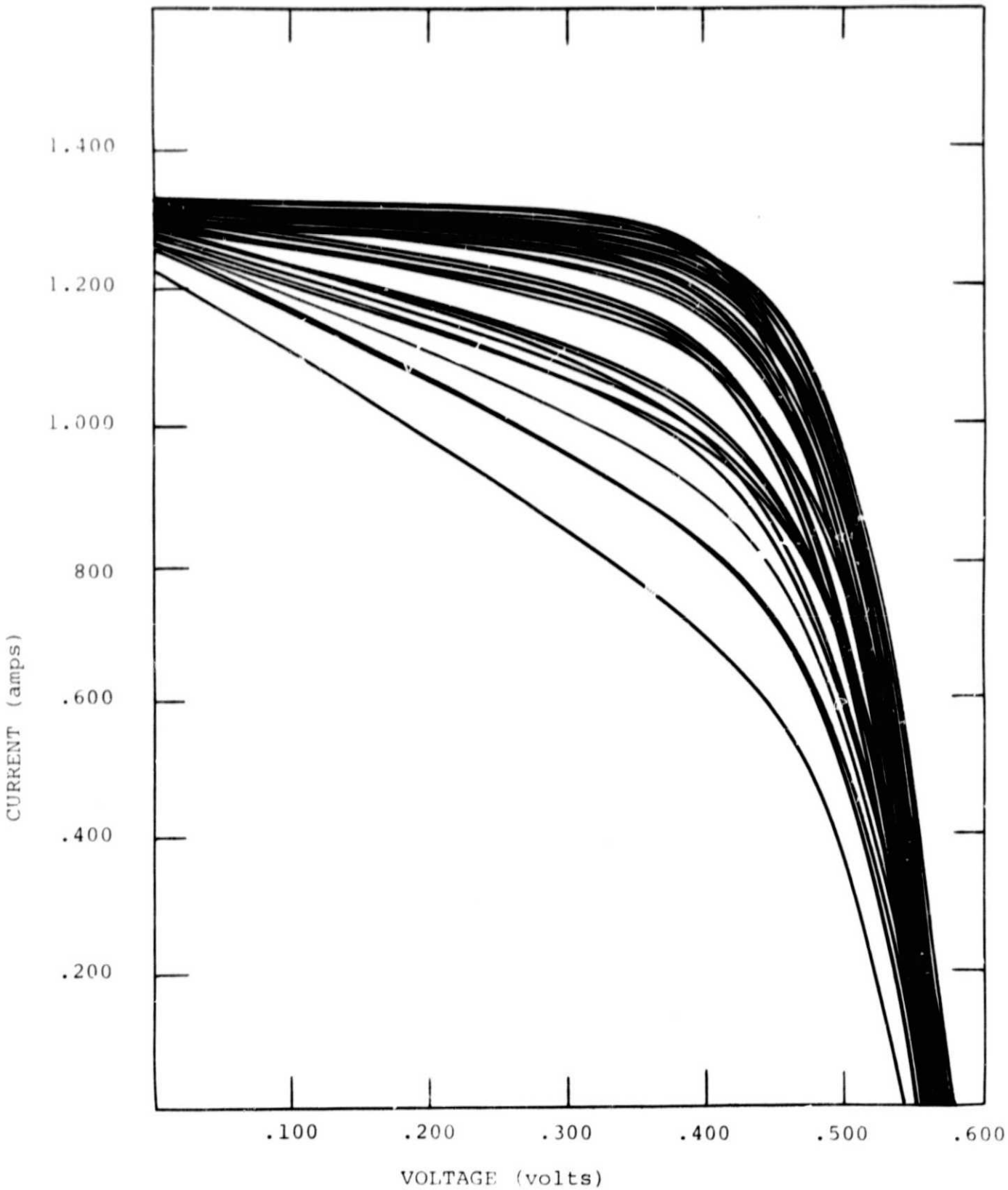


Figure 16. Electrical performance of 3 inch (76mm) nominal diameter solar cells. The cells were texturized (10% NaOH), gettered (975°C, 35 min), texturized (1% NaOH), $POCl_3$ diffused, nickel plated with an Al back and were tested at 100mw/cm^2, 28°C.

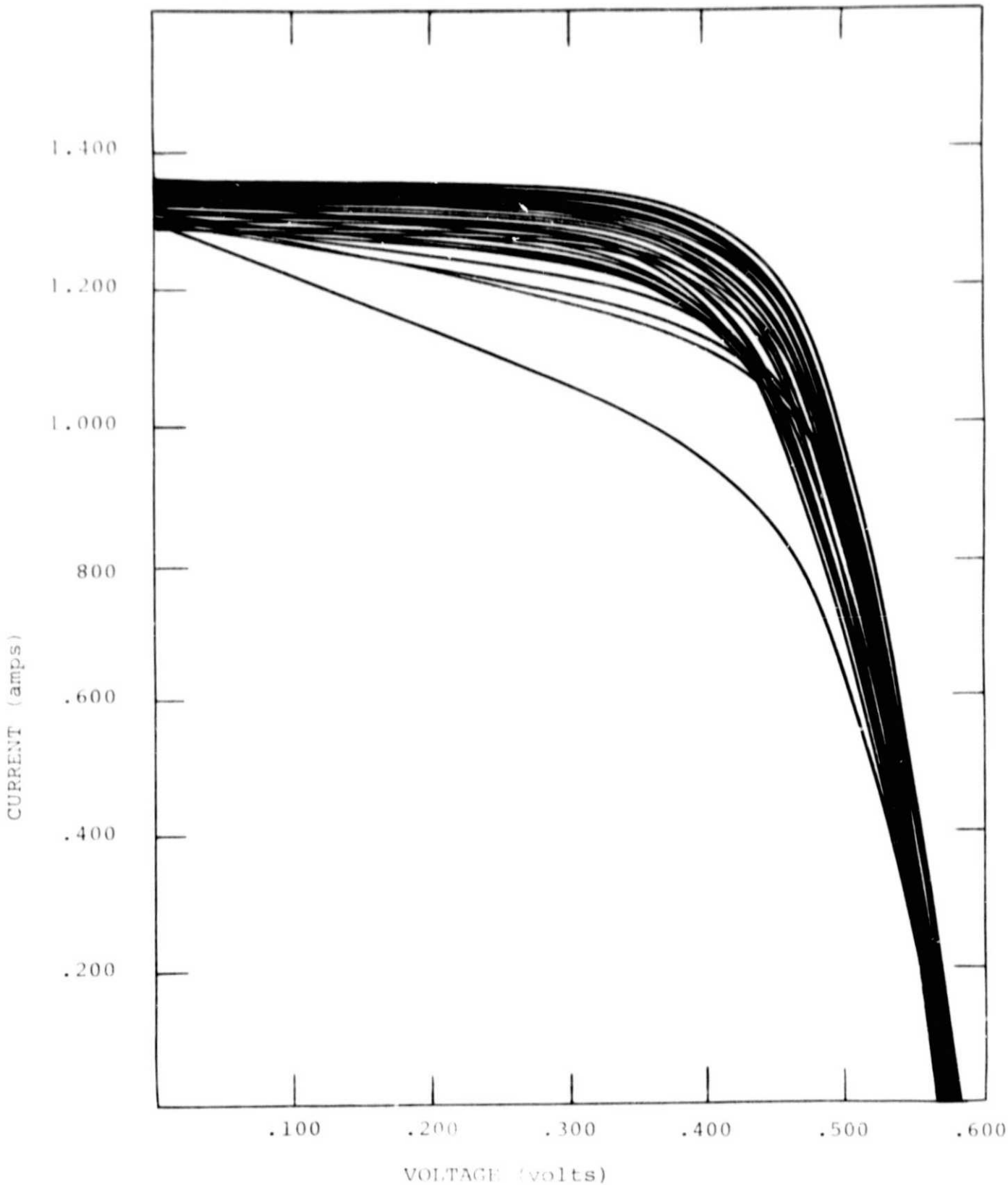


Figure 17. Electrical performance of 3 inch (76mm) nominal diameter solar cells. The cells were texturized (10% NaOH), gettered (900°C, 35 min), texturized (1% NaOH), $POCl_3$ diffused, nickel plated with an Al back and were tested at 100mw/cm^2, 28°C.

Table 5. Solar cell electrical performance results on the effects of intermediate gettering temperature on fair quality 3 inch round silicon material.

Batch	Isc (a)	Voc (v)	Ipp (a)	Vpp (v)	η (%)	FF	$\frac{\Delta\eta}{\eta}$ (%)	$\frac{\Delta FF}{FF}$ (%)
C-1. Intermediate Gettering 1050°C, 35 min , Std. Two Step Tex., Std $POCl_3$ Diff. Std. Electroless Nickel Plating, Al Back, Solder, no A.R. Coating.								
High	1.36	.585	1.22	.435	12.80	.667	18.63	12.27
Low	1.26	.565	.92	.420	9.32	.543	-32.35	-26.60
Wt.Ave.	1.30	.575	1.02	.425	10.46	.580	--	--
C-2. Intermediate Gettering (975°C, 35 min)								
High	1.32	.580	1.17	.45	12.70	.688	14.41	9.03
Low	1.22	.545	.63	.43	6.54	.407	-41.88	-35.50
Wt.Ave.	1.29	.565	1.07	.43	11.10	.631	--	--
C-3. Intermediate Gettering (900°C, 35 min)								
High	1.34	.585	1.23	.44	13.06	.690	7.58	3.29
Low	1.29	.570	1.03	.43	10.68	.602	-12.03	-9.88
Wt.Ave.	1.31	.575	1.17	.43	12.14	.668	--	--
B-2. Intermediate Gettering (875°C, 35 min)								
High	1.43	0.575	1.26	0.44	13.40	0.680	8.94	5.43
Low	1.40	0.555	1.20	0.37	10.71	0.559	-12.93	-13.33
Wt.Ave.	1.40	0.565	1.24	0.41	12.30	0.645	--	--

Batch B-2, Figure 12, was gettered at 875°C. and is included in Table 5 for comparison with Batches C-1, C-2, and C-3. Figure 12 shows a very well defined set of I-V curves. No I-V curves were found to be low in this batch of solar cells. Furthermore, no I-V curves were found to be low in Batches P-4 (Figure 4) A-4 (Figure 8) and A-5 (Figure 9). The results, therefore, show that 875°C is the optimium intermediate gettering temperature within the temperature range studied in this task.

CONCLUSIONS AND RECOMMENDATIONS

The work performed in the silicon wafer surface texturizing program this quarter has led to a number of conclusions and recommendations:

A low cost clean dry air system can replace a high cost dry nitrogen system without any adverse affects on solar cell electrical performance. The clean air unit acquired in this project effectively removed the moisture content of the air and eliminated oil and dust particles.

The texturizing process time in large scale production was found to be variable when chemical concentrations (10%/1% NaOH solutions) and temperatures in the two stage texturizing process were held constant. Extensive experimentation yielded the result that consistent texturization process times strongly depend upon initial wafer cleanliness. It is expected that the optimization of the texturizing process time can be achieved if incoming wafer cleanliness is consistently maintained by a pre-texturizing cleaning step.

A large improvement in average solar cell efficiency can be achieved by utilizing a low temperature gettering treatment in combination with a two stage texturizing process sequence. Intermediate gettering, which is performed between the two NaOH etching solutions in the two stage texturizing process, produced the highest average solar cell efficiency. The optimum intermediate gettering temperature and time was found to be 875^{o}C for 35 minutes, for the range of temperatures examined in this program. Low temperature intermediate gettering min-

imizes efficiency and fill factor dispersion and give good batch to batch reproducibility.

The gettering effect appears to be independent of the size of the silicon wafers. However, gettering has a significant effect on the quality of silicon wafer material. Silicon quality, as defined in this report, is characterized by the short circuit current, efficiency and fill factor dispersion for a batch of solar cells. Gettering improves the quality of silicon wafer material, that is, gettering raises the average short circuit current, and significantly reduces the short circuit current, efficiency, and fill factor dispersions.

The electrical performance of solar cells which have been texturized and spray-on doped, but not gettered, is very similar to solar cells which have been texturized and $POCl_3$ diffused, but not gettered. Spray-on doped solar cells which were processed with a low temperature intermediate gettering step, have significantly higher efficiencies and smaller efficiency and fill factor dispersions than spray-on doped solar cells or $POCl_3$ diffused solar cells which were not processed with a gettering step.

Sensor Technology's standard production process with intermediate gettering (includes a two stage texturizing process sequence in combination with a low temperature intermediate gettering step, $POCl_3$ diffusion, electroless nickel plating, aluminum back surface, solder and an SiO anti-reflective coating), produced the highest average batch efficiency of 13.3 percent. The highest solar cell efficiency obtained from this batch was 14.3 percent as measured under tungsten light at $100mW/cm^2$ and at $28^{\circ}C$.

PROGRESS SUMMARY AND PROGRAM PLAN

The progress summary and program plan for the In-Depth Study of Silicon Wafer Texturizing is shown in Table 6.

Table 6. Milestone Chart for In-Depth Study of Silicon Wafer Surface Texturizing

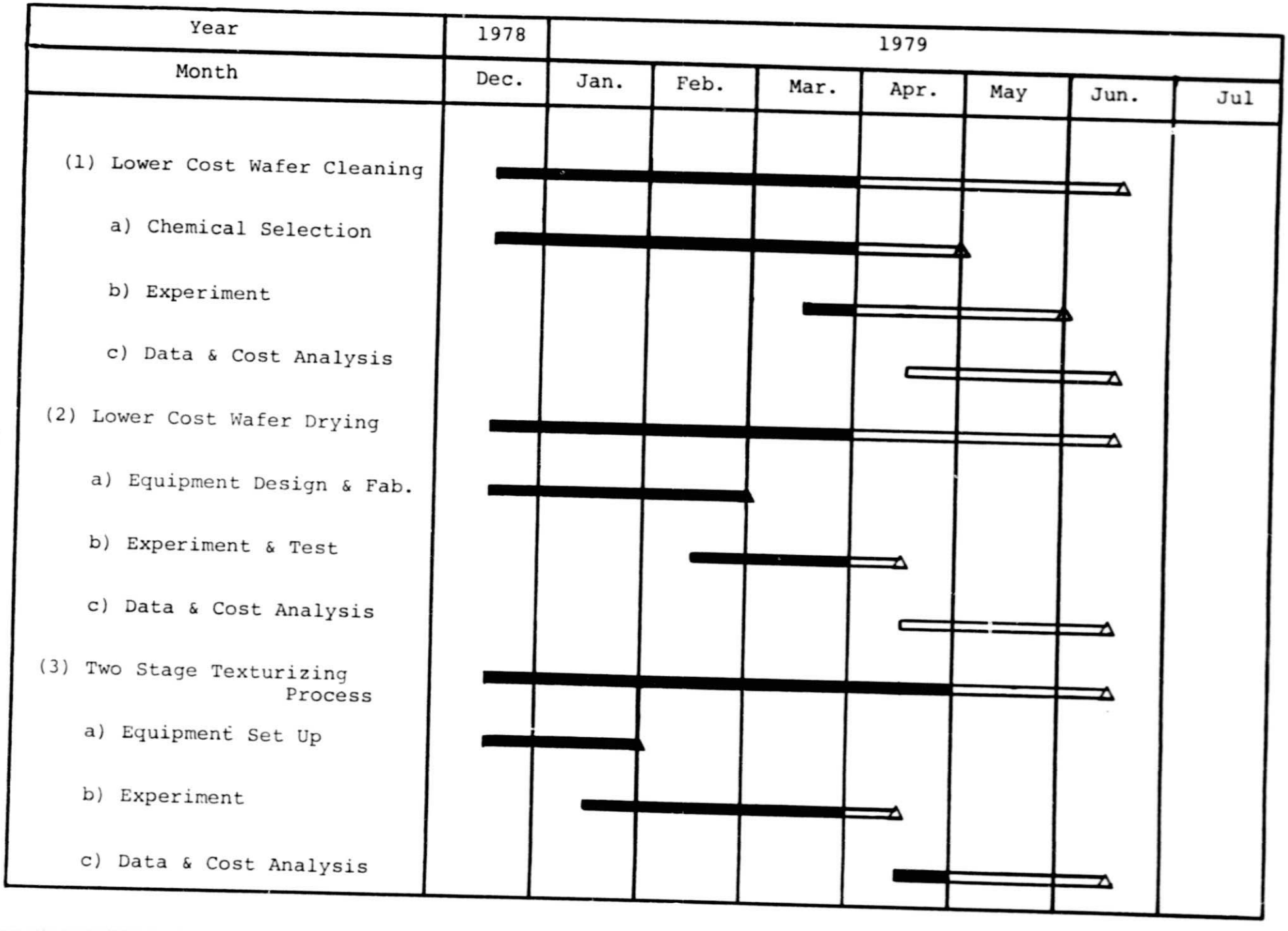
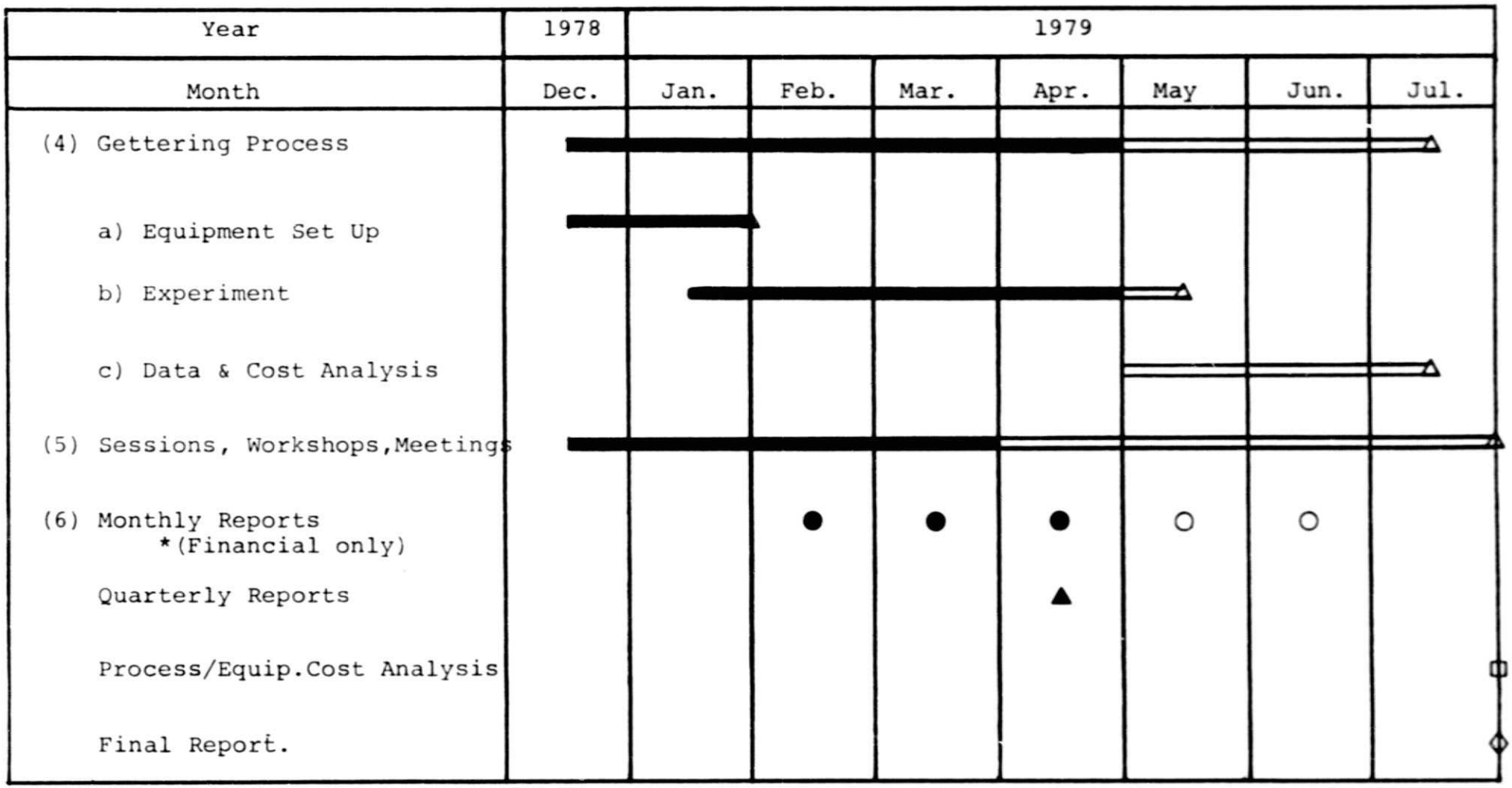


Table 6. (continued)



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