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SOLAR CELL PRODUCTION FACILITY

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by

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ABSTRACT

A technology to produce low cost solar cells was transferred to a microelectronics institution. Appropriate processing equipment was obtained and modifications to the procedure were performed which would permit the manufacture of 100-200, 3 inch diameter silicon solar cells per day.

ACKNOWLEDGEMENTS

The author wishes to express his thanks to Dr. H.D. Barber of Linear Technology Inc. for his advice on semiconductor production lines and to Dr. R. Clarke of Garrett Microcircuits for his assistance. Thanks are also expressed to Dr. J. Shewchun for his many words of encouragement.

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INTRODUCTION

The marketing of any semiconductor device is the result of 2 separate tasks which are necessary before a profitable device can be realized. These 2 tasks are the initial technological research and development of the desired device, and the transfer of this technology to mass production. Often this transfer can require as much painstaking time and energy as did the initial R&D before the production line is operating smoothly and has an acceptable yield.[1]

A high efficiency, 3 inch diameter solar cell had been developed at McMaster University.[2] It was necessary to transfer this technology to a site where appropriate facilities and equipment were available to set up a production line. All processing conditions had to be duplicated, however, with different equipment. In order to achieve a high production rate it was necessary to find automated equipment which could perform the same operations as a human but with greater speed and reliability. This would reduce manpower requirements and reduce the amount of individual wafer handling. The production line was set up in such a manner that handling of individual wafers was minimized and the entire line could be operated by at most only 3 workers.

The end result of this study was a solar cell production facility, occupying only a small corner of a large microcircuit manufacturing house, which was capable of producing 100-200, 10% (minimum) efficient, cells per day.

PREPRODUCTION SET UP

a) Facilities

Figure 1 shows a block diagram of the solar cell process.

As with any semiconductor processing, large amounts of toxic chemicals and corrosive acids are used during many of the process steps. For this reason it is necessary to have adequate ventilation and fume exhaust, not only for the safety of the operator but also to prevent cross-contamination of fumes from one processing step with those of another.

Another requirement is that of the availability of large amounts of ultrapure water. The cleaner the starting water, the lower the costs will be to purify this water to the desired level.

A large microcircuit manufacturer located in Toronto proved to be the best location to satisfy these criteria. This manufacturing company had appropriate facilities for solar cell production as well as expertise in the production line aspect of semiconductor devices in general which could be called upon should the need arise.

The actual area designated for solar cell production was situated in the southwest corner of the "thin film" room. Figure 2 illustrates the actual position and dimensions of the assigned area.

Included in this area was the use of 2 "fumehoods" equipped with sinks, water, N_2 gas, etc. In actuality these "fumehoods" are laminar flow benches which have a provision for exhaust. Figure 3 is a block diagram of the ducting and air flow in the bench.

There is no doubt the design of these work stations was intended for their use as laminar flow benches. With total recirculation (louver 2 open) and louver 1 closed, filter life can be greatly extended. However, with louver 1 open fully and louver 2 closed completely, reasonable fume removal can be obtained. It was necessary to close off louver 2 with ductape since the louvers did not provide an airtight seal. It was also found that better fume elimination occurred if fan 1 were left running and work with toxic fumes performed near the back and in the sink of the "fumehoods".

Figure 4 shows a layout of the work surfaces of the fumehoods and the placement of the various acids and solvents required for cell processing. All hot solutions are placed below the work surface down into the sink to reduce harmful fumes. As well, plastic partitions were erected between fuming baths to reduce any cross-contamination which could result.

A fundamental necessity in the production of any semiconductor device is high purity water. Although there was an in-house deionized water supply, the solar cell production area was located at the end of the water line. Thus its quality was deteriorated. It was necessary to polish this water to the desired quality for cell production. This was done using a three element Millipore Super-Q filtration unit. With an organic filter, deionizing column and final .22 micron millitube cartridge it was possible to get 18 megohm-cm water. Filter life was greatly extended since the input water was already of fairly high quality.

Water input pressures fluctuated considerably, depending upon usage of plant DI water by others in the building. The input pressure was seen to fluctuate between a high of 55 PSI and a low of 15 PSI. To help alleviate this problem and to obtain a faster flow of water, needed for all the outlets connected to the line, a water pump was connected to the input line. The teflon coated impellor would not contaminate the input water and the resulting input pressure only fluctuated by a maximum of 10 PSI. Figure 5 delineates the DI water system.

Also included in Figure 5 is a water return system, which could be installed, to take the used DI water, still of good quality, and recycle it through the filters for repolishing. This can greatly reduce DI water costs by extending filter life.[3]

A second necessary commodity which is often taken for granted in the laboratory is the nitrogen gas which is used for drying and providing the inert atmosphere during diffusion. The N_2 gas used at McMaster was the certified grade supplied by Canadian Liquid Air. Its specifications were as follows:

99.995 % N_2
16.2 ppm H_2O
20 ppm O_2
DP. -56.7 °C

Other grades of N_2 gas were also stocked by Canadian Liquid Air and others, however, nitrogen of higher purity also meant an increase in price, up to a factor of about 10 for the highest quality. The micro-circuit house also has N_2 gas. Unfortunately, this gas, of dubious purity, was supplied from their own liquid N_2 storage tank at the far end of the building. This gas was used in the plant only for blow drying and nothing as critical as providing a clean diffusion atmosphere, hence its quality was suspect. It was decided to continue using Canadian Liquid Air's certified nitrogen for all critical applications.

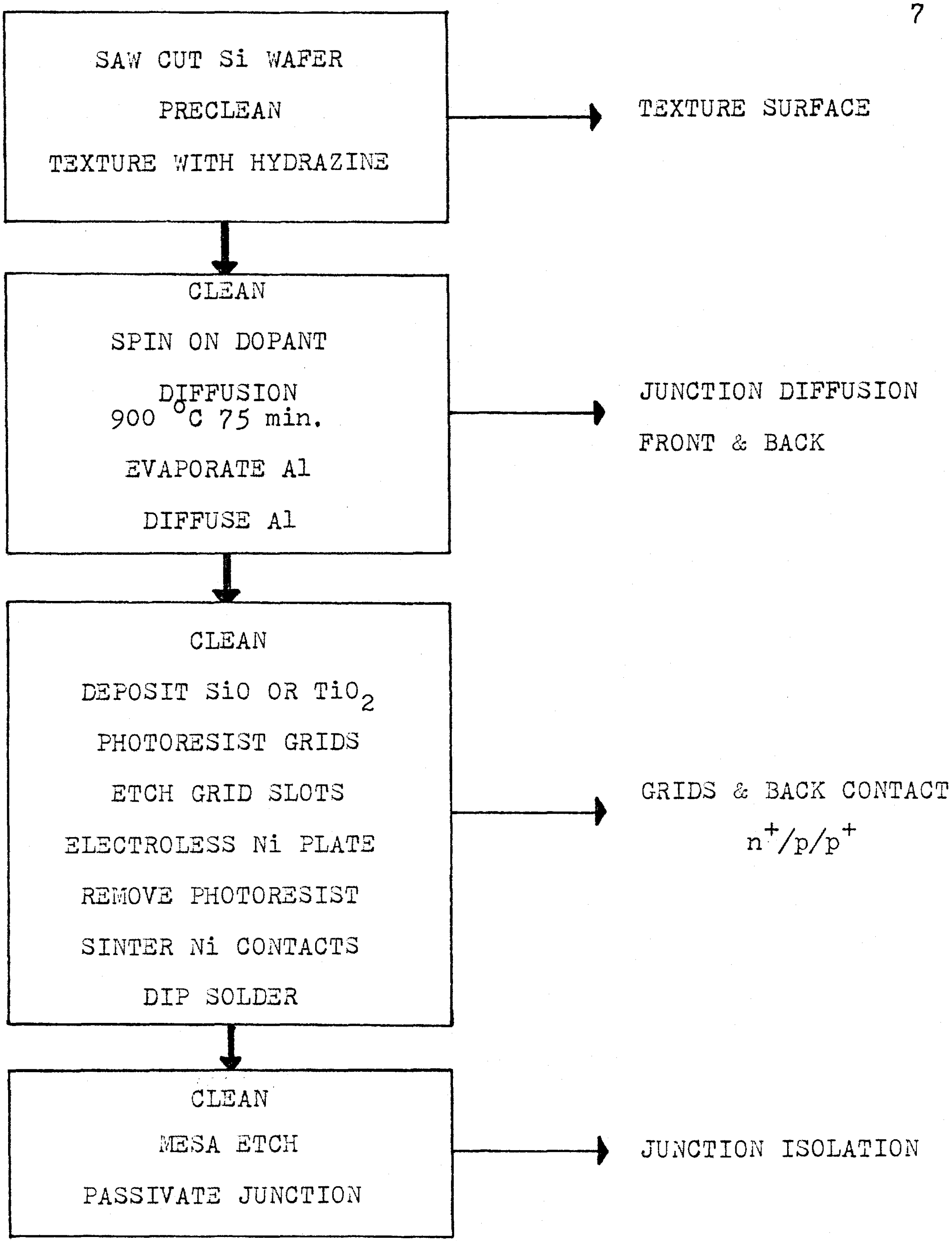


Figure 1: Block diagram of solar cell process.

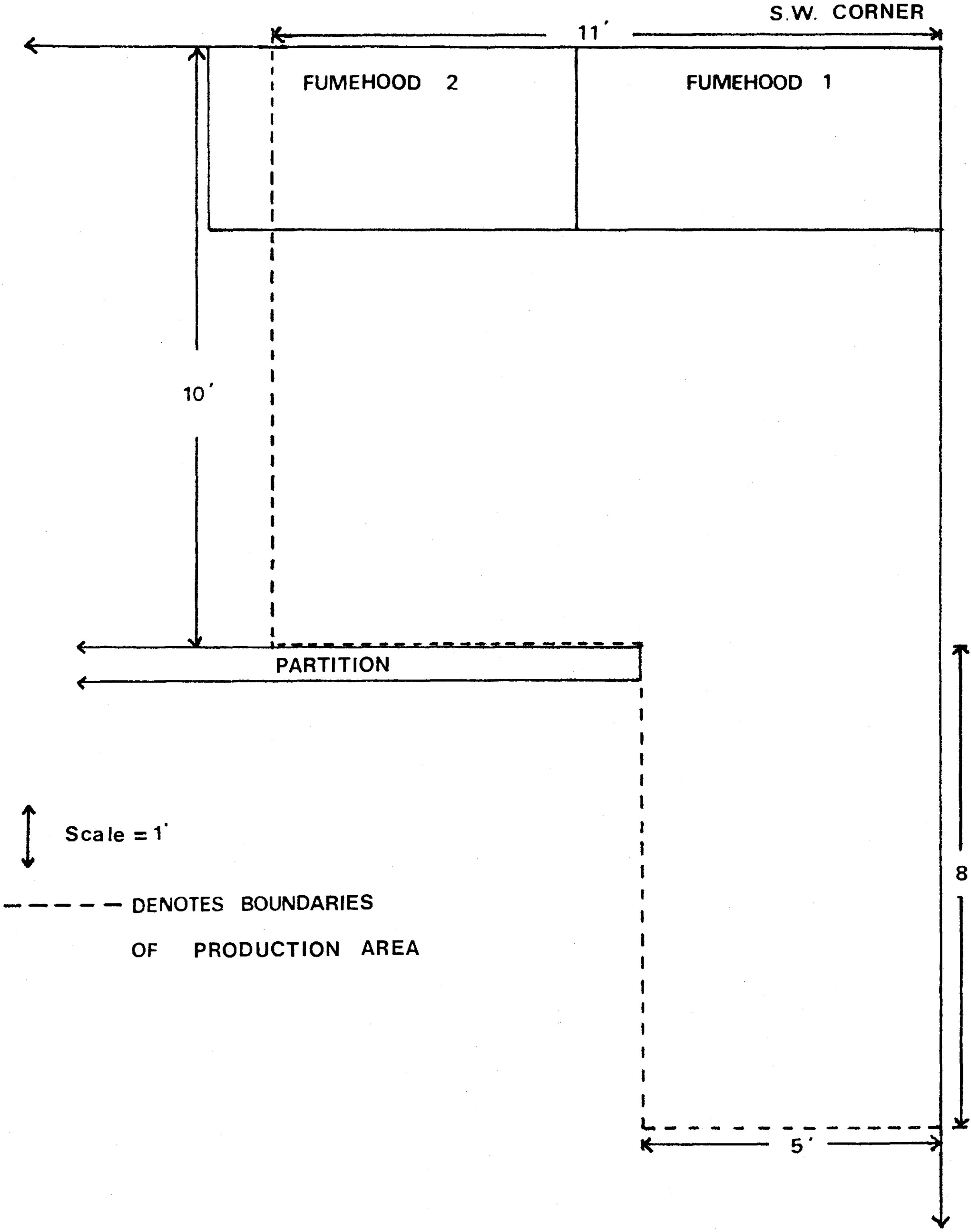


Figure 2: Solar cell production site.

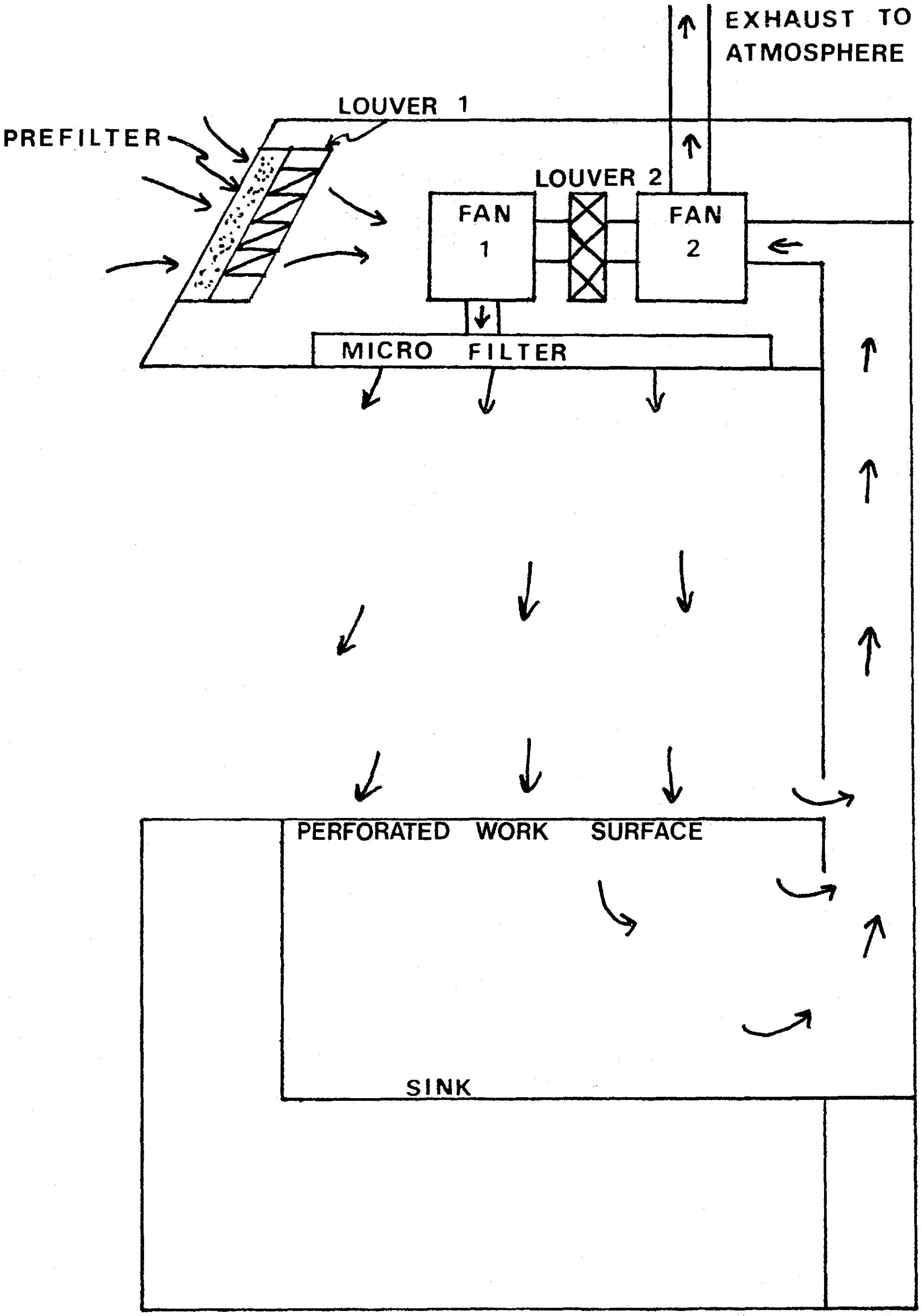


Figure 3: Air circulation in fumehood.

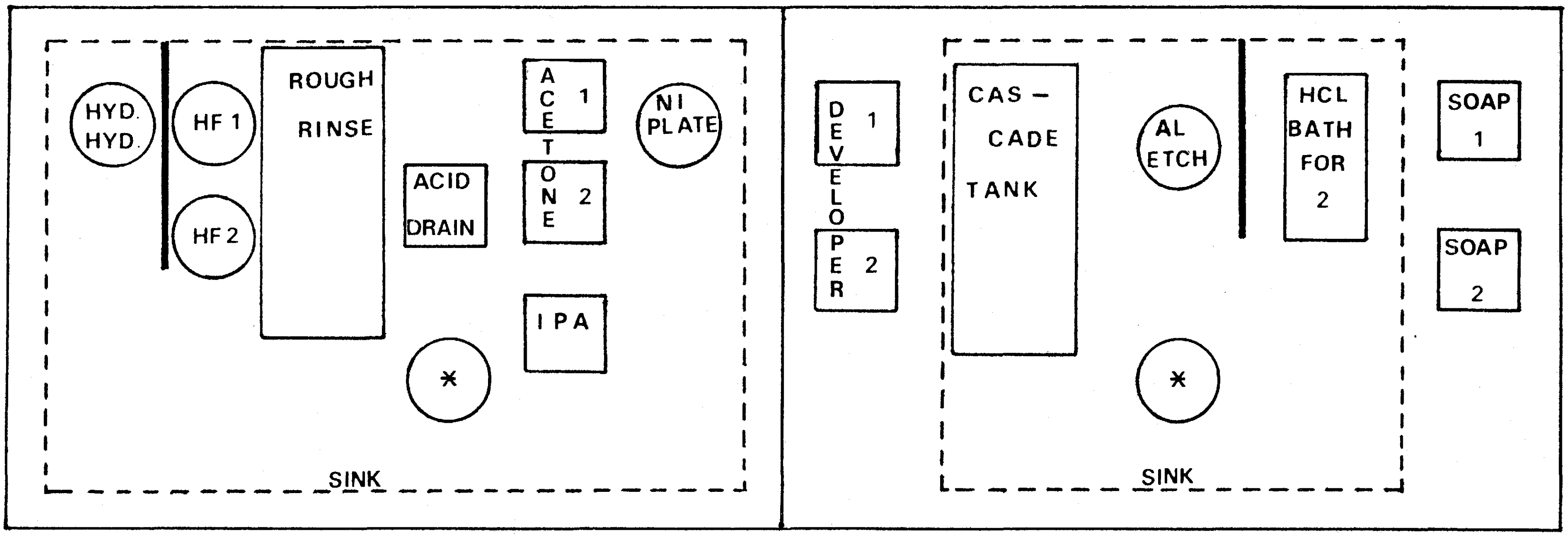
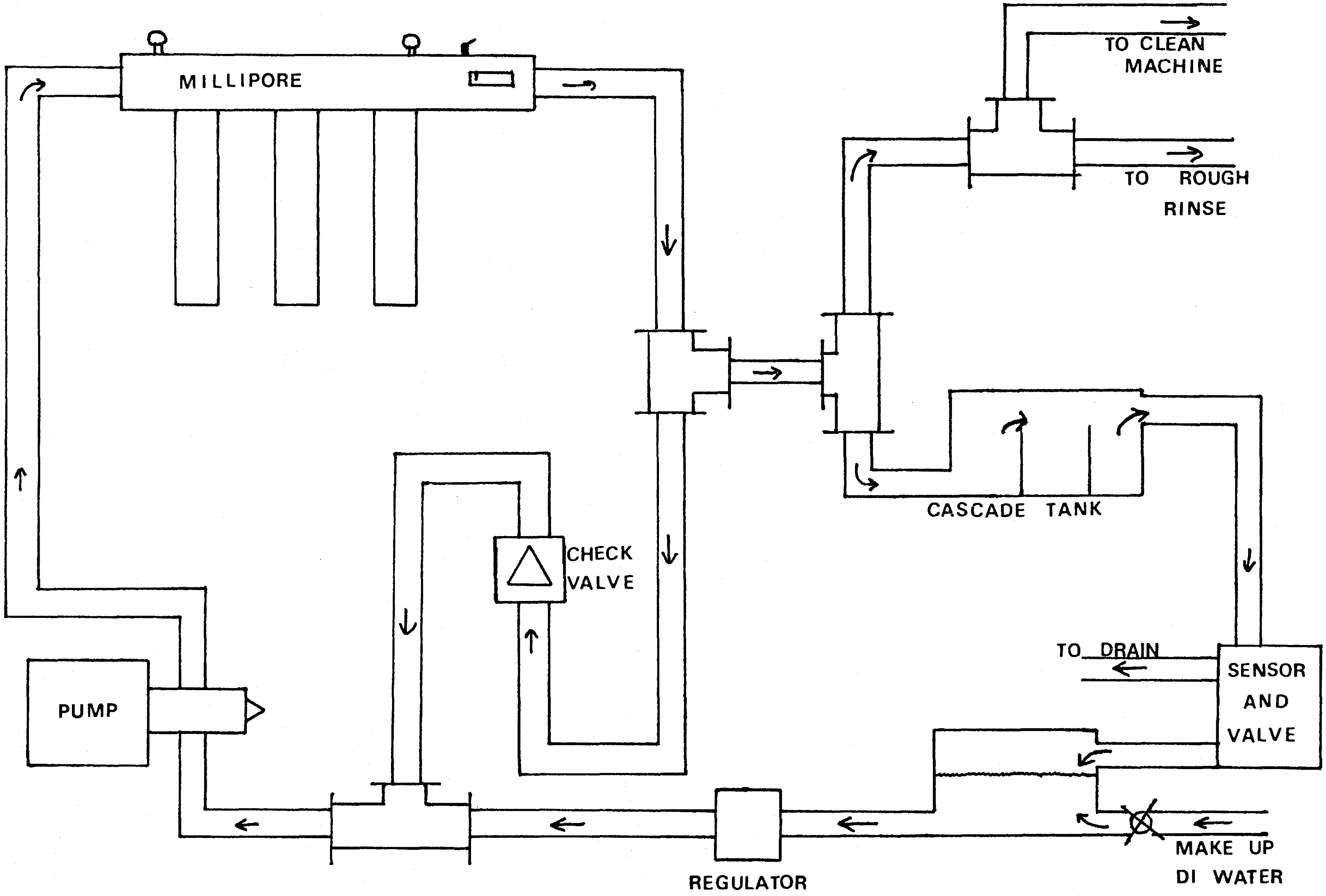


Figure 4: Chemical reagent layout in fumehoods.

Figure 5: DI water system.


MILLIPORE
TO CLEAN MACHINE
TO ROUGH RINSE
CASCADE TANK
CHECK VALVE
TO DRAIN
SENSOR AND VALVE
PUMP
REGULATOR
MAKE UP DI WATER

b) Equipment

Several criteria were the bases of the selection of the equipment ordered or designed for the production line.

The first and foremost requirement was the reduction of individual wafer handling. This was accomplished by the use of teflon wafer carriers or "baskets" made by Fluoroware Inc. A basket containing 25, 3" wafers could be put through each of the cleaning steps rather than each wafer individually. These baskets were dump transferable, meaning that all 25 wafers could be either dumped into or out of another carrier simultaneously. Some silicon wafer manufacturers deliver their slices in containers which are dump transfer compatible with these teflon baskets.[4] Thus new wafers ready for processing need not be individually handled, risking breakage and contamination.

Because these baskets were also automated machine compatible meant that they could be put into an automated piece of machinery which would then process all 25 wafers without any further handling by the operator. The operator, after loading the machine, would then be free to perform some other task.

A second criteria to be concerned with was that of wafer size. Until recently the growth and use of 3" diameter single crystal silicon wafers was unheard of.

However, now 4, 5 and even 6 inch wafers are being produced and used for semiconductor device processing. For solar cells, a practical limitation of 4" has been set because of gridding restraints.[5] Also, higher quality, but inexpensive polycrystalline silicon has been developed for photovoltaic application. These usually come as square slices, 2" to 4" on a side. Thus it was necessary not to restrict, as much as possible, the size of wafer which could be used with any equipment ordered.

The heart of any semiconductor device production line is the diffusion furnace. A Lindberg 3 tube diffusion furnace was available. Unfortunately, the heating elements were of such a small size they did not permit the use of 3" diameter silicon wafers. Thus new, larger elements were ordered with an internal open diameter of 4 3/4" which would accept up to 4" diameter wafers stacked perpendicularly to the long axis of the elements.

Because new elements were needed, new process tubes were also necessary. Three tubes made of quartz were obtained from Quartz Scientific Inc. They were 110 mm outside diameter, 105 mm inside diameter tubes with one end tapered to a 35/25 ball joint and the open end having an end cap to match. The end cap was later modified with 2 eye hooks attached to the top to facilitate its removal when hot.

Quartz was not the only material from which the

Figure 7: "Super-Spinner"

process tubes could have been made. There are two other materials which boast better performance as process tubes than quartz; silicon carbide and polysilicon. Both materials have better thermal properties than quartz and are more stable at higher temperatures. Polysilicon tubes are several orders of magnitude purer than both quartz and SiC, and do not become porous with age.

Quartz was chosen over SiC and polysilicon because it is much cheaper, alterations can be performed more easily and impurity restrictions for solar cells are much less stringent than for some other semiconductor devices, notably MOS devices. Since the maximum temperature the tubes would experience would only be $900^{\circ}C$, problems with devitrification, sagging and sticking would not be encountered.

Although the process tubes could not accept 4" diameter wafers, it was felt the extra expense incurred by ordering larger tubes was not worthwhile since the tubes would be in need of replacement by the time efficient 4" cells were successfully developed.

For wafer cleaning it was decided to use an apparatus manufactured by Corning. The unit is an acid bath which is a self contained device containing a Vycor vessel, heating unit and remote control. It is capable of quickly heating acid solutions (except HF) and maintaining its temperature to a high degree of accuracy. It replaces more conventional hotplate-beaker combinations and is capable of containing 2 wafer carriers at one time.

One piece of automated equipment, capable of handling at least 100 wafers at a time, is Fluoroware System's "Clean Machine". The Clean Machine is an apparatus which rinses and blows dry baskets of wafers with DI water and hot N_2 gas respectively. Figures 6 a) and 6 b) depict the important aspects of this equipment.

The Clean Machine is used as a final rinse and dry before dopant and photoresist applications. One of the advantages of the model 8231 is that it can be upgraded easily, by changing the turntable and cradles, to accept 4", and in fact, up to 6" diameter substrates. It can also be upgraded to process 252 wafers during one cleaning operation.

Since automation was a prime concern, a third piece of automated machinery was Machine Technology's "Super-Spinner", a picture and description of which is in figure 7. In essence, the Super-Spinner will individually remove wafers from a wafer carrier, position it on a spinner, blow off particulates with N_2 gas, dispense a fluid (dopant or photoresist), spin the substrate, dispense a second fluid and again spin, return the wafer to the carrier and move on to the next wafer.

This machine accepts the same wafer carriers as used in the clean machine and is capable of processing up to 200 wafers per hour. The same spinner can be used to dispense, first the dopant solution and then later, photoresist, with just a few valve and process cup changes. As with the other equipment ordered, this unit can be upgraded, with minimal expenditures, to accept up to 5" diameter substrates.

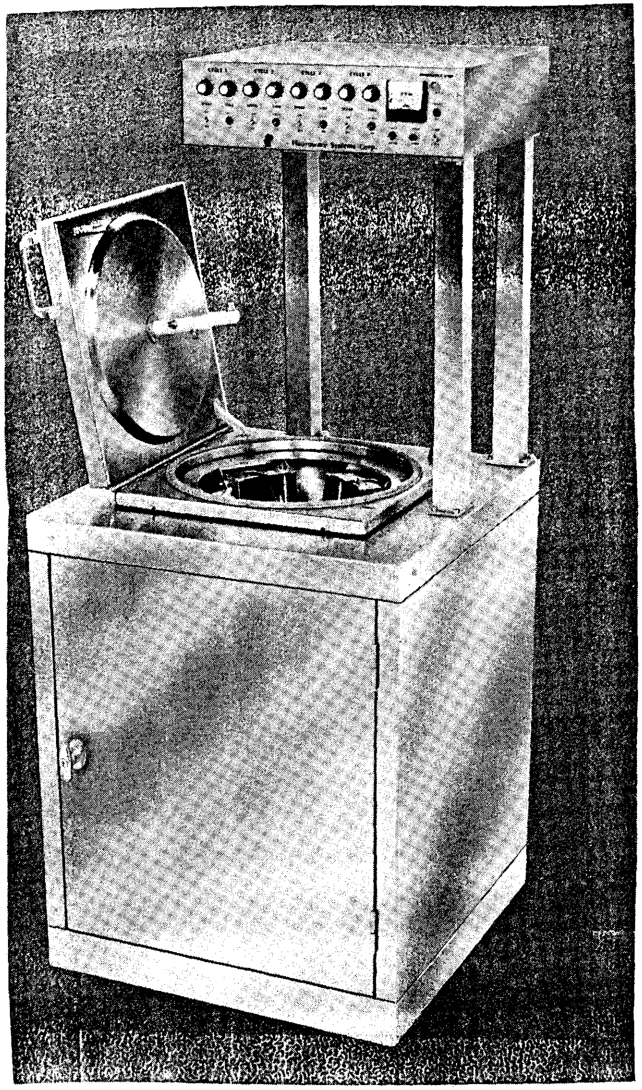
A fourth article which was needed to reduce wafer handling was Micro Glass' Transition Device. Figure 8 depicts the device and how it is used. Basically, the device will dump transfer wafers from 2, 25 slice carriers into one, 50 wafer quartz diffusion carrier and vice versa. The delicate and slow process of individually loading wafers into a quartz diffusion boat is thus eliminated.

One final piece of necessary equipment was a vacuum system. It is basically an 18" bell jar vacuum system. Unfortunately, it is rather old, but should permit evaporation onto 21 substrates simultaneously. Not much work was done to remodify the system since it may be possible to eliminate the need for a vacuum system altogether.

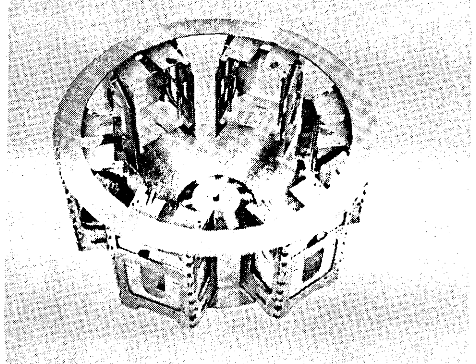
Figure 6: "Clean Machine"

a) Console and turntable

b) Rinse features



20" dia. Model 1063 / 1203



Swing style design, 6 positions
Universal buckets hold 3" to 4" standard in line cassettes.
Buckets lift out easily and can be exchanged for ones that hold 1½" to 3" standard cassettes.
316 stainless construction.

Turntables

A wide variety of standard turntables are available to handle varying needs.

Fabricated to exact engineering standards, balanced on special multiple plane dynamic balancing equipment, and tested before shipment. All stainless steel turntables are constructed from 316 stainless and thoroughly passivated.

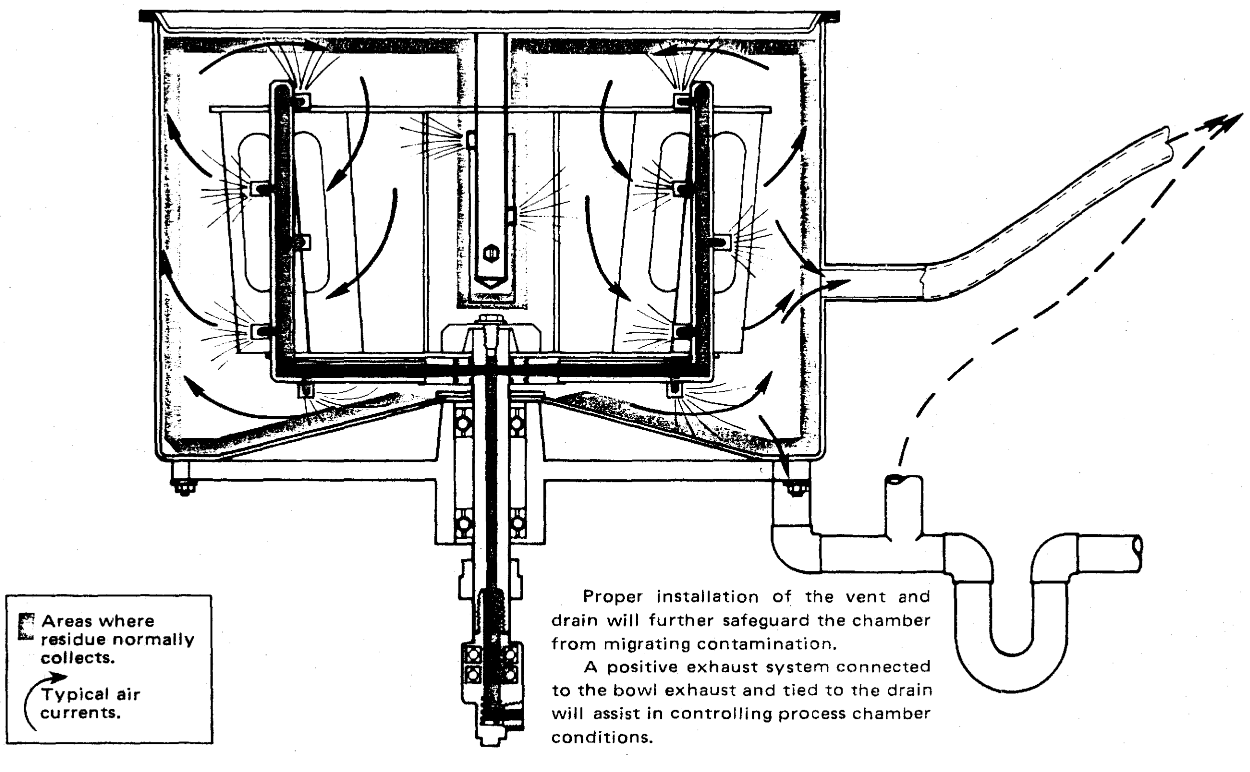
Universal designs are provided when possible to offer maximum utilization and economy. Our new turntable frames feature lift-out cradle inserts to hold wafer carriers. Just by changing inserts a turntable can switch from handling 2" through 3" carriers to 3" through 4".

If your application is unusual, we can offer engineering for special designs. Chances are we already have a solution for you.

If you're rinsing and drying...

USE THE BEST!

- The LOW RPM also means that your devices will be cleaned better without shadowing or masking from the turntable or carrier.
- A sealed chamber takes away the chance for external contaminants to migrate into the process chamber.
- Internal chamber surfaces are contoured and polished to facilitate cleaning.
- Conditions inside the process area are controlled.
- The nitrogen heater is "designed to be clean" and not produce contamination.
- The clean machine is designed to clean itself and your product.
- It is designed to remove residue and particulate from the interior of the machine, including the area under the turntable.
- Good cleaning of the chamber walls, cover, under the turntable, even the center spray post is accomplished with a pressurized spray at LOW RPM.



Proper installation of the vent and drain will further safeguard the chamber from migrating contamination.

A positive exhaust system connected to the bowl exhaust and tied to the drain will assist in controlling process chamber conditions.

The heart *of the chamber aning process is the rotating ray manifold built into the rntable. It rotates slowly and ses all surface areas and the ntral spray post. This feature noves solution and particulate idue from the interior of the amber.*

The illustration shows typical air currents inside the process chamber during the final dry cycle.

These air currents can carry particulate and residue left over from previous cycles. Redeposition of these contaminants onto the devices is avoidable.

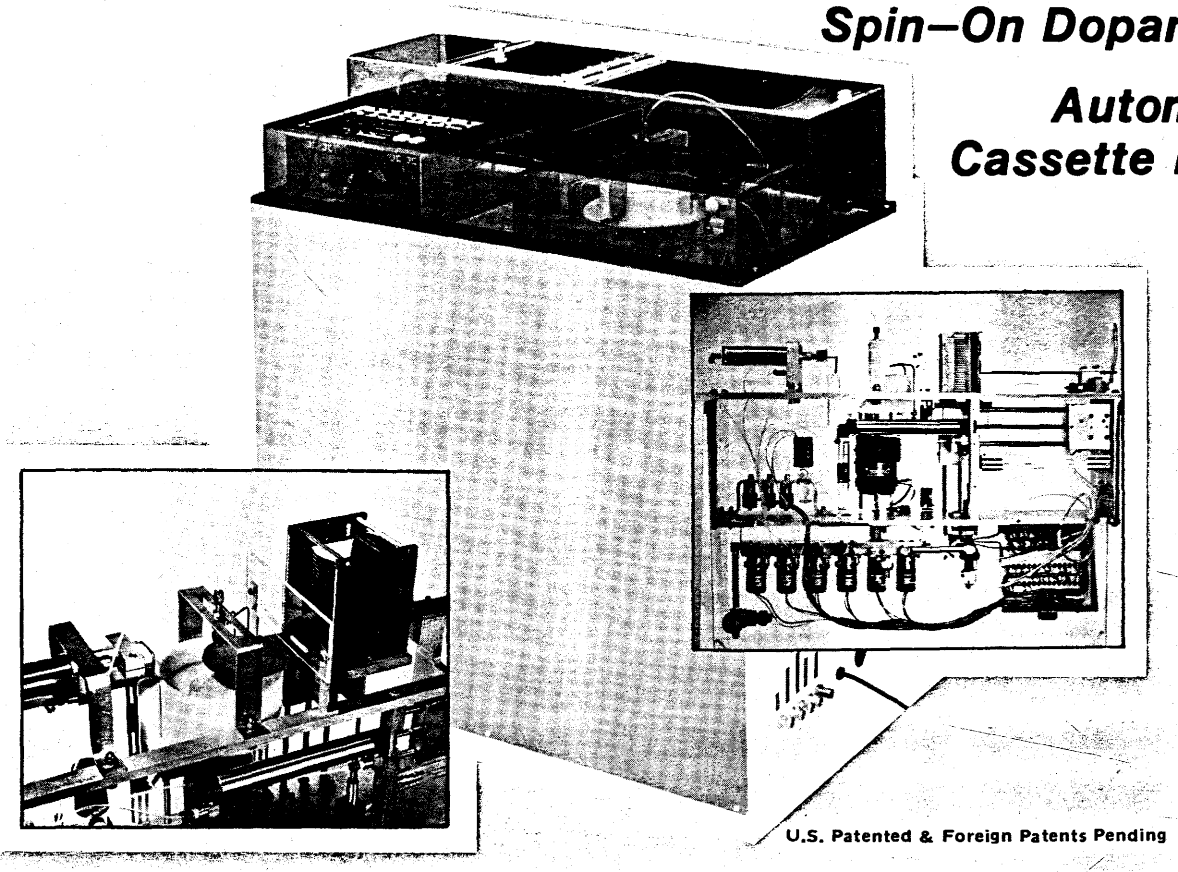
FSI's unique chamber wash* is designed to minimize these contaminants before the final dry cycle by utilizing a SLOW speed, POSITIVE spray. It cleans those hard to reach areas, under the turntable, side walls, cover and the central spray post.

MODEL 6320D
2" to 5" Capacity

Super-Spinner™

Spin–On Dopant Coater

Automatic Cassette Handling



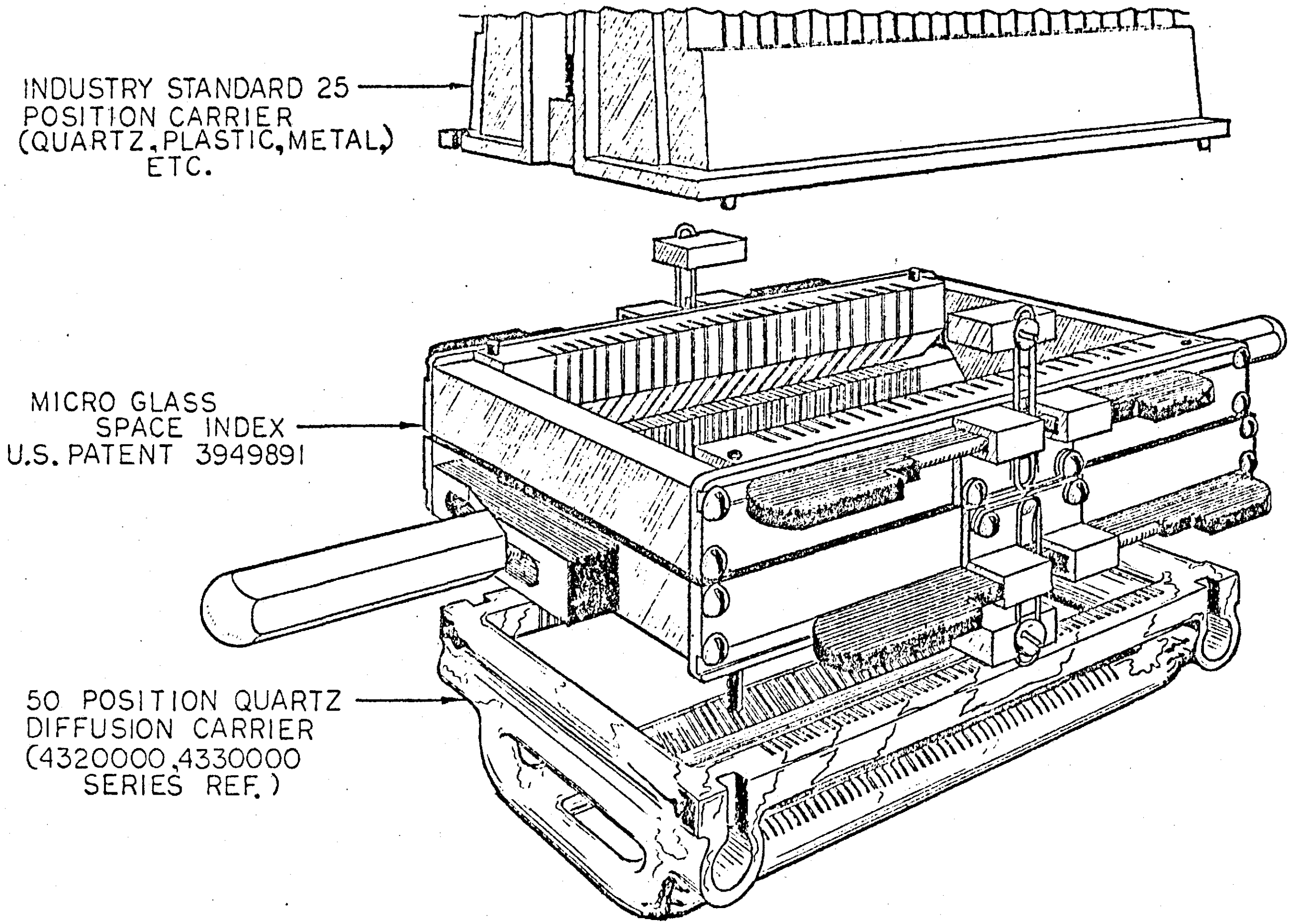
U.S. Patented & Foreign Patents Pending

- Ingenious design and rugged construction provides ultra-high reliability
- Solid State Logic used throughout
- Modular track flexibility
- All 6300 Model machines may be converted to any other 6300 Series machines
- Quick and easy change-over to different wafer sizes
- Uniload concept permits machine to be installed in only 16" of bench space with electronics, or 8" of space when electronics are removed.
- Gentle and clean wafer handling
- No pumps or complex dispense systems. Movable dispense eliminates "final drop" problems.
- Easy to clean. Only two nuts are loosened to completely disassemble process chamber.
- Total enclosure available for use with arsenic.

The Model 6320D, Spin-On Dopant Coater, is a simple, reliable and rugged machine for spin coating of dopants. The machine employs Machine Technology's proven and unique "Uniload" wafer handling system with a new dispense technique that enormously simplifies coater cleaning and maintenance.

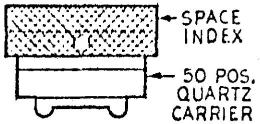
The dopant is dispensed from a movable ram. In this way no attempt is made, nor need be made to prevent "final drop." At the end of the time and orifice measured dispense, the dispense head is simply moved away from the wafer zone so that any "final drop" falls in a basin provided for that purpose. There are no pumps to clog, bellows to break, etc. A controllable orifice valve, pressure vessel, and time base are used to accurately and simply control dopant quantity. The process chamber of the Model 6320D is made of Teflon® and the chuck is of Delrin® for chemical resistance and ease of cleaning. The unit provides an exhaust plenum to eliminate splash-back and remove vapors from the process chamber.

Figure 8: Transition Device.



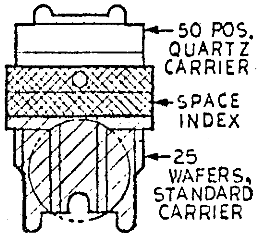
STEP 1:-

ATTACH SPACE INDEX TO EMPTY 50 POSITION QUARTZ DIFFUSION CARRIER.



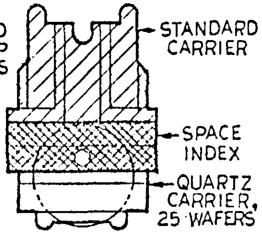
STEP 2:-

INVERT CARRIER AND SPACE INDEX ON TO STANDARD 25 POSITION CARRIER FULL OF WAFERS.



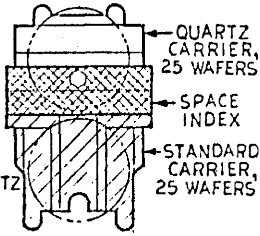
STEP 3:-

INVERT COMBINED CARRIERS AND DUMP TRANSFER 25 WAFERS INTO 50 POSITION QUARTZ CARRIER. REMOVE EMPTY 25 POSITION CARRIER.



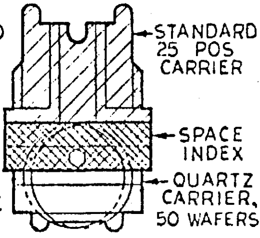
STEP 4:-

CHANGE SPACE INDEX POSITION. INVERT INDEX AND QUARTZ CARRIER ON TO SECOND 25 POS. CARRIER FULL OF WAFERS. NOTE:- FIRST WAFER GROUP IS RETAINED IN QUARTZ CARRIER BY THE SPACE INDEX.



STEP 5:-

INVERT COMBINED CARRIERS AND DUMP TRANSFER SECOND WAFER GROUP INTO QUARTZ CARRIER. REMOVE EMPTY 25 POSITION CARRIER AND SPACE INDEX. QUARTZ CARRIER IS FILLED AND FURNACE READY.



c) Process

The following is a short description of the solar cell production process. There are some slight changes in the process since it was necessary to reduce time and expenses. One notable change is the prediffusion oxidation step for a planar junction diffusion to avoid the mesa etch which is an inherently slow process and yields devices of lesser quality.

Although the planar diffusion method adds 8 more steps they do not require additional materials or equipment, the junction properties are no worse, and the actual time required would be less than that employing the mesa etch. More work space and extra tanks containing CP4, HNO_3 and trichloroethylene (an expensive organic solvent), would be required for processing. A suitable piece of equipment or method would also need to be found to apply the wax.

If the SiO_2 used as a diffusion mask were not etched away after diffusion, it would also provide an excellent passivation layer to prevent future contamination or shorting of the edge of the p-n junction.

STEPS

1. dump transfer new wafers into teflon carriers
2. wafer degrease
3. rinse in cascade tank (CT)
4. HF dip
5. rinse in CT
6. texture in hot hydrazine hydrate solution, 6-8 min.
7. rinse in CT
8. oxidize in $HCl-H_2O_2-H_2O$
9. rinse in CT
10. place 4 carriers with wafers in clean machine (CM) for final rinse and dry
11. load carrier onto Super-Spinner (SS) and spin on SiO_2 solution
12. place carrier in oven at 150-200°C to dry SiO_2
13. using transition device (TD) load 2 quartz carriers with wafers
14. put carriers in white elephant (WE) (quartz tube used to load furnace) and slide wafers into furnace
15. densify SiO_2 for 15 min. at 900°C in N_2 ambient
16. remove carriers from furnace into WE and allow to cool
17. use TD to load wafers back into teflon baskets
18. load carrier onto SS and spin on photoresist (PR)
19. place carrier in oven to bake PR
20. expose PR (first step where individual wafer handling takes place)
21. with all exposed wafers back in baskets, develop PR
22. rinse in CT

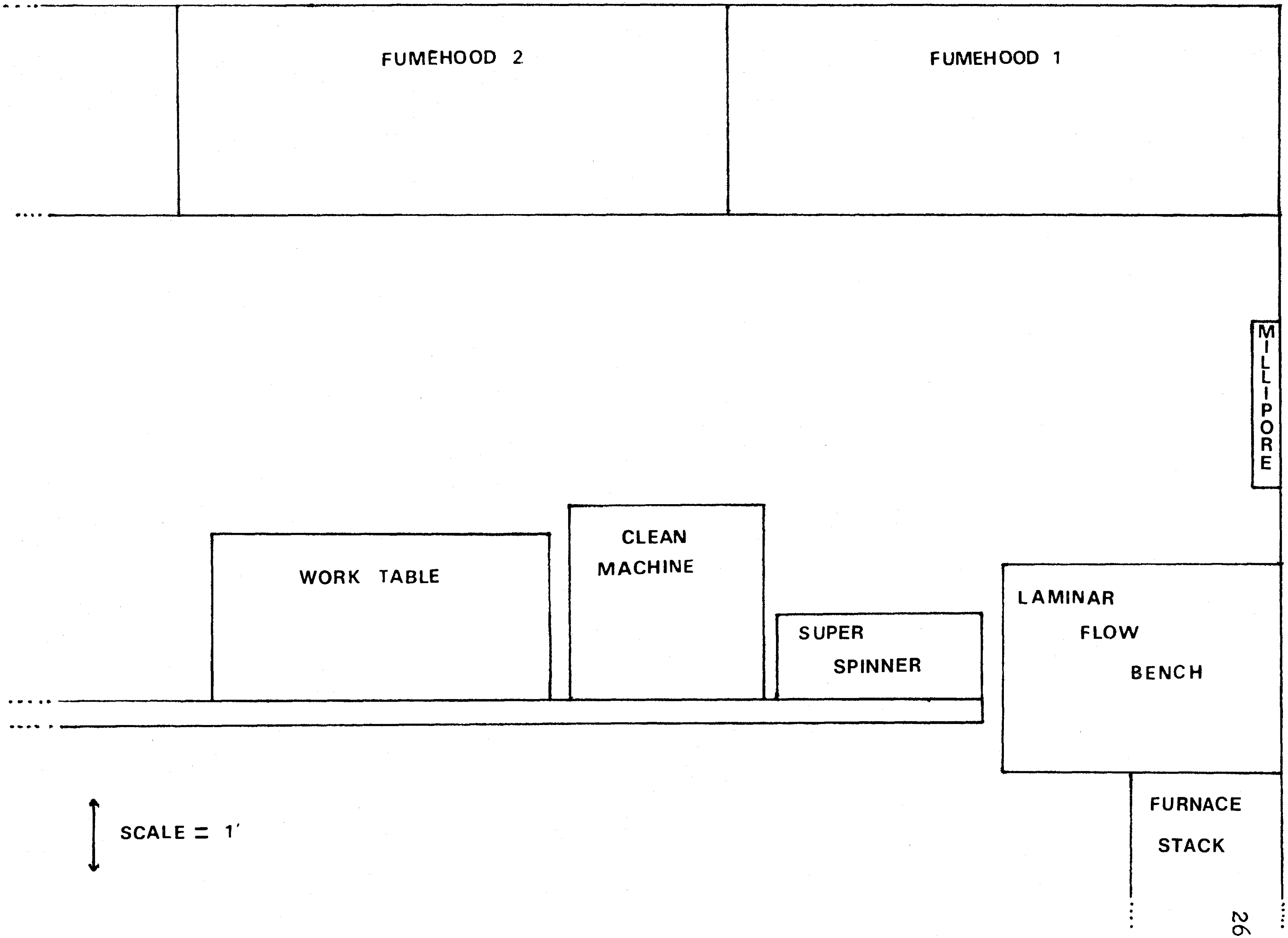
23. blow dry with N_2 gas
24. place in oven to harden PR
25. HF dip
26. rinse in CT
27. blow dry with N_2
28. remove PR in acetone
29. remove acetone with isopropylalcohol (IPA)
30. rinse in CT
31. oxidize in $H_2O_2 + HCl + H_2O$
32. rinse in CT
33. final rinse and dry in CT
34. using SS, spin on phosphorous dopant
35. place carrier in oven to dry dopant
36. using TD load quartz diffusion boats, place in WE and slide into furnace
37. diffuse phosphorous, 75 min. @ $900^{\circ}C$ in N_2
38. remove wafers into WE and cool
39. use TD to return wafers into teflon baskets
40. place 2 baskets into carrier box (CB) (dustproof box to carry wafers from one area to another) and take to vacuum system
41. load substrate holder (2nd individual wafer handling)
42. pump down and evaporate aluminum
43. return wafers to teflon baskets and CB and take to furnace
44. use TD to load quartz boats, place in WE, slide into furnace and diffuse Al @ $580^{\circ}C$ for 20 min. in N_2
45. remove to WE and cool

46. use TD to load teflon baskets
47. strip Al using Al etchant
48. rinse in CT
49. HF dip
50. rinse in CT
51. final rinse and dry in CM
52. place 2 baskets in CB and take to vacuum system
53. load substrate holder (3rd individual wafer handling)
54. pump down
55. evaporate anti-reflection coating
56. put wafers into teflon baskets and CB
57. take to Super-Spinner
58. spin on PR
59. bake PR in oven
60. expose PR (4th individual wafer handling)
61. put wafers back into carrier and develop PR
62. rinse in CT
63. blow dry in N_2
64. harden PR in oven
65. HF dip
66. rinse in CT
67. Ni plate
68. remove and cool
69. rinse in CT
70. remove PR in acetone
71. rinse in IPA

72. rinse in CT
73. blow dry in N_2
74. use TD to load quartz boats, place in WE and slide into furnace to sinter Ni, 20 min. @ 300°C
75. remove to WE and cool
76. use TD to load teflon baskets, place in CB and take to solder station
77. coat wafer with solder flux (5th individual wafer handling)
78. solder dip
79. solder dip other side
80. return wafers to basket, place in CB and return to main processing area
81. remove flux in soap and H_2O mixture
82. rinse in CT
83. blow dry in N_2
84. dump transfer finished cells into final storage box for later inspection and testing

To help visualize the actual physical processes, figure 9 is a diagram of the facilities with all equipment in their final locations. Figure 10 is a block diagram of the fabrication steps.

Figure 9: Floor plan of production area.


FUMEHOOD 2
FUMEHOOD 1
MILLIPORE
CLEAN MACHINE
WORK TABLE
SUPER SPINNER
LAMINAR FLOW BENCH
FURNACE STACK
SCALE = 1'

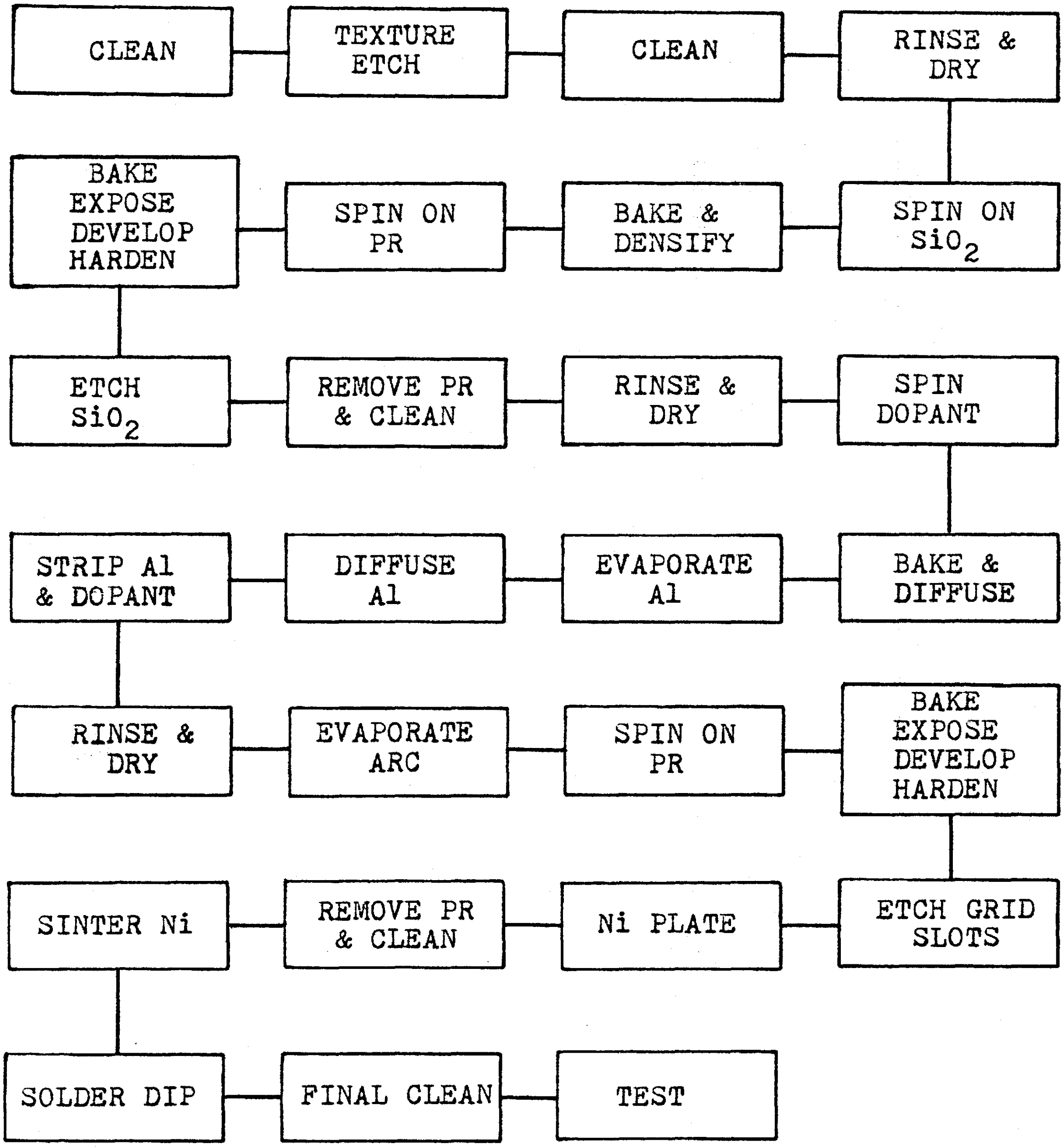


Figure 10: Block diagram of process steps.

PRODUCTION LINE CHECKOUT

Before any quantity of cells could be made it was necessary to put through some test cells. This was done using 2" diameter silicon wafers. However, the first necessary step was the preparation of the quartz furnace tubes.

There are many techniques to clean a furnace tube and often the device produced dictates the method. For instance, a cleaning step for tubes used in MOS device fabrication is a final purge in HCl gas which is necessary to remove sodium, an impurity which plagues MOS manufacturers. Because of the high tolerance to impurities exhibited by solar cells, the cleaning procedure is not as critical. One suggested cleaning method was a soak in a solution of $H_2SO_4 + H_2O_2$.[6] However, the quantity of acid and peroxide necessary to soak a 6' furnace tube as well as safety considerations made this method impractical.[7]

Another method which is quite common and had been used previously at McMaster is an overnight soak in dilute HF. This was the method ultimately used but only on one furnace tube. Only one tube was etched to avoid contaminating all three tubes in case something went wrong with the cleaning procedure.

After cleaning and installing the furnace tube it was necessary to calibrate the furnace control settings and determine the profile of the furnace. Again there are many techniques, some of which are very complex but precise, to determine the temperature profile of a furnace. The easiest and most readily applicable method was simply to place a thermocouple with very long leads, encased in a quartz capillary tube, down the length of the furnace tube. By altering the position of the thermocouple, the temperature at any position within the tube could be determined to within $\pm 1^{\circ}C$.

The calibration of the control settings was performed only at the temperatures which would be used during processing. The results are shown in figure 11. A profile of the furnace at $900^{\circ}C$ is shown in figure 12.

As can be seen, the flat of the furnace extends for a length of approximately 20 inches, which means that 3 quartz diffusion carriers, (each carrier is about 6" long), or 150 wafers, can be placed within this zone for simultaneous diffusion. With further manipulation of the controls it should be possible to extend the zone to a size capable of accepting 4 diffusion carriers simultaneously. At lower temperatures the zones should be even longer since the magnitude of the heat lost through the ends will not cause such a sharp drop in the profile.

It was then possible to produce a test cell. However, it was decided to produce the simplest cell possible in order to reduce the number of "possibilities" in the event of a poor device. A cell was to be made without a textured surface, no AR coating and only aluminum contacts. A 2" diameter cell was made which exhibited poor diode characteristics and a front contact which had poor adherence. This was determined to be due to the method of evaporating the aluminum.

The vacuum system used was designed to be used with alumina crucibles as the mode of heating the evaporant. Unfortunately, alumina crucibles tend to outgas and release alumina in quantities sufficient to degrade the quality of the evaporated film unless great care is taken. It was decided to utilize the standard tungsten coil with a suitable shroud to avoid evaporating aluminum throughout the entire bell jar. With this modification a good device was finally made with no further problems. Some final debugging of the complete system is necessary until full scale production can begin.

Figure 11: Temperature measured vs temperature dialed for top furnace tube.

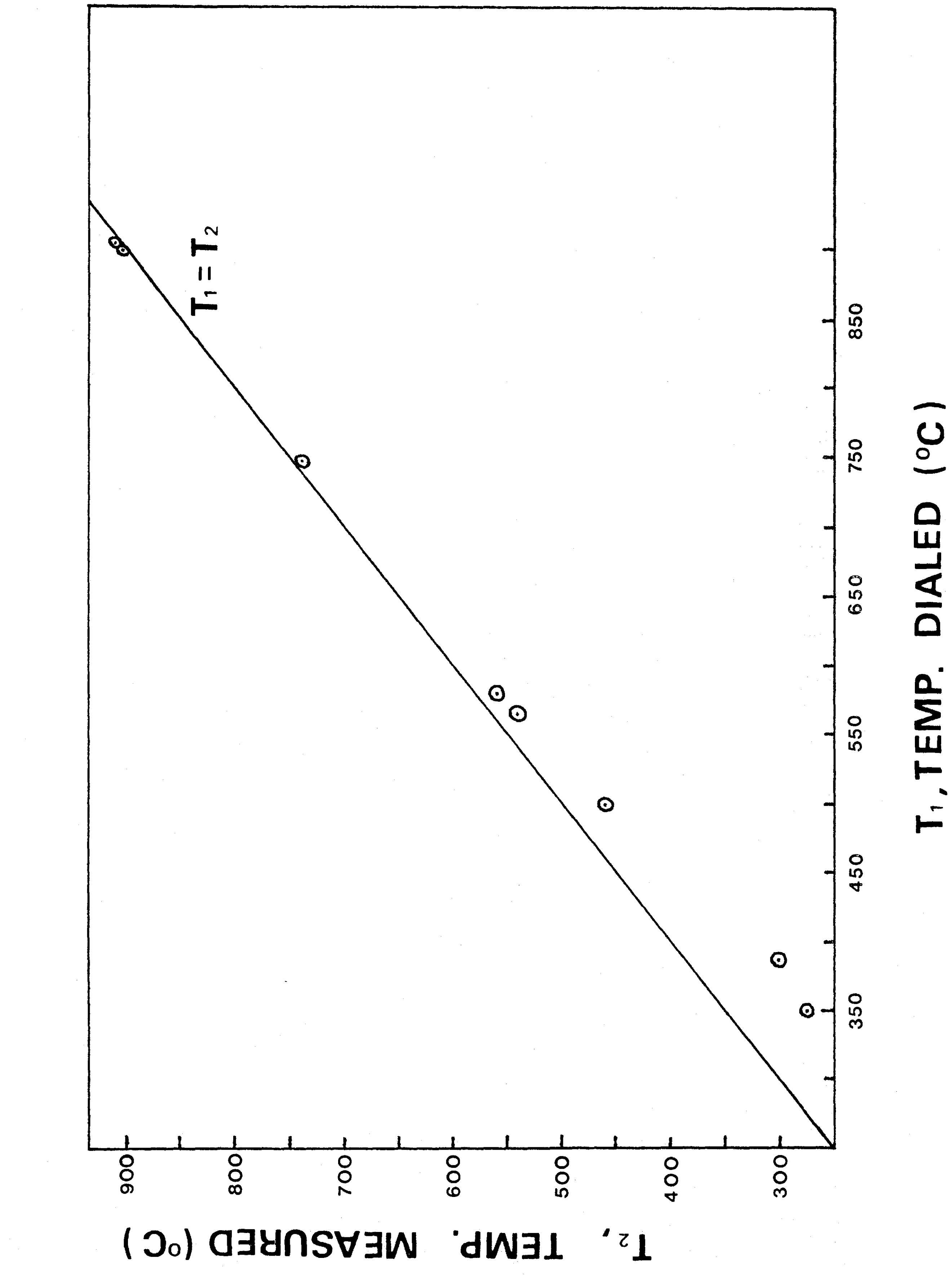
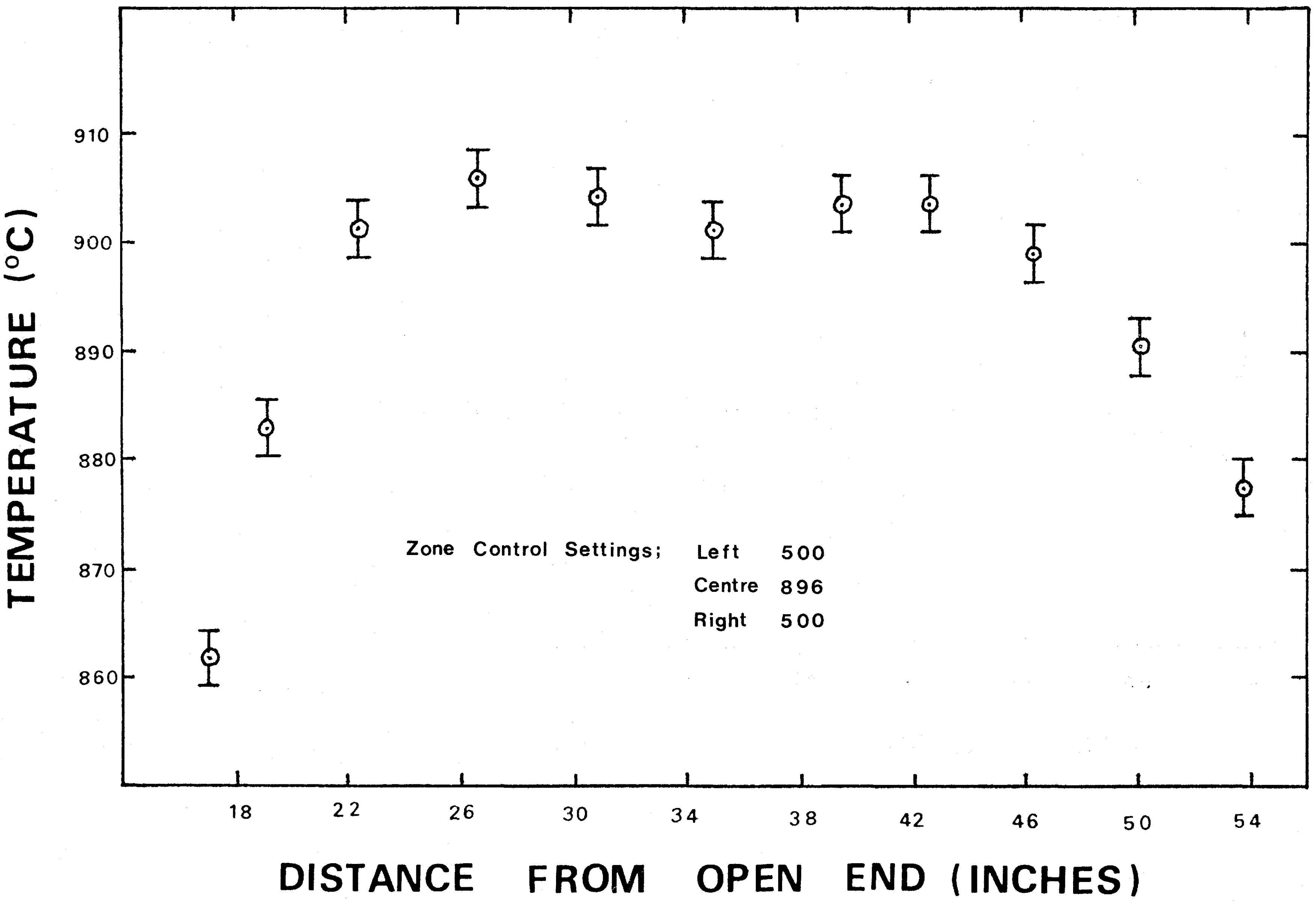

T₁ = T₂
T₁, TEMP. DIALED (°C)
T₂, TEMP. MEASURED (°C)
350
450
550
650
750
850
300
400
500
600
700
800
900

Figure 12: Temperature profile for top furnace tube at 900°C.


TEMPERATURE (°C)
910
900
890
880
870
860
Zone Control Settings; Left 500
Centre 896
Right 500
18
22
26
30
34
38
42
46
50
54
DISTANCE FROM OPEN END (INCHES)

DISCUSSION

Although the production line is almost ready to manufacture solar cells, there still are some modifications needed to reduce manufacturing costs and perhaps increase efficiency.

The use of hydrazine hydrate as a texturing solution is extremely expensive. Other alternatives exist which are much cheaper and in particular, a dilute NaOH solution seems to be the direction most of the industry has turned.[8] The uniformity and reproducibility of the surface texture can also be improved. Several techniques have been suggested which sensitize the surface before texturing. Among these techniques are included pre-texture dips in hot CCl_4[9] and $Na_2SiO_3 \cdot XH_2O$[10].

A second area of concern is the method of obtaining a p^+ BSF region. Evaporating aluminum is a slow and thus costly step. The problem is twofold since nickel plating p^+ silicon is a notoriously difficult process.[11] Spin-on boron and boron-gallium dopants were found ineffective to produce a platable p^+ region. However, recently there has been mention of a screen printable aluminum paste which can be applied to the back of a cell.[12] The firing process results in a Si-Al alloy which yields a p^+ region and highly conductive back contact. An overlayer of some solderable paste must then be put down to permit cell interconnects to be fastened. It has been reported that cells with screen printed Al back contacts have better characteristics than those with evaporated Al contacts.[13]

A second evaporation which should be eliminated is that of the AR coating. A TiO_2 solution has been developed which can be spun on to a substrate to form an antireflective coating. However, this is effective only on polished substrates and not on irregular or textured surfaces. It may be possible to spray the solution to form a good AR coating. An added attraction to this method would be the possibility of physically masking the front grid pattern during spraying. This would eliminate a photoresist step, another time consuming operation.

One final step which poses many problems is the solder dip. The current manual placement of the fluxed substrate on the surface of molten solder is quite unreliable. In instances it was necessary to re-dip the cell because of incomplete coverage. Because the wafer is withdrawn from the solder surface at some inclination, the solder flows to the lower edge and often leaves clumps or balls of solder in different locations. The back surface especially is uneven and can cause problems during its mounting on a panel. The highest risk of breakage is also encountered during the soldering process since there is considerable stress placed on the wafer when it is removed from the solder bath.

One possible alternative to solder dipping would be the use of a screen printable solder paste. A paste containing the desired solder mixture and flux compound could be screen printed onto the front and back contacts of the solar cell and placed in an appropriate oven to be heated to melt and flow the solder. This should reduce the unevenness of the solder surface and should permit a finer grid structure. However, the cost of the solder paste may be too high to warrant the selection of this method.

Other possible alternatives must be available, however, none have been determined as yet.

One aspect of the production line which has not been given any consideration as yet is that of the rate of production of solar cells. It should prove interesting to compare the throughput of the present process and the altered process incorporating the aluminum paste and sprayed TiO_2 AR coating. For simplicity the effects of yield and equipment downtime will be neglected.

A simple way to determine productivity would be to consider the slowest or least productive step in the production line. Clearly in the present process the 2 vacuum evaporations are the slowest steps. During one evaporation, approximately 21 wafers can be processed simultaneously. If one assumes it takes approximately 1 hour to load, pump down and evaporate; and the fact that each cell undergoes 2 separate evaporations, then this step has an effective rate of 11½ cells/hour. In a typical 8 hour day this would mean a maximum of 8 x 11½ = 92 cells/day production.

On the other hand, if these evaporations were eliminated by the previously mentioned processes, the slowest step would be the exposure of photoresist. A typical rate for this would be 1/minute or 60/hour. Since only one photoresist step would be necessary with the new process, a daily maximum production rate of 8 x 60 = 480 cells would be achievable.

Unfortunately, both of these cases are ideal in the sense that they do not consider any other process steps involved in the production of a device. Another point to remember is that although a particular process may have a higher output for its slowest step than another process, it may have so many more steps involved in the total process that the production rate may indeed be lower.

To understand this more clearly let us follow the production of a batch of 100 Si wafers, in 4 baskets of 25, into solar cells. If we follow the previously outlined steps on pages 22-25 it should help to visualize what is going on.

Steps 1-9 should take ~22 minutes/basket. However, when the first basket finishes step 9 it must wait for step 10 until the last basket is finished, which is another 20 minutes. Step 10 takes ~20 minutes and step 11 ~60 minutes. While the last 25 are at step 11, the others are already at step 12, thus add only 15 minutes for step 12 for the last basket. Steps 13-17 should take 10, 15, 30 and 10 minutes respectively. Step 18 consumes 60 minutes, add 10 minutes for step 19 by the same reasoning as step 12 and 30 minutes for step 20. Steps 21-32 should take a total of 33 minutes. Step 33 should take 20 minutes and 34, 60 minutes. Allow 15 minutes for step 35, 10 minutes for 36 and 75 minutes for diffusion, step 37. Steps 38 and 39 will take 40 minutes altogether. The process steps up to step 39 are common to both production techniques and requires ~555 minutes to complete.

Steps 40-73 apply only to the original process. Using similar times to those above and allowing 60 minutes to evaporate onto 21 wafers simultaneously, these steps require 797 minutes. The large time requirement is due to 2 separate vacuum evaporations; aluminum and SiO. These also result in an additional 600 minutes to the processing time.

The final steps which include a nickel sinter and dip soldering only entail 127 minutes. This results in a total of 1,479 minutes or about 25 hours necessary to produce 100 cells.

To compare this with the altered process, let us look at the new steps and the times needed:

39. diffused wafers are in teflon baskets
    a) HF dip } 7 minutes
    b) rinse in CT } 7 minutes
    c) clean machine, 20 minutes
    d) screen print Al paste, 70 minutes
    e) fire paste, 15 minutes
    f) screen print silver paste pad, 15 minutes

       (as the wafers come from firing they can be printed with Ag and placed on the conveyer furnace again)
    g) fire Ag paste, 15 minutes
    h) spray TiO_2, 60 minutes
    i) dry TiO_2 in oven, 10 minutes
    j) using TD, load quartz carriers, 10 minutes
    k) densify TiO_2 in furnace, 10 minutes
    l) cool in WE, 15 minutes
    m) using TD, load teflon baskets, 10 minutes
    n) nickel plate, 8 minutes
    o) cool, 2 minutes
    p) rinse in CT, 1 minute
    q) blow dry in N_2, 1 minute
    r) use TD to load quartz carriers, 10 minutes
72. sinter Ni

These steps add to a total of 279 minutes; 518 minutes less than the previous process. Thus it would take 961 minutes = 16 hours, or 2 days to produce 100 cells. As can be seen, it takes much less time to produce a batch of 100 cells by the new process.

Figure 13 is a flowchart depicting the process. The numbers in each box are the times (in minutes) required to process 100 wafers. From the chart, 2 bottlenecks can be seen quite clearly. The first is the evaporation of Al and SiO. The second occurs at the spinner which is used 4 different times during processing.

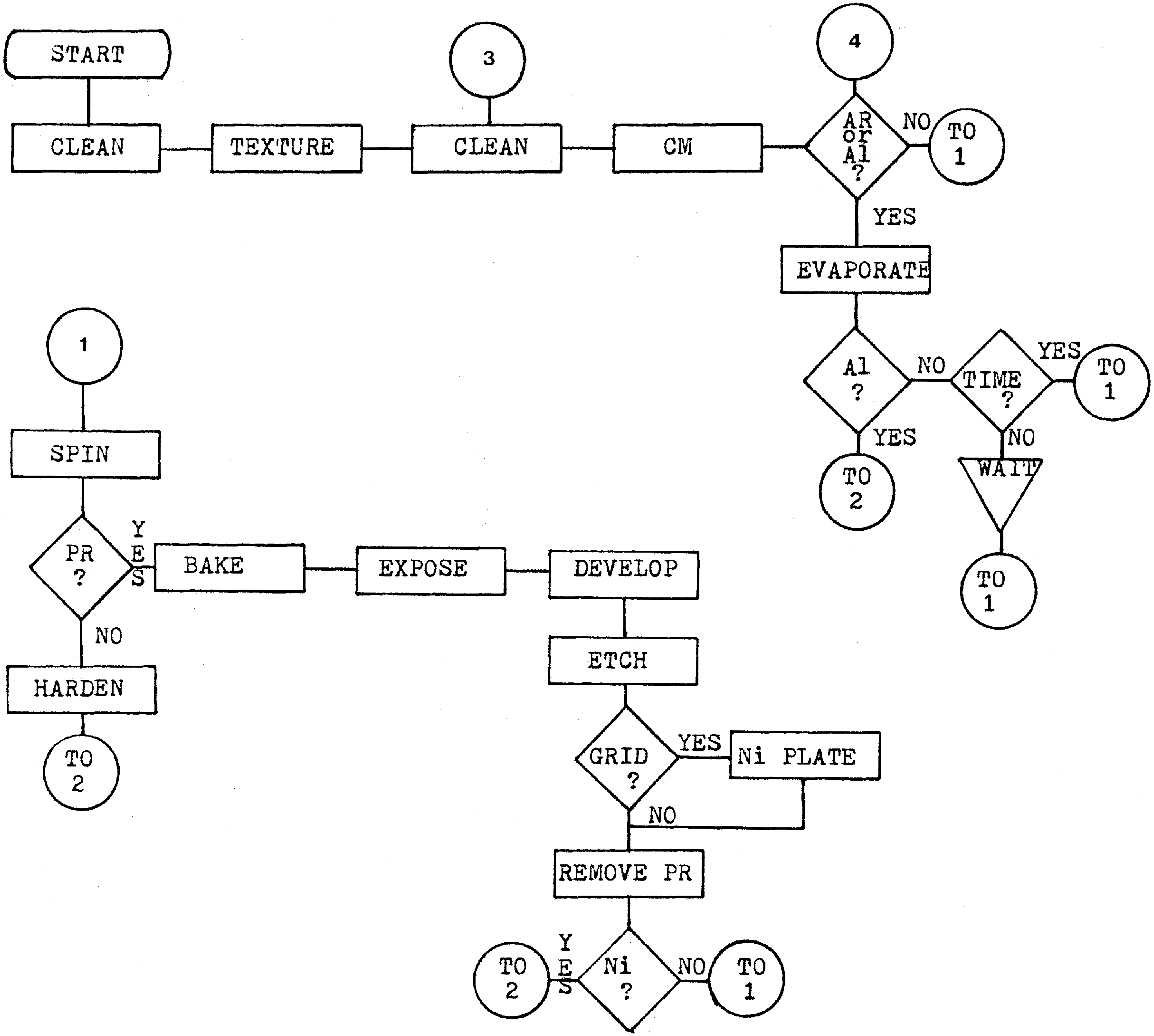
The fact that 2 days are required to produce 100 cells does not imply a production output of 50 cells/day. The rate depends on how many of these batches of 100 can be undergoing processing simultaneously. For instance, while 100 wafers are being dip soldered, another 100 wafers might, say, be having an AR coating applied, while another 100 could be in the diffusion furnace, and so on. Thus it should be possible to have between 300 and 500 wafers undergoing processing at any one time. This would then imply a production rate of 150-250 cells/day. With a modest 2/3 yield the production line would be producing 100-167 acceptable solar cells per day or, neglecting equipment downtime, 25,600-42,700 cells/year. This would mean the capability of yearly producing cells with an electrical generating capacity of 11.5 to 21 kilowatts.

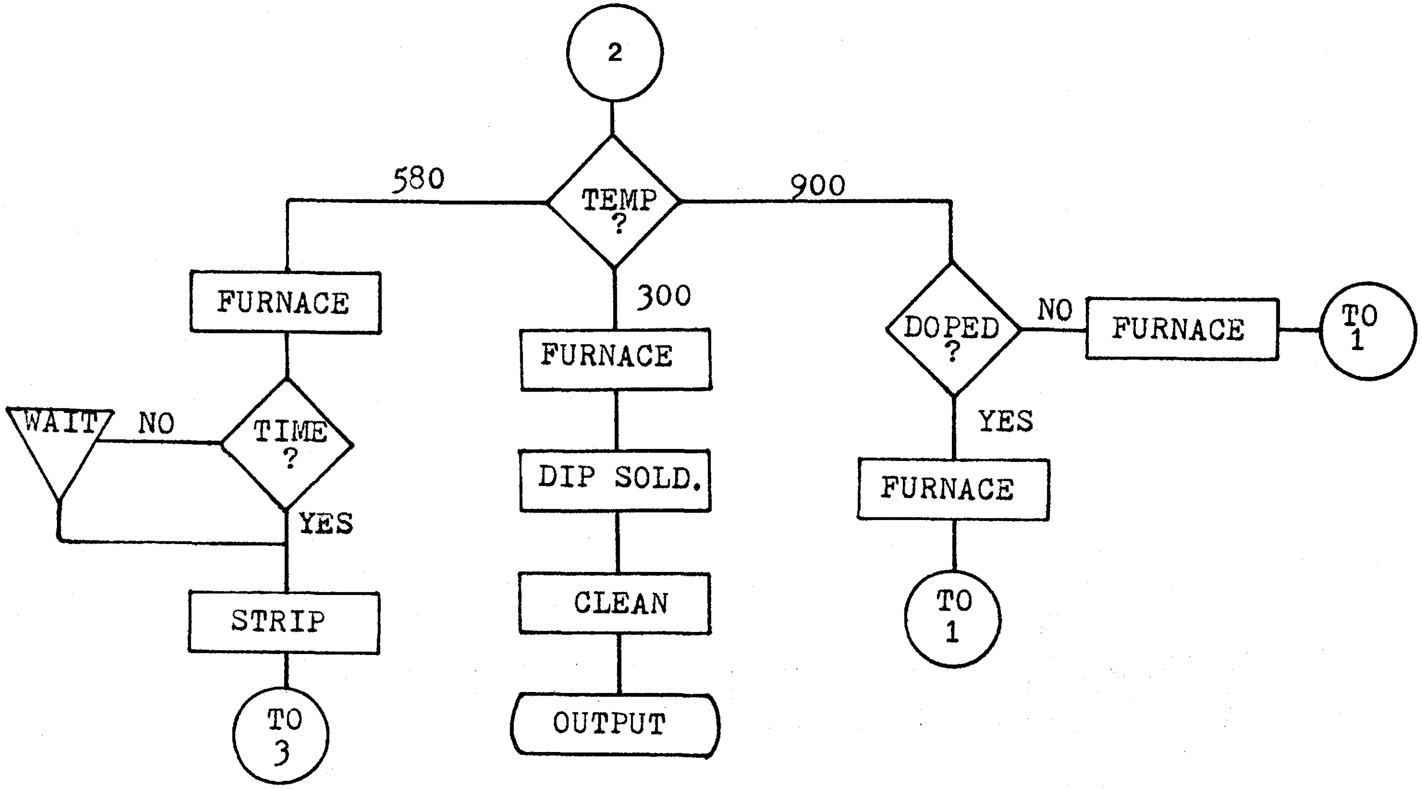
Another aspect that deserves consideration is the working day or work week. Each day, at the end of working hours, semiprocessed cells will have to be left until the next morning. The possibility of contaminating these partially processed cells exist. Fortunately, there are some stages at which processing can be stopped and the wafers left for some period of time without device deterioration. Wafers can be left for several days after aluminum diffusion and after application of the AR coating. An alternative to this approach would be to run a 24 hour work day with three shifts so that no gaps in processing result.

A second problem mentioned earlier which may occur is the fact that only one spinner is available. It may happen that one batch of cells is waiting for dopant application while another batch is being photoresisted. This slow down will reduce productivity. One solution is to run through perhaps 500 wafers at a time for dopant application and then change over the spinner to run through the same 500 later with photoresist. An alternative to this is to purchase another spinner, an expensive proposition.

The manpower requirements for this production line are small. Three and perhaps only 2 people are needed to operate equipment and load baskets etc. One person should be occupied full time with the vacuum system. However, during pump down this person could help out with other duties. The second person would be in charge of the first part of the processing such as wafer cleaning and diffusion. The third person would be responsible for nickel plating and dip soldering. If the process were altered, eliminating the vacuum evaporations, this person would probably look after the screen printing operations.

Figure 13: Process flow chart.


START
CLEAN
TEXTURE
3
CLEAN
CM
4
AR or Al ?
NO
TO 1
YES
EVAPORATE
Al ?
NO
TIME ?
YES
TO 1
YES
TO 2
NO
WAIT
TO 1
1
SPIN
PR ?
YES
BAKE
EXPOSE
DEVELOP
NO
HARDEN
TO 2
ETCH
GRID ?
YES
Ni PLATE
NO
REMOVE PR
TO 2
YES
Ni ?
NO
TO 1


2
TEMP ?
580
300
900
FURNACE
TIME ?
WAIT
NO
YES
STRIP
TO 3
FURNACE
DIP SOLD.
CLEAN
OUTPUT
DOPED ?
NO
FURNACE
TO 1
YES
FURNACE
TO 1

CONCLUSIONS

A production line for 3" silicon solar cells was set up which was capable of producing up to 100 cells per day. With a few process modifications, the line, requiring at most 3 operators should be able to produce 200 cells per day or over 50 kW of electrical power generation per year.

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2. Kukulka, High Efficiency, Low Cost 3" Diameter Silicon Solar Cells, Master's Project, McMaster University, Hamilton, 1979.

3. Private discussion with M. Fields, Millipore Corp.

4. Monsanto's "Flip-Tran" cassette is one example.

5. Private discussion with J. Shewchun.

6. Private discussion with D. Barber, Linear Technologies Inc.

7. The addition of H_2O_2 to H_2SO_4 results in an exothermic reaction which can be quite violent.

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