JPL NO. 9950-534

DOE/JPL 954796-81/12

Distribution Category UC-63, List of 02/23/81

[redacted]

Contract 954[illegible]
Quarterly Report July to October 1980
(DRD Line Item 6)

(DOE/JPL-954796-81/12) ANALYSIS AND EVALUATION IN THE PRODUCTION PROCESS AND EQUIPMENT AREA OF THE LOW-COST SOLAR ARRAY PROJECT Quarterly Report, Jul. - Oct. 1980 (Pennsylvania Univ.) 174 p HC A08/MF A01 G3/44

N81-23622

Unclas 42382

UNIVERSITY of PENNSYLVANIA

The Moore School of Electrical Engineering

PHILADELPHIA, PENNSYLVANIA 19104

The JPL Low-Cost Silicon 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.

DOE/JPL-954796-81-12
Distribution Category UC-63, List of 02/23/81

ANALYSIS AND EVALUATION
IN THE PRODUCTION PROCESS
AND EQUIPMENT AREA
OF THE
LOW-COST SOLAR ARRAY PROJECT

Contract 954796
Quarterly Report July to October 1980
(DRD Line Item 6)

Subject: Assessment Of Metal Deposition Processes

January 1981

M. Wolf and H. Goldman

The JPL Low-Cost Silicon 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.

Summary

In this quarterly report, the attributes of the various metallization processes have been investigated which express themselves in economic results.

a.) It has been shown that several metallization process sequences will lead to adequate metallization for large area, high performance solar cells at a metallization add-on price in the range of \$6.- to 12.-/m^2, or 4 to 8¢/W(peak), assuming 15% efficiency.

b.) Conduction layer formation by thick film silver or by tin or tin/lead solder leads to metallization add-on prices significantly above the \$6.- to 12.-/m^2 range.

c.) The wet chemical processes of electroless and electrolytic plating for strike/barrier layer and conduction layer formation, respectively, seem to be most cost-effective.

d.) Vacuum deposition of the strike/barrier layer can be competitive with electroless plating.

e.) The final selection of a process sequence may hinge on small, but important effects connected with masking, such as underspray under shadow masks, overplating of the edges of the barrier layer, registration problems, etc.

f.) The use of the AR coating as the metallization mask may be even more attrative as it may avoid some of the problems mentioned in point e.).

g.) Some further development effort should be expected

to be needed after carefully observed pilot line operations may reveal problems of process controllability, yield, or like those mentioned in points e.), which may influence initial solar cell performance or cause long term degradation.

TABLE OF CONTENTS

LIST OF TABLES

I. INTRODUCTION

The manufacturing methods for photovoltaic solar energy utilization systems consist, in complete generality, of a sequence of individual processes. This process sequence has been, for convenience, logically segmented into five major "work areas": reduction and purification of the semiconductor material, sheet or film generation, device generation, module assembly and encapsulation, and system completion, including installation of the array and the other subsystems. For silicon solar arrays, each work area has been divided into 10 generalized "processes" in which certain required modifications of the work-in-process are performed. In general, more than one method is known by which such modifications can be carried out. The various methods for each individual process are identified as process "options". This system of processes and options forms a two-dimensional array, which is here called the "process matrix ".

In the search to achieve improved process sequences for producing silicon solar cell modules, numerous options have been proposed and/or developed, and will still be proposed and developed in the future. It is a near necessity to be able to evaluate such proposals for the technical merits relative to other known approaches, for their economic benefits, and for other techno-economic attributes such as energy consumption, generation and disposal of waste by-products, etc. Such evaluations have to be as objective as possible in light of the available information, or the lack thereof, and have to be periodically updated as development progresses and new information becomes available. Since each individual process option has to fit into a process sequence, technical interfaces between consecutive processes must be compatible. This places emphasis on the specifications for the work-in-process entering into and emanating from a particular process option.

The objective of this project is to accumulate the necessary information as input for such evaluations, to develop appropriate methodologies for the performance of such techno-economic analyses, and to perform such evaluations at various levels.

The reduction of quartzite to metallurgical grade silicon has previously been examined, and the comparative evaluations of competing Czochralski techniques for growing single crystal, cylindrical ingots, and of slicing processes to produce single crystal silicon wafers were performed. The subsequent "work area" in the process sequence for fabricating solar arrays is the conversion of the silicon wafers to solar cells. This process involves many steps. One of the key process steps is the front junction formation. Of the major junction formation process options which are currently available, gaseous diffusion was examined in more detail as the classically most successful process. Then, alternate options, including modified diffusion processes and ion implantation were studied for their potential as lower cost or higher efficiency, mass production processes.

After junction formation, the next major step in cell fabrication is metallization. The metal pattern is needed to collect and deliver the current from the photovoltaically active parts of the solar cell to a terminal where the load can be conveniently connected. The input work-in-process specifications, procedures, attributes, technical readiness, and costs for current and proposed major metallization processes have been examined, as well as the requirements for ancillary processes, such as masking, sintering, etc. These metallization processes are: wet chemical plating which includes immersion, electroless, and electrolytic plating; vacuum deposition where the metal can be vaporized by thermal energy, by an electron beam, or by sputtering with Argon ions; and thick film screen printing of noble and base metals with and without the presence of frits. A number of variations of these three principal process groups was investigated. One example of such variations is the application of various types of strike and sensitizing layers before the plating of the actual "conduction layer". A variation of vacuum deposition (or of ion implantation) is ion plating, where the vaporized metal atoms are ionized either by an Argon plasma or by an RF field, and accelerated towards the deposition area by an electrostatic field. Further, a variation of thick film screen printing is the Midfilm process which incorporates some aspects of the photoresist process.

Not only does the conduction layer as such have to be applied to the cell but its pattern has to be defined, at least on the front surface of the cell, in accordance with the results of design calculations to obtain high cell efficiency. This pattern will normally be designed to minimize both the series resistance losses and the area coverage. This particular report concentrates on the principal options for applying the metal to the silicon surface, and particularly on their costs. In some cases, the pattern definition process steps are connected with AR-coating formation, in others, they are an integral part of the metallization procedure, as in thick film screen printing. The processes for pattern definition have not yet been examined as extensively as the metallization process options, and are omitted where they do not form part of the metallization process itself.

As in the previous studies of processes, the evaluations were started with the current methods of metallization for which a large amount of the needed information is normally available. Nevertheless, substantial gaps or uncertainties were found in important information required for both technical and economic evaluation of the currently practiced processes. In proceeding to the evaluation of processes which are still in the developmental or even conceptual stage, the gaps in needed information become very large. In these cases, it is necessary to fill the gaps more extensively with estimates based on extrapolations or analogies.

TABLE I

Principal Metallization Process Options

I. Contact Masking

A. Standard positive or negative photoresist procedures (Kodak, Shipley, etc.)

B. Midfilm process (developmental)(Spectrolab)

C. Printing of resist (offset, screen, etc.)

D. Spraying of resist

E. Plasma etching (shadow mask) of AR coating (Motorola)

II. Plating

A. Pd (immersion + electroless)/Ni(electroless)/solder (dip)(Motorola)

B. Pd (immersion + electroless)/Ni(electroless)/Cu (electrolytic)(Motorola)

C. Pd (immersion)/Ni(electroless)/Cu(electrolytic) (Motorola)

D. Ni (electroless)/Cu(electrolytic)(ASEC)

E. Au (electroless)/Ni(electroless)/solder (dip) (Photowatt, Solar Power, Solar Systems)

F. Ni(electroless)/solder (dip)(Solarex)

III. Thick-film screen printing

A. Ag ink with glass frit (ARCO Solar)

B. MoO_3:Sn ink (developmental)(SOL/LOS)

C. Fritless Ag or Cu ink using AgF and germanium or silicon alloys as fluxes (developmental) (Bernd Ross Assoc.)

IV. Vacuum deposition

A. Ti-Pd-Ag evaporation (Spectrolab, ASEC)

B. Ti-Pd evaporation followed by electroplating of Ag (Spectrolab, ASEC)

C. Ti-Pd evaporation followed by electroplating of Cu (Westinghouse)

II. The Principal Metallization Process Options

From the large matrix of potentially useful metallization process options, the more important processes are listed in Table I. In regular manufacture of solar cells, so far only the plating processes E and F have been applied, as well as the thick film printing process III A, and the vacuum deposition process IV A. The latter, as a system of proven high reliability on high performance solar cells, has been applied primarily in the fabrication of cells for application on spacecraft. The remaining processes are either developmental or have been used in pilot line fabrication of solar cells. However, a few of these processes, such as II D or IV C, may become production processes in the near future.

Not mentioned in Table I have been sintering steps, which are used with all thick film processes, and have also been applied after most immersion or electroless plating steps, as well as after the vacuum deposition of silver. The metallization processes which include a solder dip, have generally been carried out without a separate sintering step. The brief heating cycle connected with the solder dip, however, may have a similar effect as a sintering step.

Through the years, it has been found again and again, that electroless plated layers without a subsequent sintering step tend to show occasional incidences of weak contact adhesion. Experience has also shown that the electroless plating of nickel on silicon is a process which is difficult

TABLE II

A. Plating

1) Pd-Ni-solder (Motorola)

a) Immersion Pd Coat and Sinter

1. Dip for 10 sec in a 10:1 H_2O:HF solution, followed by a DIH_2O rinse (30 sec in a 50:1 H_2O:HF solution, no DIH_2O rinse).

2. Immersion Pd for 2 min, followed by DIH_2O rinse (immersion Pd for 3 min, followed by a 5 min DIH_2O rinse.)

Option A.

(3) Aqua regia dip for 5 sec, followed by a 15 min DIH_2O rinse.

(4) Dip for 20 sec in a 50:1 H_2O:HF Solution

(5) Immersion Pd for 5 min, followed by a 5 min DIH_2O rinse.

(6) Spin dry and inspection.

(7) Sinter for 15 min @ 300°C with N_2 purge.

(8) Dip for 20 sec in a 50:1 H_2O:HF solution.

(9) Immersion Pd coat for 2 min, followed by a 2 min DIH_2O rinse.

Option B.

3. Spin-dry and inspection.

4. Sinter for 30 min @ 300°C with N_2 purge.

5. High pressure scrub (both sides).

6. Dip for 5 sec in 10:1 H_2O:HF solution, followed by DIH_2O rinse.

7. Immersion Pd coat for 15 sec, followed by a DIH_2O dip.

b) Electroless Pd Coat and Sinter

1. Electroless Pd coat for 95 sec, followed by DIH_2O rinse. (electroless Pd coat for 45 sec, followed by a 10 min DIH_2O rinse).

2. Spin-dry and inspection.

3. Sinter for 30 min at 600°C with N_2 purge (300°C for 15 min with N_2 purge).

c) Electroless Ni plating

1. Electroless Ni plate for 5 min at 80°C, followed by 10 min DIH_2O rinse.

2. Spin-dry and inspection.

---

d) Solder

1. Immerse cell in solder flux (type RA, Kester 1544), and allow excess to drain.

2. Immersion in solder (Kester 60:40 Sn:Pb) at 240°C for 1 sec.

3. Remove excess flux by agitating in TCE.

4. Second dip in TCE.

5. let stand in acetone for 5 min.

6. Rinse in DIH_2O and spin-dry.

Note: The process details listed as Option A as well as those shown in parenthesis at other steps were obtained from the LSA Process Specification Format supplied by Motorola.

The remaining details were obtained from Quarterly and Final Reports, as well as by private communication of H. Goldman with personnel of the respective organizations.

2) <u>Au-Ni Plating (Sensor Technology)</u>

1. Dip for 30 sec in concentrated 48% HF.

2. Electroless gold coating dip for 30 sec, followed by a DIH_2O rinse for 4 min (Small quantities of HF have been added to the gold solution for the reaction to proceed at RT).

3. Electroless Ni plating at 83°C for 4 min, followed by two deionized water rinses of 4 min each.

4. Spin-dry and inspection.

Note: Solar Power Corp. and Solar Systems, Inc. also do electroless Ni plating, apparently with preceding electroless gold plating, but their detailed procedures are not available.

B. Thick Film Processes (Screen-Printing)

1) Thick Film Screen Printing (RCA)

1. Mixing of metal powder (90 wt% Ag) and frit (10 wt% lead borosilicate) with organic vehicle (6 wt% ethyl cellulose (N-300) and 94 wt% Carbitol).

2. Screen printing of metal pattern on wafer (includes preparation, mounting, and cleaning of screen).

3. Heat treatment of wafer for drying and removing volatiles: 15 minutes at 125°C; followed by a 90-120 sec sinter at 675-700°C.

2) Thick Film Screen Printing of MoO_3:Sn (SOL/LOS)

1. A 4:1 wt mixture of Sn:MoO_3 is blended in a 2:1 wt ratio with an organic vehicle which consists of 25 wt% ethyl cellulose and 75 wt% trichloroethylene. Traces of titanium resins are added to the ink (to ensure an ohmic contact?).

2. Screen printing of wafers.

3. The wafers are air dried to remove volatiles, baked at 400°C to burn out carbon, and heated at 700°C for 0.5h in a nitrogen and hydrogen atmosphere to reduce the MoO_3 and sinter the metal contact.

3) Thick Film Screen Printing of an Al BSF and Contact (Spectrolab)

1. Etch back-surface with HF for 15-60 sec, DIH_2O rinse and dry.

2. Screen print Al ink using a 200 mesh screen. The ink consists of 70% Al, 28% terpineol, and 2% ethyl cellulose. Size of Al particles is 6-8 μm.

3. Air dry at 250°C for 10-15 min.

4. Melt in air at 900°C for 30 sec.

5. Removal of oxidized Al by dipping in 1% NaOH solution, followed by ultrasonic cleaning.

C. Photoresist Type Processes

1) Typical Photoresist Process (Kodak)

1. Application of Koday Micro Positive Resist 809 photoresist to wafer with spinning at 5200 rpm for 30 sec.

2. Pre-baking of wafer for 30 min at 90°C.

3. Exposure through a mask with a 200 Watt high pressure Hg lamp for 8-10 sec (energy flux $\geq$ 170 mW/cm^2).

4. Development with agitated Micro Positive Resist Developer diluted 1:1 with H_2O, followed by a deionized water rinse for 30 sec.

5. Air dry with jet of nitrogen.

6. Post-bake at 90°C for 30 min.

7. Mild HF etch.

8. Application of metal (i.e. by vapor deposition, dipping, plating, etc.).

9. Washing away of undeveloped resist with isopropyl alcohol for 30 sec, followed by a 5 sec deionized water rinse.

2) MIDFILM Process (Sepctrolab)

1. Application of MIDFILM photoresist resin either by spin-on or spray-on. Wafers are first rinsed with trichloroethane.

2. Exposure of coated wafer with a mercury lamp through a mask (28 mW/cm^2 for 3 sec).

3. Application of metal powder and removal of excess powder.

4. Sintering of wafer at 600°-800°C for 40-60 sec.

D. Vacuum Metal Deposition and Plating

1) Ti-Pd-Aℓ-Ni deposition followed by Ag plating (Westinghouse).

1. Wafers are loaded into the entrance airlock portion of the vacuum deposition system which is pumped down for 15 minutes. The wafers are then transported into the deposition chamber. The metal fluxes are: 0.09 g/m^2 for Ti, 0.242 g/m^2 for Pd, 8 g/m^2 for Aℓ, and 0.054 g/m^2 for Ni. After this, the wafers are transported into the exit airlock portion of the system where they are brought up to atmospheric pressure.

2. Dip in a buffer solution for 15 min.

3. Stripping of photoresist with overlying metal in acetone for 20 min.

4. Sintering for 20 min at 400°C in N_2 atm.

5. Electroplating of silver for 5 min.

6. DIH_2O rinse and dry.

to control. To improve process control, a number of organizations prefer to precede the electroless nickel plating by one or more electroless plating steps depositing gold or palladium layers. At times, however, these processes have exhibited their own control problems, which led to a lively debate of their real merits. Since statistics on the process control problem or the associated cell yields are not available, this variable between the different process options could not be entered into the economic analysis.

Details of the process sequences, as they were given in various progress reports by contractors of the LSA program, are summarized in Table II. Such detailed process descriptions can form the starting point for an economic analysis.

In the thick film (screen printing) processes, the printing inks are found to be the major cost item. The formulation of these inks has become the basis of an industry of apparently prosperous small companies, except that one of the major suppliers is E.I. DuPont de Nemours and Company. The industry jealously guards its "trade secrets" in the largely empirically evolved formulation of these inks, although they seem to be quite well known within the industry. Under the LSA program, two companies have given details on the formulation of these inks. This information is summarized in Table III. It is noteworthy that these inks generally have a relatively low metal content. Consequently, upon drying and sintering, the volume of the ink shrinks to approximately 50% of that

TABLE III

Comparison of the Compositions of the Inks Used by RCA and Lockheed

A) RCA Ink: (80 wt% solid, 72 wt% Ag)

Source: RCA Process Specification for Thick Film Screen Printed Metallization

The ink constituents are:

	Wt%	ρ (g/cm^3)	Vol %
		Solids	
Ag	90.3	10.49	85.0
glass frit	9.7	6.376	15.0
		Vehicle	
butyl carbitol	94	0.99	94.3
ethyl cellulose	6	1.13	5.7
		Ink	
Solids	80	9.872	28.8
Vehicle	20	0.997	71.2

The density of the solids is equal to:

$$\rho_{solid} = (0.903/10.49 + 0.097/6.376)^{-1}$$
$$= 9.872 \text{ g/cm}^3,$$

while the vehicle density is:

$$\rho_{veh} = (0.94/0.99 + 0.06/1.13)^{-1}$$
$$= 0.997 \text{ g/ml}.$$

The ink density is then:

$$\rho_{ink} = (0.20/0.997 + 0.80/9.872)^{-1}$$
$$= 3.552 \text{ g/cm}^3.$$

It can be readily shown that the volume fraction of the solids in the wet ink is given by:

$$V_{solid} = \frac{\rho_{ink} - \rho_{veh}}{\rho_{solids} - \rho_{veh}} = 0.288$$

During drying and firing, the ink has been reported to shrink to about half its volume. Therefore the solid volume fraction in the sintered ink should be 57.6%.

B) Lockheed (65 wt% Ag, Dupont 7095 ink)

Source: Lockheed, Final Report DoE/JPL 954898-78/4, p. A-29 (10/78).
W. Robson, Dupont, private communication (9/79).

The ink constituents are:

	Wt%	ρ (g/cm^3)	Vol %
		Solids	
Ag	93 †	10.49	81.6
Glass Frit	7 †	3.5	18.4
		Vehicle	
Dupont 8250	95*	0.94	95.8
ethyl cellulose	5*	1.13	4.2
		Ink	
Solids	69.9 †	9.203	19.3
Vehicle	30.1 †	0.9480	80.7

Using the procedures as shown in the first part of this Table, the following values are obtained:

$$\rho_{solid} = 9.203,$$

$$\rho_{veh} = 0.948,$$

$$\rho_{ink} = 2.541,$$

and

$$V_{solids} = 19.3\% .$$

Lockheed reports a volume shrinkage of 50% in drying, which would lead to solids volume of 38.6% in the dried ink. There may be additional shrinkage upon sintering.

* estimated
† given by DuPont.

of the wet ink, as applied. Also, because of ink viscosity and screen geometry, the maximum application thickness of the wet ink is usually considered to be 20 to 25 μm, resulting in a line thickness near 10 to 12.5 μm after sintering. RCA, however, has been able to formulate an ink which can repeatably be applied in 25 μm thickness (wet), and which shrinks only to about 80% of its original volume upon sintering, that is, to a line thickness of about 20 μm.

Six generic metallization processes have been selected for a more detailed comparative analysis. The available information on these processes has been tabulated on UPPC formats which are contained in Appendix I. These six processes are: thick film screen printing as a process which requires neither masking nor a strike or barrier layer; electroless nickel plating for the formation of a strike or barrier layer; vacuum evaporation for consecutive deposition of a nickel barrier layer and a copper conduction layer; sputtering of a copper conduction layer; electrolytic plating of a copper conduction layer; and, finally, solder dipping for build-up of a conduction layer over a metal strike layer which, for this case, usually is nickel.

The thick film screen printing process is essentially a state-of-the-art process, using automatic cassette unloaders and loaders, automated single wafer handling including a collator between the screen printer output and the belt furnace (or furnaces) used for drying and sintering.

The electroless plating process described here is a conceptual scale-up of the current, essentially beaker-type plating operations, projected to use automatic wafer handling into and out of the baths, as well as automatic liquid recirculation and replenishment of the plating and rinsing baths. The vacuum evaporation process is based on a large scale, fully automated deposition system with continuous evaporation. Similar systems have been built and operated successfully, although not in the semiconductor or solar cell industries. The wafers would move past the evaporation boats on their wafer/mask holders on a one meter wide track, that is about nine 10 cm x 10 cm cells abreast, and the source material would be evaporated from approximately one meter long graphite boats which are heated by electron beams. The wafer/mask holders would enter the system in batches through an airlock and be disassembled from the batches into a continuous flow within the deposition chamber. After complete metal deposition on one side, the wafer/mask holders are turned over for deposition on the second side, as all evaporation takes place upward from the source boats. After completion of the deposition on the second side, the wafer/mask holders are reassembled into batches for exit from the system through a second airlock.

The sputter deposition would proceed in a way similar to that projected for the vacuum deposition. Here, the deposition of only one metal has been considered. Also, the system studied here has a lower capacity than that investigated for vacuum deposition. While the sputter deposition system does not need the electron beam guns and their power supplies, which the vacuum deposition system incorporates, it needs rf power supplies to maintain the glow discharge for sputtering. Also, the sputter targets need to be replaced periodically, while the source metal can be supplied continuously for vacuum deposition. Further, the sputter system needs gas pressure and flow control. Beyond this, the systems should be quite similar.

For the electrolytic deposition of copper over a pre-existing strike layer, two different types of automated plating systems have been proposed by two different fabricators of such systems. The one is an inline tank system, called a finger plating system, where each individual cell would be, after unloading from a cassette, automatically attached to a holder ("finger") which also makes the electrical cathode contacts. These fingers are attached to a belt or chain. They immerse the cells sequentially and for the appropriate times into the various plating and rinse tanks. The required immersion times and the belt speed determine the physical lengths of the tanks, which turns out to be of the order of 60 feet for the throughput rates required here. The wafers are assumed here to be plated on both sides simultaneously. The second plating system is a "carousel" machine where holders, with groups of cells attached, are immersed in a tank for a given time period, then removed and transported to the next tank in a circular movement, and immersed there. While the finger plating machine is based on continuous, linear movement, the carousel machine works with periodic movement. Here, the tanks have only to be large enough to hold the required number of holders in essentially stationary fashion. Both machines function equally automated, and their prices, for the same throughput rate, are comparable, that is approximately a quarter million dollars. Exact prices will be available only after such a machine has been fully specified and pre-designed.

III. Selection of Metals for the Conduction Layer.

The question of a process sequence, or several sequences ultimately to be selected for the low cost fabrication of high performance solar cells, is closely connected with the selection of the metal to be used for the conduction layer of the solar cell. Since this layer constitutes a significant amount of metal on the cell, the cost of the raw metal alone can make a major process cost contribution. In addition, a given process usually is not capable of depositing any selected metal. Thus, the selection of the metal will, to a degree, determine the ultimate process selection. This may be illuminated on the example of the thick film processes. The conventional thick film processes are principally of very low cost in their execution. They use relatively inexpensive equipment of high throughput rates, with little labor required for the operation. However, in the conventional form of these thick film processes, reasonably good conductance in the metal layers can be achieved only by the use of silver which is a rather expensive metal. Of the two developmental processes in thick film deposition, the molybdenumtrioxide/tin process uses tin for the conduction layer which also is rather expensive in the thicknesses needed to achieve adequately low sheet resistance, while the fritless process which is still in relatively early development, could apply the inexpensive copper.

PRECEDING PAGE BLANK NOT FILMED

TABLE IV

Physical and Cost Data of Various Metals of Interest for Solar Cell Metallization

1 Metal	2 Resistivity μΩcm	3 Density g/cm^2	4 1975 Price ¢/g	5 Thickness needed for 1.67 mΩ sheet resistance μm	6 Mass needed to cover 1m^2 at this thickness g/m^2	7 Cost of metal for this layer ¢/m^2	8 Cost of metal for a 100 Å thick layer ¢/m^2
Aluminum (Al)	2.655	2 7	0.09 (1)	15.9	42.9	3.86	0.002
Copper (Cu)	1.67	9.0	0.14 (1)	10.0	90.0	12 6	-
Molybdenum (Mo)	5.2	10.2	7.0 (3)	31.1	317	2220	0.71
Nickel (Ni)	6.85	8.9	0.485 (1)	41.0	365	177	0.04
Gold (Au)	2.35	19.3	450 (1)	14.1	272	122,460	86.9
Palladium (Pd)	10.8	11.4	177 (3)	64.7	738	130,550	20.2
Platinum (Pt)	10.5	21.45	514 (1)	62.9	1349	693,490	110
Silver (Ag)	1.6	10.5	16.14 (1)	9.6	100 8	1627	1.7
Solder (50:50 Sn·Pb)	15	8.9	0.7 (3)	89.8	799	559	-
Tin (Sn)	11	7.3	0.67 (1)	65.9	481	332	0.05
Titanium (Ti)	43	4.5	7.0 (2)	257.5	1159	8110	0.32
Tungsten (W)	5.65	19.3	7.0 (3)	33.8	652	4570	1.35
Zirconium (Zr)	41	6.5	48 (3)	245.5	1596	7660	3.12

1. Electronic News, 20 (1060) (12/75)
2. SAMICS Cost Account Catalog, ERDA/JPL-954800-77/21 (9/77).
3. MC/B Chemical Reference Manual (6/73).

These metal cost considerations are illustrated in Table IV which lists the more likely metals to be used in the metallization process, the thickness of a layer needed to achieve the same sheet resistance as a 10 μm thick layer of copper, and the costs of a square meter of such a layer. It is seen that this metal cost alone of such a layer covers five orders of magnitude, and that for only two candidate metals, aluminum and copper, the cost is in a range where it does not make a major contribution to the total cost of metallization. Even tin, whose price per unit mass does not differ greatly from that of aluminum or copper, has to be used in such a thick layer that the metal cost for a layer of comparable conduction is two orders of magnitude above that of the other two metals. This large required thickness is the consequence of tin's relatively high resistivity.

In contrast to the requirements of the conduction layer, a number of metals are applicable for use in strike or barrier layers. In this application, the metals may be used in layer thicknesses in the order of twenty to a few hundred Angstroms. To permit an evaluation of the metal cost for use in such strike or barrier layers, the cost of a one-hundred Angstrom thick layer of metal has also been listed in Table IV.

It may be noted that outside of the resistivity, the density of the metal plays a significant role towards its ultimate cost. An example of this is a comparison between aluminum and copper. As the resistivity of aluminum is proximately 50% higher than that of copper, the layer thickness needed for equal sheet resistance is also approximately 50% higher. However, the density of aluminum is less than 1/3 of that of copper, so that the total mass of aluminum needed on a square meter is less than half of that of copper. Since the metal prices are always based on unit mass, and the aluminum price is approximately 2/3 of that of copper for equal mass, the final cost of the conduction layer for aluminum ends up being less than 1/3 of that of copper.

It may be noted that this discussion has not provided the complete picture for the cost of metal used in a particular process. As was discussed in section III. (of the Quarterly Report No. 954976-81-11), not every type of process results in bulk conductivity of the deposited metal layer. Thus, a larger amount of metal may actually be needed to achieve the same sheet resistance as a layer of bulk conductivity. In addition, different deposition processes utilize the metal at differing efficiencies. This means that frequently, only a fraction of the metal used is actually deposited on the desired areas of the cell. This leads to significant variations in the cost of the metal actually used in the different processes.

IV. Metal Utilization in the Various Deposition Processes

The electroless and electrolytic plating systems, as well as the solder dipping of partially metallized semiconductors, generally deposit material only on the areas to be plated, either because they are already covered by a strike layer or because the not-to-be-plated areas are covered with a contact mask (resist). Also, the metal contained in the plating baths can be utilized very effectively, particularly through the praxis of "replenishing". Consequently, these processes have a high "plating efficiency", which refers to the source metal utilization.

In contrast, the vacuum deposition methods "spray" the deposition material in a cone from the source, and deposit it both on the to-be-plated and the not-to-be-plated areas. This causes large differences in the so-called plating efficiency. A significant fraction of the spuriously deposited material can, however, be recycled, that is repurified and formed into the shape required for the source material of the deposition process. For copper deposition, the primary requirement is adequate purity of the metal, and freedom from oxygen. For vacuum deposition, the copper is fed in wire or rod form to the source boats, while in sputter deposition, the material has to be brought into the shape of the targets, which usually are flat plates. Also, the sputter targets cannot be fully utilized, so that a part of the target material has to be recycled. Consequently, in the following analysis, the material usage is divided into that for virgin material and that for recycled material.

Of the total material evaporated from the source, only a fraction ends up on the desired areas of the substrate. Other fractions of the material are deposited on the walls and other interior parts of the vacuum evaporation chamber, on the mechanical device which holds the substrates and masks in their relative positions, (usually called the substrate holder), and on the masks themselves. A part of this spuriously deposited material can be reclaimed. Consequently, two prices for the source material will be applicable. One will be the price of the "virgin" material, which is composed of the commercial raw material price plus the price of further processing to the desired purity level and the physical shape may be rods or pellets for vacuum evaporation, or flat plates for the targets of sputter systems. The other is the price of the recycled material which may contain the price of further purification costs, depending on the condition and purity of the reclaimed material, and of physical shaping.

Four different quantities relative to the amount of source material used are of interest. The first one is the gross amount of material used which is the amount of material evaporated or sputtered from the source. This quantity is of importance for determining the life of the source boat or of the sputter target, and for determining the rate at which the source material has to be supplied. A second quantity is the amount of material which actually ends up on the substrate. This is the real "direct material". The third quantity is the net amount of source material used, which is the material deposited on the substrate plus the amount of material lost in one cycle of the process. This is the amount of source material to be bought at the price of the virgin material. The fourth quantity finally is the amount of material reclaimed, which can be replaced at the recycling price.

The "gross deposition area" is determined by the holder. This area is composed of the projected area of the holder itself, excluding any open areas, and the area of the masks, including their openings, A_{mask}. This gross deposition area shall be designated as the "holder area" A_{hold}. Only a fraction of the material which leaves the source boat, is actually deposited on this holder area. This fraction is commonly called the deposition efficiency η_{dep}.

Deposition will generally be carried out until a certain thickness d of the deposited layer has been reached. Since, in the case of solar cells, metal has to be deposited both on the front and the rear surfaces of the substrate, two different thicknesses d_F and d_R for the front and rear deposited layers, respectively, may be involved. The mass M_{evap} of the gross amount of source material used is then determined by:

$$M_{evap} = \frac{A_{hold}}{\eta_{dep}} (d_F + d_R)\ \rho_{Met}\ ; \tag{1}$$

where ρ_{Met} is the density of the source material. The deposition efficiency is an empirical quantity which depends on the set-up of the given deposition apparatus. It will normally be determined experimentally from the holder area and the gross amount of material evaporated, in inverse application of eq. (1). A number of 70% has been quoted for the deposition efficiency as representative of experience data in large area depositions, as discussed here.

The mass M_{subs} of the material deposited on the desired areas of the substrate is given by:

$$M_{subs} = (A_{subs,F} d_F + A_{subs,R} d_R)\ \rho_{Met}\ ; \tag{2}$$

This quantity is part of the net amount of metal used, whose mass M_{net} is expressed by:

$$\begin{aligned} M_{net} = A_{hold}\rho_{Met} \Bigg\{ & \frac{1-\eta_{dep}}{\eta_{dep}} (d_F + d_R)(1-r_{wall}) \\ & + (1-f_{hold})(d_F + d_R)(1-r_{hold}) + f_{hold} \\ & \cdot \Big[(1-f_{mask,F})\ d_F + (1-f_{mask,R})\ d_R\Big]\ (1-r_{mask})\Bigg\} \\ & + M_{subs}\ ; \end{aligned} \tag{3}$$

In this equation, the first term in the large brackets represents that amount of material which is deposited on the walls and other parts of the vacuum system, and which is not recycled. It is expressed as the gross amount of material evaporated minus the material deposited on the holder area, multiplied by $(1-r_{wall})$ where r_{wall} is the fraction of this material which is recycled. The second term in the large brackets of eq. (3) gives the fraction of the material deposited on A_{hold}, but excluding the material deposited on the mask area A_{mask}, expressed by the factor $(1-f_{hold})$. Again, the fraction $(1-r_{hold})$ of this material is not recycled.

Finally, the last term in the large brackets describes the material which is deposited on the masks, but excluding that deposited on the substrate areas which are represented by the openings in the mask. Again, the fraction $(1-r_{mask})$ is not recycled and enters here. The last term outside of the brackets finally is the material deposited on the desired areas of the substrate (M_{subs}), as given by eq. (2).

The mass of the material that is recycled, finally is given by:

$$M_{recl} = A_{hold}\rho_{Met} \left\{ \frac{1-\eta_{dep}}{\eta_{dep}} (d_F + d_R)\, r_{wall} + (1-f_{hold})(d_F + d_R)\, r_{hold} + f_{hold} \left[(1-f_{mask,F})\, d_F + (1-f_{mask,R})\, d_R \right] r_{mask} \right\} \tag{4}$$

This relationship essentially contains the three terms in the large bracket of eq. (3), except that the fractions recycled, r, appears rather than (1-r).

V. Comparative Economic Evaluation

So far, only the metal deposition processes by themselves have been evaluated, that is excluding any masking or mask removal steps, where these are separate from the metallization process itself. In these evaluation activities, it has been found more difficult to attain adequate process data for a meaningful evaluation than it has been with the processes analyzed previously. Part of this difficulty is probably attributable to the larger variety of processes used in this area. Beyond this, however, it was found more difficult even to attain a consistent set of data on an existing process with a good experience base. Such an economical data set of a well-understood process has been used as the basis for extrapolation to the future large-scale processes in the other process areas. In addition, it appears that the jump in process technology from the processes currently used for solar cell metallization, to those to be applied in the future is, at least in the automation part, larger in this process area than in those analyzed previously. This is best illustrated by the fact that a significant part of current metallization is based either on a vacuum deposition process which, although called automated, does not differ significantly from those used with laboratory type evaporation systems. Much of the alternate metallization used on current production lines is based on the electroless nickel plating process, which is carried out in a manner very close to a beaker type of operation, that is on a near laboratory scale. The only process used to some extent in current solar cell production which is close to an automated large scale process, is the thick film process. This process, however, will be less attractive for the future because of the high metal cost and the limit on achievable line width.

To achieve a comparison basis for the principal process options, projections have been made to the performance of these processes at comparable production rates, and with equipment of comparable levels of automation. For this comparison purpose, the six generic processes listed in section II of this report have been selected and subjected to these extrapolations. One of these processes includes the pattern definition as such: the thick film deposition process. The other processes require masking of one type or another for the pattern definition, and their costs have not been included in the present analysis. In some cases, the AR-coating serves as the mask, and thus does not contribute additional costs.

In physical vapor deposition, the masks can be of either of two types. They can be contact or temporary masks (resist), or they can be shadow masks which can be reused many times. A third possibility exists which involves the deposition of metal over the whole substrate area, application of a resist over the areas on which deposition is desired, and subsequent removal of the material (etching) from the areas on which deposition was not desired, followed finally by removal of the resist from the remaining deposited material. Particularly where the area of desired deposition is relatively small, as on the front areas of the solar cells, this process is relatively cumbersome and expensive. In addition, it seems that the deposited and resist materials can never be completely removed, so that the surfaces would remain in a somewhat altered state after application of this procedure. Consequently, this approach will not be discussed further.

The method most commonly used in physical vapor deposition employs the shadow mask. It is very practical where only thin films are deposited, perhaps up to a few thousand Angstroms in thickness, or where the open area in the mask is very large and the opening dimensions are not critical. These conditions are not fulfilled for the front area of the solar cell, where the desired open area is only about 3.4% of the total area, and the line width may be near 25 μm. With a deposit of 10 μm thickness, the openings in the mask would be substantially reduced during the course of a single deposition. Thus, the mask would have to be removed from the holder after only a few depositions, and the deposited material cleaned off. This consumes not only labor and chemicals (with subsequent disposal and reclaiming problems) but it also significantly shortens the life of the mask.

The second alternative consists in the application of a temporary mask, usually in the form of a photoresist.

At the edge of the resist to the open areas, a step in height occurs. In the deposition, the thickness of the deposited layer is generally reduced at this step. In the subsequent removal of the resist, the deposited layer usually separates at this step, so that the part of the layer which was deposited over the resist, can be readily removed with the latter. At a 10 μm thick deposition, however, as considered here for deposition of the conduction layer, the material deposited over the step will still be of sufficient thickness and consequently mechanical strength, that removal of the deposit over the mask without damage to the deposited layer in the open areas cannot be expected.

Although the vacuum deposition (or sputter deposition) even of 10 μm thick copper layers is basically one of the economically feasible processes, the problems encountered with the masking for fine line pattern generation make it unfeasible for the deposition of the conduction layer on the front of large area solar cells. The process can, however, be economical and practical for the deposition of thin strike or barrier layers in preparation for the deposition of the conduction layer by other processes, such as electrolytic plating. In this case, the direct material component of the costs may be reduced to near negligible levels, except when palladium should be used, and the cost of the vacuum system may be cut in half because of the greatly reduced deposition time. Thus, the total process may, for

TABLE V

Comparative Tabulation of Direct Material Consumption and Cost for the Principal Metallization Options

Option		Metal	Thickness µm	Metal Mass on Cell (a) g/m^2	Plating Effic'y. %	Recycl. Rate %	Net Metal eff. g/m^2	Gross Metal Required g/m^2	Approximate Cost of Metal ¢/g	Approximate Cost of Metal $\$/m^2$
3.5.01-01	T.F. Screen Printing	Ag w/frit	20 (b)	6.5 front (c)	90	50	94.7	12 (i)	70 (i)	8.40
3.6.03-03	Vacuum Evaporation	Ni/Cu	0.1 Ni, 10 Cu	3.1 front 90 back	1.7 front 50 back (d)	75,50 (e)	51(v) 25.7 overall	181.5(v) 178.5(r)	0.3(v)(f) 0.13(r)	0.78 Cu + 0.02 Ni
3.6.04-03	Sputtering	Cu	10	dto.	dto.	75,50 (h)	7.23	188(v) 263(r) (j)	0.33(v) 0.15(r)	1.015
3.6.03-02	Electroless Plating (g)	Ni	0.5	4.6	90	-	90	5 1 18(h)	6.50(h)	0.289
3.6.04-01	Electrolytic Plating	Cu	10	92.4	95	-	95	97.3	0.200	0.195
3.6.04.02	Solder Dip	60·40 Sn Pb	55	520 (c)	95	-	94.7	547.4	1	5.474

a. Metals assumed to cover 3 4% of front area (25 µm line width), 100% of back, unless noted otherwise.
b. For layer after sintering, contains 50% by volume Ag.
c. Grid line/bus coverage taken as 6.2% commensurate with minimum line width of 125 µm.
d. Refers to metal on grid line.
e. Numbers refer to recycling efficiency of metal on machine's interior and holder, and that on mask, respectively.
f. Price of copper
g. Used as a "strike" or "barrier" layer prior to electrolytic deposition, vacuum evaporation, or sputtering of other metals, or to solder dipping.
h. In the form of $NiCl_2 \cdot 6H_2O$
i. Refers to complete ink including frit, binder, formulating, etc.
j. Includes recycled target material.
(v) Applies to the virgin material used.
(r) Applies to the additional recycled material used

thin layer deposition, be only 1/3 to 1/2 of that found for conduction layer deposition, and may become competitive with the wet chemical processes.

As has been done previously, the UPPC forms have been used as a combination guide and checklist for the accumulation of detailed process information. For the six generic processes discussed, the filled-in forms are enclosed to this report in Appendix I. To facilitate the comparison of the important attributes of these processes, the relevant data have been compiled in Tables V through IX.

Table V contains a comparative tabulation of the direct material consumption and its costs. It is evident that the screen printing process and the solder dipping process incur direct material costs, which are as much as a factor of 40 above those of the lowest cost process. Clearly, costs of \$5 and \$8 per square meter of cells for the direct materials alone place these processes out of competition for a low cost, large scale production line. This conclusion is amplified by the fact that both of these processes cannot generate very narrow line widths, and thus result in cells of inherently lower than optimum efficiency. Such a reduced efficiency constitutes another economic penalty.

It may also be noted that the data given in Tables V to IX for the thick film screen printing process apply only to the metallization on the front surface of the cells, in contrast to those for the remaining processes which apply to

TABLE VI

Comparison of Indirect Material Consumption For The Principal Metallization Options

Option		Consumable	Cost of Consumables $/m^2$	Description of Supplies (Unit Cost)	Cost of Supplies $/m^2$	Electricity Name-plate Rating (and duty cycle) and Consumption	Electricity Cost $/m^2$ (a)	Total Indirect Mat. Cost $/m^2$
3.5.01-01	T.F. Screen Printing of Ag	Xylene Solvent ($0.52/lb)	0.030	Print Screens ($25 ea.) Squeegees ($0.40 ea.) Thermocouples and misc.	0.275 0.0[illegible]5 0.10 0.410	35 kW(50%) 1.5kWh/m^2	0.075	0.515
3.6.03-03	Vacuum Evaporation of Ni/Cu	Pump oil ($30/qt, 4 qt/wk) Graphite crucible ($1000 ea.)	0.017 0.800 0.817		-	80 kW(30%) 200 kW(45%) 2.4 kWh/m^2	0.12	0.937
3.6.04-03	Sputter Deposition of Copper (10 μm)	Argon ($100/332$ft^3$) Pump oil (as under 3.6 03-03)	0.049 0.017 0.066	-	-	20 kW(75%) 45 kW(30%) 1.06 kWh/m^2	0.053	0.119
3.6.03-02	Electro-less Plating of Ni (0 5 μm)	Plating solution	0.494	-	-	20 kW(75%) 0.5 kWh/m^2	0.025	0.519
3.6.04-01	Electrolytic Plating of Cu (10 μm)	Replenishing solution ($13/gallon)	0.282	-	-	5 kWh/m^2	0.250	0.532
3.6.04-02	Solder Dipping (55 μm)	Flux ($6.75/gal) DIH_2O ($6.60/m^3)	0.363 0.053 0 416	-	-	15 kW(95%) 0.27 kWh/m^2	0.013	0.429

a. Unit cost is $0.05/kWh

front and back metallization. If metallization would also be applied to the back surface by screen printing to a thickness adequate for a low sheet resistance, the metal costs (silver) for this back surface layer would be completely prohibitive. However, Dr. D'Aiello of RCA Laboratories has shown that an adequately low effective sheet resistance can be obtained when the back surface is covered with only 0.4 µm of silver, but overlaid with several bus lines over the whole length of the cell. The bus lines may be of bulk metal ribbon or wire. For a layer of this thickness, the total costs of a screen printed back layer would equal those of the thick film front layer shown as option number 3.5.01-01.

Table VI summarizes the indirect material costs for the six generic processes. Interestingly, the total indirect material costs all fall within one order of magnitude. In vacuum evaporation, the cost of the graphite crucibles accounts for most of the indirect material costs. Since the sputter system does not use crucibles, but obtains the source material from the sputter targets, the corresponding costs are shifted from the indirect materials category to the direct materials category, as the fabrication of the target plates is more costly than that of rod or wire for the evaporation source material. In the thick film process, the replacement costs for the print screens and the squeegees account for the major part of the indirect material cost, while in the wet chemical plating processes, the cost of the chemicals for the plating

TABLE VII

Comparison of Labor Requirements For The Principal Metallization Options

	Option	Gross output (m^2/h)	Uptime	Net Output (m^2/g)	Labor Type	Hourly Rate $/h	Effort per Station %	Direct Labor Cost $/$m^2$ (a)	Indirect Labor Cost $/$m^2$ (b)	Total Labor Cost $/$m^2$
3.5.01-01	T.F. Screen Printing of Ag	12	95	11.4	Assembler Maint. Mech.	5.65 7.40	25 20	0.264 0.277 0.541	0.135	0.676
3.6.03-03	Vacuum Dep. of Ni/Cu (10 μm)	48	85	41	Assembler Maint. Mech.	5.65 7.40	50 20	0.147 0.077 0.224	0.056	0.280
3.6.04-03	Sputter Dep. of Cu (10 μm)	30	90	27	Assembler Maint. Mech. Elec. Tech.	5.65 7.95 7.40	100 10 10	0.446 0.063 0.058 0.567	0.142	0.709
3.6.03-02	Electroless plating of Ni (0.5 μm)	30	88	26.4	Assembler	5.65	100	0.456	0.114	0.570
3.6.04-01	Electrolytic plating of Cu (10 μm)	30	95	28.5	Assembler	5.65	100	0.422	0.106	0.528
3.6.04-02	Solder dipping (55 μm)	30	88	26.4	Assembler	5.65	100	0.456	0.114	0.570

a. Includes a load factor of 113% for benefits and 8780 h/year staffing
b. Taken as 25% of direct labor cost

solutions makes the predominant contribution. It is interesting to note that the electricity consumption appears considerably greater in the electrolytic plating process than in the vacuum evaporation or sputter deposition processes, although the latter require the pumping power besides the power needed for the vaporization of the source material.

In the six projected generic processes, the total labor costs fall into a rather narrow range (Table VII). The only observation to be made is that the largest throughput system shows the lowest labor costs per unit area of cells metallized, while the lowest throughput system , the thin film screen printing process, is near the peak of the labor costs. The relatively high labor content of the sputter deposition system is probably more due to the estimation of the individual making the projection than to actual experience data.

In the capital equipment area, summarized in Table VIII, the prices of the automated screen printing machine and the furnaces are probably the most reliable ones, as they represent the current state of the art. The prices for the vacuum deposition, sputtering and electrolytic plating systems are estimates given by the manufacturers of such equipment. The plating equipment costs shown include an allocation of about one third of the total for the relatively high installation and chemical waste treatment system costs. The vacuum evaporator and the sputter system costs apply to fully automated systems. Since double-sided deposition

TABLE VIII

Comparison of Capital Requirements For The Principal Metallization Options

Option		Annual Output 10^5 m^2/y	Cycle Time Min	Equipment Needed (Unit Cost)	Equip Cost $\$/m^2$ (a)	Facility Area m^2	Facility Cost $\$/m^2$ (b)	Total Capital Cost $\$/m^2$
3.5.01-01	T.F. Screen Printing of Ag	0.94	0.05	Screen Printer (50k) Dryer (20k) Furnace (35k)	0.113 0.045 0.070 0.237	40	0.076	0.313
3.6.03-03	Vacuum Dep'n. of Ni/Cu (10 μm)	3.38	55	Evaporator ($ ∿ 2 Mill)	1.264	97.5	0.052	1.316
3.6.04-03	Sputtering of Cu (10 μm)	2.23		Sputterer (∿ 3 Mill)	2.865	60	0.048	2.913
3.6.03-02	Electroless Plating of Ni (0 5 μm)	2.18	20	Compl. System ($44k)	0.053	8.4	0.007	0.060
3.6.04-01	Electrolytic Plating of Cu (10 μm)	2.36	15	Autom. Plating Machine ($60k)	0.543	90	0.068	0.611
3.6.04-02	Solder Dipping (55 μm)	2.18	1	Soldering System ($50k)	0.049	9.3	0.022	0.071

a. Using an annual charge rate of 21.35%

B. Using an annual charge rate of 179.13$/m^2

is needed, the turn-over of the cell and mask holder in the deposition chamber and a second set of source material boats, including all their controls, are required. Consequently, the manufacturer has given the system cost as twice that of a system for single-sided deposition, which is more common. The capital equipment costs for the electroless nickel plating and solder dipping equipment represent relatively unsophisticated projections from the current operation which is essentially manual, and may thus be viewed as the least reliable estimates, probably being on the low side.

Table IX provides the summary of the cost comparisons contained in Tables V through VIII. In addition, it gives the add-on price for the individual processes, computed according to the SAMICS-IPEG methodology. The first two lines of Table IX describe two processes which provide the total metallization, including the barrier layer below the copper layer in the case of vacuum deposition. But, as discussed before, vacuum evaporation is really not suited for full conduction layer deposition on the front surface because of the masking problem for fine line deposition of thick layers. It can therefore be readily applied only to the rear surface metallization or the deposition of a barrier or strike layer. In the latter case, the price may be in the range of one third to one half of that shown in the last two columns. It may also be reiterated that the thick film silver process applies only to the front layer metallization,

TABLE IX

Cost Summary For The 6 Principal Metallization Options

Process Option		Remarks	COSTS: Metal $/m^2$	Indirect Mat'ls. $/m^2$	Tooling etc. $/m^2$	Elect. Power $/m^2$	Labor $/m^2$	Capital Equip't $/m^2$	Facility $/m^2$	Price $/m^2$	Price ¢/W(pk)
3..5.01-01	Thick Film Ag	Front only Rear at 0.4 µm thickness gives equal cost	8.40[1]	0.030	0.410	0.075	0.676	0.237	0.076	13.150	8.77
3.6.03-03	Vacuum Deposition of Nickel Barrier and Copper Conduction Layers	Both sides Cu ∿ 10 µm thick	0.797	0.817	-	0.12	0.28	1.264	0.052	5.772	3.85
3.6.03-02	Electroless Ni Strike or Barrier Layer	Both sides. Requires contact mask. ∿ 0.5 µm thick	0 289[2]	0.494	-	0.025	0.06	0.053	0.007	1 908	1.3
3.6.-04-02	Solder Dipping	Both sides Requires ∿ 0 5 µm thick Ni or other solderable metal	5.668	0.416	-	0.013	0.569	0.49	0.022	8.997	6.0
3.6.04-01	Electrolytic Plating of Copper Conduction Layer	Both sides. ∿ 10 µm thick. Requires Ni strike layer.	0.195	0.282	-	0.250	0.556	0.543	0.068	3.216	2.14
3.6.04-03	Sputter Deposition of Copper Conduction Layer	Both sides ∿ 10 µm thick. Requires barrier layer, registration.	1.015	0.066	-	0.053	0.708	2.865	0.048	9.221	6.15

1. Cost of ink
2. Cost of $NiCl_2 \cdot 6H_2O$ crystals

and that its price would have to be doubled if rear surface metallization is to be included.

The third line in Table IX gives the cost summary for a nickel strike or barrier layer, deposited by electroless plating. Its price is approximately 1.9 $\$/m^2$, or 1.3¢/W(peak). It is thus seen that the price of vacuum deposition of such a barrier or strike layer may be competitive with that of an electroless plated layer, particularly in consideration of the fact that the former does not require separate masking/ demasking steps. The last three lines of Table IX all contain conduction layer metallization processes. It is seen that the electrolytic plating of copper is clearly the conduction layer deposition process of lowest cost. The thick film silver deposition process and the solder dipping are clearly out of range because of the high metal costs. The sputter deposition of a conduction layer on the front surface suffers under the same masking problem as the vacuum evaporation process. In addition, the major price difference between sputter deposition and vacuum deposition seems to lie in the capital equipment costs. This difference is based on the equipment manufacturers estimates, and may disappear once a proper price determination for this type of equipment has been carried out.

The conclusion to be drawn from this economic analysis, as evident from Table IX, is thus that the electroless deposition of a strike or barrier layer, and the electrolytic

electrolytic plating of a copper conduction layer seem to be the lowest cost processes among the available options. In addition, these two processes are capable of the best line resolution and therefore of producing the highest efficiency solar cells. The vacuum deposition of a strike or barrier layer, using fully automated, high-throughput equipment, can possibly be competitive with the electroless plating approach.

VI. Preparation of SAMIC Format A Input Information from the UPPC Forms.

The Format A has been developed to present the important cost data of any solar cell manufacturing process in a standardized form, and thus facilitate the entry of such data into the SAMIC computer program. Consequently, the information to be entered on Format A represents a summary of the results of an elaborate information collection and pre-processing effort. The UPPC forms have been developed specifically for the purpose of facilitating this information collection and pre-processing effort, and of documenting all the detail information which is needed for the proper evaluation of a process. They have also been intended to form a guide and a check list for the information collection, with space provided for the work-up and explanation of the data entered or arrived at by calculation. In a secondary application, the forms can be used for a manual evaluation of the costs and prices of the process being studied. This evaluation normally follows the SAMIC-IPEG methodology.

The UPPC system is composed of 16 individual forms (Appendix II), each dedicated to the collection of specific types of information. Each form may be used as many times as space is needed to document the available information, or may not be used at all. Therefore, Form 1 is used in essence as a Table of Contents, to document the complete set of forms used for the description of a particular process. Form 2 contains the general description of the individual process and the specifications for the input work-in-process. Form 3 contains a listing of the direct materials used, including their specifications, the quanities required, and the unit cost. The similar Form 4 is devoted to the information collection for the indirect materials used. In Form 5, the expendable tooling needed for the execution of the process and the energy consumption in the process are listed. This form also contains a summation of the direct and indirect material costs and the costs of expendable tooling and energy. Form 6 accumulates information about the direct labor needed for the execution of the process, separated by labor categories and job activities. Entries are made for the amount of labor required at the process station, the labor rate, and the loading. The latter, according to the SAMIC-IPEG system, includes the employee benefits and the cost of replacement personnel to achieve 8280 h staffing per year. In addition, the form contains provisions for similar listing of the indirect labor. Form 7 is dedicated to the collection of information on the capital equipment needs, including its installation cost, its throughput rate and availability, as well as provision for servicing costs, which may include labor as well as parts or outside service. In addition, the useful life and the capital charge rate are to be entered. Form 8 is concerned with the facility needs of the individual process, including the floor area and the charge rate. There is additional provision for determination of the energy used in the facility for heating, air-conditioning and lighting, as well as the cost of maintenance of the facility broken down into labor, supplies, and outside services. Forms 9-1, 9-2 and 9-3 are devoted to the determination of the amounts of salvaged work-in-process, direct, and indirect materials, respectively, as well as to the determination of their salvage credits with or without incurring reprossing costs. Forms 10 and 11 are dedicated to the accumulation of data relating to the solid, liquid or gaseous wastes or by-products possibly generated in carrying out the individual process, including specification of the types of wastes, their toxicity, biodegradability, and other characteristics of interest with respect to disposal, as well as their energy content, the amount generated, and the costs of waste treatment and disposal, or credits achievable by salvage. In the LSA program, data of this type have not yet become available, but as the processes are proceeding towards the pilot line stage, the accumulation of such data will become more urgent. Forms 12, 13-1 and 13-2 facilitate the summation of the cost data accumulated in the preceding forms and a manual price calculation according to the SAMIC-IPEG methodology. Forms 14 and 15 are devoted to a process performance evaluation and the specification of attributes of the output work-in-process, respectively, but have usually not been used. Form 16, finally, is a generalized work sheet to be used for the documentation of additional data or of calculations carried out in preparing entries for any of the preceding forms.

The transformation of the information accumulated on the UPPC forms to that required for entry into the SAMIC Format A has been found to be best carried out in the following way:

a. UPPC Form 2 contains the process description to be summarized on line A-2 of Format A. It also contains the input work-in-process description needed for item A25 in Part 6 of Format A.

b. The process description on UPPC Form 2 usually includes the throughput rate of the process. Otherwise, the throughput rate will be found on Forms 7 and 8. Multiplying this throughput rate with the yield contained in item 7.42 or 7.44 of UPPC Form 12, provides the output rate for item A6 of Part 2 of Format A. (The throughput rate on the UPPC forms may be expressed as an hourly or a yearly rate, and has to be converted to a rate per minute for entry into Format A.)

c. The process description of UPPC Form 2 frequently includes the time of the product at the individual station, to be entered in item A7 of Format A.

d. UPPC Forms 3, 4, and 5 contain the data for direct and indirect materials, as well as expendable tooling, and energy consumption, for direct transfer to items A20 through A23 in Part 5 of Format A. The UPPC forms contain the consumption rates in any practical units, such as grams per square meter of solar cell area. These numbers have to be converted to consumption per minute for entry into Format A by use of the throughput rate discussed under point b. above. As far as the materials of the proper specifications can be found in the Cost Account Catalog, the catalog number and price from this Cost Account Catalog will normally have been entered in the UPPC forms.

e. The direct labor costs of UPPC Form 6 can be directly transferred to items A16 through 19 of Part 4 of Format A. Again, the Cost Account Catalog data will have been used in filling out the UPPC forms. (Indirect labor data, if they should have been entered on the UPPC forms, will not be transferred to Format A.)

f. The equipment data of UPPC Form 7 will be directly transferred to items A9 through 14 in Part 3 of Format A. (The current version of the UPPC Form 7 does not provide for entry of a base year for the equipment price or for the salvage value. The latter has usually not been available, and therefore been assumed as zero.)

g. Form 7 also contains the machine availability, or up-time fraction to be entered into item 8A of Part 2 of Format A.

h. The facilities data from UPPC Form 8 are directly transferable to items A16 through 19 of Part 5 of Format A.

i. Salvage credits or costs of waste or by-product processing or disposal, eventually to be contained in UPPC

Forms 9 through 11, will normally be entered into items A20 through 23 in Part 5 of Format A.

j. Form 12, in items 7.41 through 7.44, contains the data for conversion rate and yield to be entered into items A26 and A27 of Part 6 of Format A.

Making the transfers and conversions discussed in these points a. through j., Format A's were readily filled out for the six generic processes discussed in sections II to V of this report. These Formats A are included in Appendix II of this report.

TABLE X

No.	Potential Process Sequence (Add-on prices in $\$/m^2$)				Total Price
1.	Apply Mask ∿3.-(E)	Electroless Metal Ni-Sinter-Ni ∿4.- (UP) Au-Ni 6.24 (PhotoW.) Pd-Sinter-Pd-Ni 4.14(Mot.)	Remove Mask ∿1.-(E)	Solder Dip ∿1.30+5.70 Metal	15.- to 18.-
2.	Apply Mask ∿3.-(E)	Electroless Metal Pd-Sinter-Pd-Ni 4.14(Mot.)	Electrolytic Metal Cu 3.22(UP)	(Remove Mask) ∿1.-(E)	∿11.40
3.	Vac. Deposit Metal Ti-Pd-(Ni) 2.84(West.)(UP)	Sinter 0.10(Mot)	Electrolytic Metal Cu 3.22(UP)	-	∿6.16
4.	Screen Print Silver	Dry/Sinter	-	-	
	7.30+14.30 Ag(Lockh) to 10.30+9.30 Ag(RCA)				∿20.- to 22.-
5.	Apply "Midfilm"	Powder Metal Ag	Sinter	Conductor Layer Build-up (Electrolytic Cu)	
	2.77+2.09 Ag(Front Only)			3.22	8.08

(E) = estimated

VII. Potential Metallization Process Sequences.

Applying the data from Table IX as well as data from the LSA contractors contained in numerous progress reports, potential process sequences can be constructed and evaluated. A small sample of such potential process sequences is shown in Table X. These sequences contain all the associated process steps required for complete metallization, particularly masking where required.

Table X leads to several observations. The first is, that the data from the various sources have become quite consistent. The second is that process sequences can produce complete metallization in the \$6.- to 12.-/m^2 (4 to 8¢/W(peak)) range, and that the processes including thick film silver or solder dipping fall significantly above this range. It is also seen that the vacuum deposition of a strike/barrier layer (sequence 3) may be competitive with the electroless plating process (sequence 2). In the latter, significant costs are incurred in contact masking and mask removal. However, it is not clear that the sequence 3 will result in high efficiency and long life solar cells, without use of a contact mask. The vacuum deposition through a shadow mask can result in "underspray" with consequently reduced light transmission. Further, the electrolytic plating over the strike layer may bring copper in contact with the silicon at the edges of the strike layer, and result in degradation of performance in time. Clearly, the approach of using the

AR coating as a permanent plating mask is appealing since it can eliminate this latter problem. It would, however, likely eliminate the vacuum deposition process for the strike/barrier layer, since it would require the additional process step of registration of the shadow mask to the contact mask (AR-coating), and involve the difficulty of maintaining this precise registration throughout all subsequent handling until the strike layer deposition is complete.

It has also to be determined whether electrolytic plating-up of a sintered silver layer resulting from the Midfilm process is possible. On small area cells, such build-up may not be necessary, as the sheet resistance may be adequately low for grid lines of small length. The other alternative, for large area cells, would be to design a metallization pattern with a larger number of bus lines.

The SOL/LOS Mo/Sn process has not been considered further, since it relies on tin as the main conductor and therefore will not be cost effective, at least as intended to be applied now. The fritless copper thick film process has basic merit, but requires a lot more development until it can be considered competitive with the more established processes.

It has thus been seen that a few basic process options exist for the low-cost metallization of large area, high performance solar cells. But it has also been seen that potential pitfalls exist with at least some of these options, and that some pilot line experience with careful attention to ultimate process cost, controllability and yield, and potential initial or long term solar cell performance degradation is needed, possibly with subsequent further development work.

VIII. Conclusions.

Several process sequences have been identified which should be capable of producing the required metallization for large area, high performance solar cells in the \$6.- to 12.-/m^2, or 4 to 8¢/W(peak) price range. Any process relying on use of a conduction layer of tin, or lead-tin alloy, or of thick film silver, falls above this range. Electroless plating processes for strike or barrier layer formation, and electrolytic plating of the conduction layer, primarily considering copper, appear as the more cost-effective processes. Vacuum deposition of the strike or barrier layer, based on use of a variety of metals, may be competitive with the electroless plating processes. The use of the AR coating as a plating mask is very attractive, but not compatible with the vacuum deposition of strike or barrier layers. Vacuum or sputter deposition of conduction layers for the front of solar cells appears impractical because of masking problems. In general, careful evaluation of pilot line operation of the most hopeful process sequences will be needed to reveal potential problems with respect to process controllability and yield as well as initial or gradual solar cell performance degradation. Once such problems are recognized, additional development work may be indicated.

Aluminum could be an alternative to copper as the conduction layer metal. The impracticality of depositing it by wet chemical methods, the problems of masking in vacuum evaporation for the front metallization, and the limitations in lead-bonding to aluminum, however, have led to its omission from the discussion.

APPENDIX I

DETAIL DATA FOR 6 GENERIC METALLIZATION PROCESSES

Process No. 3.5.01-01

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Device Fabrication

Subprocess: Contact Metallization (Front only)

Option: Thick Film Screen Printing of Silver

INDEX

Form	Pages	Rev.	Date	Remarks
1		1	2-81	
2	1 to 2	2	2-81	
3	1 to 1	2	2-81	
4	1 to 1	1	9-79	
5	1 to 1	2	2-81	
6	1 to 1	1	9-79	
7	1 to 1	1	9-79	
8	1 to 1	1	9-79	
9-1	1 to -			
9-2	1 to -			
9-3	1 to -			
10	1 to -			
11	1 to -			
12	1 to 1	1	2-81	
13-1	1 to -			
13-2	1 to 1	1	2-81	
14	1 to -			
15	1 to -			
16	1 to -			

Revision 2 Date 2-81

Process No. 3 . 5 . 0 1 - 0 1

0.1 Value Added:	$/

Process Description: The wafers are unloaded from cassettes, inserted in a screen printer, and the ink is applied. Wafers are then collated and dried and sintered in a belt furnace, and re-loaded into cassettes. The metal area coverage on the front surface is assumed to be 6.2% with a line width of 125 μm and thickness (after sintering) of 20 μm, and 3 bus lines. Output rate of screen printer is 1200 wafers/h and utilization rate is 95% for an effective output rate of 1140 wafers/h, or 11.40 m^2/h. This process description covers only front surface metallization.

1. Input Specification: (Continuation on Form 2, page 2)

Name of Item: Silicon wafers with N^+PP^+ junctions

Dimensions: 10-cm square and about 300 μm thick

Material:

Other Specifications:

1.1 Quantity Required: / Unit Cost: $/

1.2 Input Value:	$/
1.3 Input Cost:	$/

Note to Item 1.3: Use price, if input produced in own plant.

Revision 2 Date 2-81

Process No. 3 . 5 . 0 1 - 0 1

0.1 Value Added:	$/

Process Description: The process can apply metallization on one side, and requires duplication in equipment and operations for metal application to the rear surface. A 100% rear surface metallization at 0.4 μm thickness after sintering would have approximately the same material consumption as shown here.

1. Input Specification.

Name of Item:

Dimensions:

Material:

Other Specifications:

1.1 Quantity Required: / Unit Cost: $/

1.2 Input Value:	$/
1.3 Input Cost:	$/

Note to Item 1.3: Use price, if input produced in own plant.

Process No. 3 . 5 . 01 - 01

Form 3

Page 1 of 1

2.1 Direct Materials:

Revision 2 Date 2-81

2.1 1 Type. Silver ink paste, similar to that described by RCA ;

Specification: Wet layer thickness is 25 μm, application eff. 90%, with 50% of waste ink recycled. ;

Quantity Required. ~ 12 g/ m^2, Unit Cost: 0.70 \$/ g*, Cost: 8.40 \$/ m^2

2.1_ Type: ;

Specification. ;

Quantity Required. ___/___, Unit Cost ___\$/___, Cost: ___\$/___

2.1_ Type. ;

Specification: ;

Quantity Required. ___/___; Unit Cost: ___\$/___; Cost: ___\$/___

*Includes formulation cost of \$0.30/g.

2.1 Subtotal Direct Materials:	8.40 \$/ m^2

Process No. 3 . 5 . 0 1 - 0 1

Form 4

Page 1 of 1

Revision 1 Date 9-79

2.2 Indirect Materials (incl. supplies and non-energy utilities):

2.2.1 Type: Xylene, $\rho = 0.87 g/m\ell$

Specification: Used as a solvent for the ink. Usage is about 30 $m\ell/m^2$ cells.

Cost is \$0.52/lb for reagent grade (J.T. Baker, 12/79)

Quantity Required 26.1 g/m^2, Unit Cost 1.146 \$/kg, Cost 0.030 $\$/m^2$

2.2_ Type

Specification

Quantity Required ___/___, Unit Cost ___\$/___, Cost ___\$/___

2.2_ Type:

Specification

Quantity Required ___/___, Unit Cost ___\$/___; Cost ___\$/___

2.2 Subtotal Indirect Materials. 0.030 $\$/m^2$

Process No. 3 . 5 . 01 - 01

Form 5

Revision 2 Date 2-81

2.3 Expendable Tooling.

2.3 1 Type. Print screens - replaced every shift. (∿ 9000 cells)

Quantity Required: 0.011 screens/ m^2 : Unit Cost: 25 $/scr. Cost: 0.275 $/$m^2$

2.3 2 Type. Squeegees - replaced every hour (∿ 1000 cells)

Quantity Required: 0.088 squeegees/ m^2 : Unit Cost: 0.40 $/sqe. Cost. 0.035 $/$m^2$

2.3 3 Type. Thermocouples and misc. replacement parts

general estimate Quantity Required ____ /____ : Unit Cost: ____ $/____ Cost: 0.10 $/$m^2$

2.3 _ Type: ____

Quantity Required. ____ /____ : Unit Cost: ____ $/____ Cost. ____ $/____

2.3	Subtotal Expendable Tooling:	0.410 $/$m^2$

2.4 Energy

2.4 1 Type: Electricity, name plate rating is 35 kW (mostly belt furnace)

Quantity Required. 1.5 kWh/m^2. Unit Cost: 0.05 $/kWh Cost: 0.075 $/$m^2$

2.4 _ Type: ____

Quantity Required: ____ ____. Unit Cost: ____ $/____ Cost. ____ $/____

2.4 Subtotal Energy Costs:	0.075 $/$m^2$
2 5 Subtotal 2.1 to 2.4:	8.915 $/ m^2
2.6 Handling Charge: 5.26 % of item 2.5	0.469 $/ m^2
2.7 Subtotal Materials and Supplies: (2.5 + 2.6)	9.384 $/ m^2

Process No. 3 . 5 . 01 - 01

Form 8
Page 1 of 1
Revision 1 Date 9-79

4 2 Facilities:

4.21 Type: Screen Printer and furnace area Floor Area: 40 m^2; Throughput: 94,400 m^2/y

Charge Rate: 179.13* $/(m^2·y);

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services ______$/y

Total Cost: 7,164 $/y 0.076 $/$m^2$

4.2_ Type: ______ Floor Area: ______m^2, Throughput. ______ ______/y

Charge Rate: ______$/(m^2·y);

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost: ______$/y ______$/______

4.2_ Type. ______ Floor Area: ______m^2; Throughput ______ ______/y

Charge Rate: ______$/(m^2·y),

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies ______$/y

Outside Services: ______$/y

Total Cost: ______$/y ______$/______

*Includes energy use

4.2 Subtotal Facilities: 0.076 $/$m^2$

4.3 Equipment and Facilities Subtotal . 0.313 $/$m^2$

Process No. 3 . 5 . 0 1 – 0 1

Revision 1 Date 2-81

7. Process Cost Computation

7.11 Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)	10.408 $/ m^2
7.22 Other Indirect Costs: (0.059 x 4.1 + 0.108 x 4.2) % of 7.11	0.022 $/ m^2
7.21 Total Operating Add-on Costs of Process:	10.430 $/ m^2
7.22 G & A ______% of 7.21	- $/
7.31 Total Gross Add-On Cost of Process	10.430 $/ m^2
7.32 Credit for Salvaged Material (5.8)	- $/
7.33 Cost of Work-in-Process Lost (5.3)	NA $/
7.34 Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	10.430 $/ m^2
7.35 Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	NA $/
7.36 Loading on Item 7.35 at Rate ______%	NA $/
7.37 Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)	$/

7.41 Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	NA ____/____
7.42 Practical Yield	99 %
7.43 Effective Yield (7.41 x 7.42)	99% /____
7.44 Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	0.99 m^2 / m^2

7.51 Cost of Unit of Good Output Work-in-Process (7.37 - 7.44)	NA $/
7.52 Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	10.536 $/ m^2

Process No. 3.5.01-01

Form 6
Page 1 of 1
Revision 1 Date 9-79

3.1 Direct Labor

3.11 Category Semiconductor Assembler (SAMICS B5464D) Activity: machine monitoring and operation
Amount Required: 0.25 h/ h, Rate: $ 5.65 /h; Load 113 %*; Cost 0.264 $/ m^2

3.12 Category: Maintenance Person (SAMICS B5176D) Activity: Repair and service
Amount Required. 0.2 h/ h; Rate: $ 7.40 /h; Load 113 %*; Cost. 0.277 $/ m^2

3.1_ Category: ______ Activity ______
Amount Required: ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost. ______ $/ ______

3.1 Direct Labor Subtotal 0.541 $/ m^2

3.2 Indirect Labor Taken as 25% of direct labor

3.2_ Category: ______ Activity: ______
Amount Required ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______
Amount Required ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______
Amount Required: ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2 Indirect Labor Subtotal: 0.135 $/ m^2

3.3 Subtotal 3.1 and 3.2	0.676	$/ m^2
3.4 Overhead on Labor: 5.26 %	0.035	$/ m^2
3.5 Subtotal Labor	0.711	$/ m^2

*Includes 36% benefits and the requirement of 1.57 persons/shift.

Process No 3 . 5 . 0 1 - 0 1

Form 7
Page 1 of 1
Revision 1 Date 9-79

4.1 Equipment

4.11 Type: Screen Print Apparatus with cassette unloader and collator (Welter Model 44-PS)

Cost: 50,000 $; Installation Cost: - $; Throughput 12 m^2/h,

Plant Oper'g Time 8280 h/y, Machine Avail'ty 95 %; Machine Oper'g Time 7866 h/y

Servicing Costs: Labor ____ h/y at ____ $/h; Parts or Outside Service ____ $/y

Useful Life: 7 y, Charge Rate 21.35 % of Cost/y, Capital Cost 10,700 $/y | 0.113 $/$m^2$

4.12 Type Drier - dries ink

Cost: 20,000 $, Installation Cost - $, Throughput. 12 m^2/h,

Plant Oper'g Time 8280 h/y, Machine Avail'ty: 95 %, Machine Oper'g Time 7866 h/y

Servicing Costs: Labor ____ h/y at ____ $/h, Parts or Outside Service ____ $/y

Useful Life 7 y, Charge Rate. 21.35 % of Cost/y, Capital Cost 4,270 $/y | 0.045 $/$m^2$

4.13 Type. Belt driven sintering furnace

Cost 35,000 $, Installation Cost: - $, Throughput 12 m^2/h,

Plant Oper'g Time 8280 h/y; Machine Avail'ty 95 %, Machine Oper'g Time 7866 h/y

Servicing Costs Labor ____ h/y at ____ $/h; Parts or Outside Service ____ $/y

Useful Life. 7 y, Charge Rate: 21.35 % of Cost/y, Capital Cost: 7,470 $/y | 0.070 $/$m^2$

4.1 Subtotal Equipment Cost; 0.237 $/$m^2$

Process No. 3.5.01-01

Form 13-2
Page 1 of 1

Revision 1 Date 2-81

8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation:

0.9274* 0.237 \$/ m^2 from Subtotal 4.1 = 0.220 \$/ m^2

1.946* 0.076 \$/ m^2 from Subtotal 4.2 = 0.148 \$/ m^2

Subtotal = 0.368 \$/ m^2

8.22 Costs of Amortization of the One-Time Cost:

0.192* 9.384 \$/ m^2 from Subtotal 2.7 = 1.802 \$/ m^2

0.192* 0.711 \$/ m^2 from Subtotal 3.5 = 0.137 \$/ m^2

0.2958* 0.237 \$/ m^2 from Subtotal 4.1 = 0.070 \$/ m^2

2.77* 0.076 \$/ m^2 from Subtotal 4.2 = 0.211 \$/ m^2

Subtotal = 2.220 \$/ m^2

8.23 Total Net Cost of Equity (8.21 + 8.22): 2.588 \$/ m^2

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process:
(Divide Subtotal 8.23 by 0.99 m^2 / m^2 from 7.44)

2.614 \$/ m^2

8.25 Price of Process (7.52 + 8.24) 13.150 \$/ m^2
or 8.77¢/W (peak)

8.26 Price of Work-in-Process (7.51 + 8.24) \$/

Process No. 3 . 6 . 0 3 - 0 3

Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Device Fabrication

Subprocess: Contact Formation (Front and Rear)

Option: Vacuum deposition of a nickel barrier layer and copper conducting layer

INDEX

Form	Pages	Rev.	Date	Remarks
1		1	2-81	
2	1 to 2	1	2-81	
3	1 to 1	1	2-81	
4	1 to 1	1	2-81	
5	1 to 1	1	2-81	
6	1 to 1	1	2-81	
7	1 to 1	1	2-81	
8	1 to 1	1	2-81	
9-1	1 to -			
9-2	1 to -			
9-3	1 to -			
10	1 to -			
11	1 to -			
12	1 to 1	1	2-81	
13-1	1 to -			
13-2	1 to 1	1	2-81	
14	1 to -			
15	1 to -			
16	1 to 4	-	2-81	

Revision 1 Date 2-81

Process No. 3 . 6 . 03 - 03

0.1 Value Added:	$/

Process Description: Wafers are placed and locked into reversible holders which also hold the shadow mask for the contact and grid metallization pattern definition on the front side. The holders are ca. 1 m wide and hold 10 cells across their width. The holders are placed in batches into the air-lock chamber of the system, from where they proceed into the main chamber after pump-down to the main chamber pressure ($\sim 10^{-6}$Torr). In the main chamber, the holders are sequentially removed from the batch and passed flat in continuous flow over the evaporation boats which are ca. 1 m long and deposit

(Continued on Form 2, page 2)

1. Input Specification:

Name of Item. N^+PP^+ Silicon cell ready for metallization, with freshly removed oxide layer, without mask.

Dimensions: 10-cm square

Material:

Other Specifications:

1.1 Quantity Required: / Unit Cost: $/

1.2 Input Value:	$/
1.3 Input Cost:	$/

Note to Item 1.3: Use price, if input produced in own plant.

Revision 1 Date 2-81

Process No. 3 . 6 . 0 3 - 0 3

0.1 Value Added.	$/

Process Description: metal simultaneously over the whole width of the holder. The boats are continuously recharged with rod of the appropriate metal. They are electron beam heated. The evaporation rate and speed of the holder movement determine the metal thickness. After deposition on one side, the holders are turned over in the machine and passed over another set of boats. After deposition on the second side, the holders are re-assembled into batches and passed out of the machine through a a second air-lock chamber.

1. Input Specification: (See Notes on Form 16, page 1)

Name of Item:

Dimensions:

Material.

Other Specifications:

1.1 Quantity Required: / Unit Cost: $/

1.2 Input Value:	$/
1.3 Input Cost:	$/

Note to Item 1.3: Use price, if input produced in own plant.

Process No. 3 . 6 . 0 3 - 0 3

Form 3

Page 1 of 1

Revision 1 Date 2-81

2.1 Direct Materials.

2.11 Type. Copper, rod, 1/8" dia., oxygen free (99.9% Cu), ρ=8.96 g/cm^3

Specification: Surface coverage is 3.4%, front, 100% back. Evaporation efficiency is 70% on mask and holder, 50% on to mask. Metal recovery rate is 75% for wall and holder deposits, 50% for mask deposits. Usage ~ 120t/y

Quantity Required 181.5 g / m^2, Unit Cost: ~ 3 $/ kg ; Cost. 0.545 $/$m^2$

2.12 Type. Copper, rod from recycled material.

Specification. 178.5 g/m^2 copper are recycled at an assumed recycling cost of 1.30 $/kg

Quantity Required: 178.5 g / m^2, Unit Cost. 1.30 $/ kg ; Cost: 0.232 $/$m^2$

2.13 Type: Nickel wire, (99.9%), ρ = 8.91 g/cm^3

Specification: Plating thickness is 0.1 µm, and evaporation and recovery efficiencies are same as copper's

Quantity Required 1.8 g / m^2, Unit Cost ~ 11 $/ kg , Cost. 0.020 $/ m^2

2.1 Subtotal Direct Materials.	0.797 $/ m^2

Process No. 3 . 6 . 03 – 03

Form 4

Page 1 of 1

Revision 1 Date 2-81

2.2 Indirect Materials (incl. supplies and non-energy utilities)

2.2.1 Type: Vacuum pump oil Convoil 20,

Specification. Need 4 qt. per week

3 shift/day at 7 day/wk operation at net output of 41 m^2/h

Quantity Required. 5.8×10^{-4} qt/m^2, Unit Cost 30 \$/qt, Cost 0.017 \$/m^2

2.2.2 Type Graphite boats

Specification Size 8" x 12" x 30", set in water-cooled structure. Two or more crucibles used for copper, two for nickel. Experience has shown that 1000 lbs of copper can be evaporated from one crucible. At 50% deposition efficiency, 360 g/m^2 copper need to be evaporated, 3.6 g/m^2 nickel.

Quantity Required. $8 \cdot 10^{-4}$ cruc/m^2, Unit Cost 1000 \$/cruc, Cost 0.800 \$/m^2

2.2._ Type

Specification

Quantity Required __/__, Unit Cost __\$/__, Cost __\$/__

2.2 Subtotal Indirect Materials. 0.817 \$/m^2

Process No. 3 . 6 . 0 3 - 0 3

Form 5

Revision 1 Date 2/81

2.3 Expendable Tooling:

2.3_ Type: (Masks not charged here.)

Quantity Required: ______ ___/___ : Unit Cost: ___$/___ Cost: ___$/___

2.3_ Type: ______

Quantity Required: ______ ___/___ : Unit Cost: ___$/___ Cost: ___$/___

2.3_ Type: ______

Quantity Required: ______ ___/___ : Unit Cost: ___$/___ Cost: ___$/___

2.3_ Type: ______

Quantity Required: ______ ___/___ : Unit Cost: ___$/___ Cost: ___$/___

2.3	Subtotal Expendable Tooling:	___$/___

2.4 Energy

2.4 1 Type: Electricity, name-plate rating 100 kW for pumps, 200 kW for e-beams. Energy usage 3kWh/lb evaporated.

Quantity Required: 2.4 kWh/m^2 : Unit Cost: 0.05 $/kWh Cost: 0.12 $/$m^2$

2.4_ Type: ______

Quantity Required ______ ______ : Unit Cost: ___$/___ Cost: ___$/___

2.4 Subtotal Energy Costs	0.12 $/$m^2$
2.5 Subtotal 2.1 to 2.4:	1.734 $/$m^2$
2.6 Handling Charge: 5.26 % of item 2.5	0.091 $/$m^2$
2.7 Subtotal Materials and Supplies: (2.5 + 2 6)	1.825 $/$m^2$

Process No. 3 . 6 . 03 - 03

Form 6
Page 1 of 1
Revision 1 Date 2/81

3.1 Direct Labor

3.11 Category: Semiconductor Assembler (SAMICS B5464D) Activity: Loading, unloading, & machine monitoring
Amount Required: 0.5 h/ h , Rate: $ 5.65 /h; Load 113 %; Cost: 0.147 $/ m^2

3.12 Category: Maintenance Mechanic (SAMICS B5176D) Activity: Machine service and repair
Amount Required: 0.2 h/ h ; Rate: $ 7.40 /h; Load 113 %; *Cost: 0.077 $/ m^2

3.1_ Category: ____ Activity: ____
Amount Required ____ h/ ____ ; Rate: $ ____ /h; Load ____ %; Cost: ____ $/ ____

3.1 Direct Labor Subtotal: 0.224 $/ m^2

3.2 Indirect Labor Taken as 25% of direct

3.2_ Category: ____ Activity: ____
Amount Required: ____ h/ ____ , Rate: $ ____ /h; Load ____ %; Cost: ____ $/ ____

3.2_ Category: ____ Activity: ____
Amount Required: ____ h/ ____ ; Rate: $ ____ /h; Load ____ %; Cost: ____ $/ ____

3.2_ Category: ____ Activity: ____
Amount Required: ____ h/ ____ ; Rate: $ ____ /h; Load ____ %; Cost: ____ $/ ____

3.2 Indirect Labor Subtotal: 0.056 $/ m^2

3.3 Subtotal 3.1 and 3.2	0.280	$/ m^2
3.4 Overhead on Labor: 5.26 %	0.015	$/ m^2
3.5 Subtotal Labor	0.295	$/ m^2

*Includes benefits (36%) and requirement of 1.57 workers/shift.

Process No. 3 . 6 . 03 - 03

Revision 1 Date 2/81

4.1 Equipment

4 11 Type: Airco Temescal evaporator

Cost: ~ 2,000,000 \$; Installation Cost: ________ \$; Throughput: 48 m^2 /h,

Plant Oper'g Time 8280 h/y, Machine Avail'ty. 85.5%; Machine Oper'g Time 7038 h/y

Servicing Costs Labor ________ h/y at ________ \$/h, Parts or Outside Service: ________ \$/y

Useful Life 7 y; Charge Rate: 21.35 % of Cost/y; Capital Cost: 34,160 \$/y | 1.264 \$/m^2

4.1_ Type: ________

Cost ________ \$, Installation Cost: ________ \$, Throughput: ________ /h,

Plant Oper'g Time ________ h/y, Machine Avail'ty. ____ %, Machine Oper'g Time ________ h/y

Servicing Costs: Labor ________ h/y at ________ \$/h, Parts or Outside Service ________ \$/y

Useful Life ________ y, Charge Rate: ________ % of Cost/y, Capital Cost ________ \$/y | ________ \$/____

4.1_ Type ________

Cost ________ \$, Installation Cost ________ \$, Throughput: ________ /h,

Plant Oper'g Time ________ h/y; Machine Avail'ty ____ %, Machine Oper'g Time ________ h/y

Servicing Costs: Labor ________ h/y at ________ \$/h, Parts or Outside Service ________ \$/y

Useful Life. ________ y, Charge Rate. ________ % of Cost/y, Capital Cost ________ \$/y | ________ \$/____

4.1 Subtotal Equipment Cost	1.264 \$/m^2

Process No 3 . 6 . 0 3 - 0 3

4 2 Facilities

4.2.1 Type: Equipment space Floor Area: 97.5 m^2, Throughput: 337,800 /y

Charge Rate: 179.13* $/(m²·y),

Energy Use:				
Heating		/y at	$/	
Air Cond'g		/y at	$/	
Lighting		/y at	$/	

Maintenance Costs:

Labor: h/y at $/h

Supplies: $/y

Outside Services: $/y

Total Cost 17,465 $/y — 0.052 $/m²

4.2._ Type Floor Area. m^2, Throughput: /y

Charge Rate $/(m²·y),

Energy Use				
Heating		/y at	$/	
Air Cond'g		/y at	$/	
Lighting		/y at	$/	

Maintenance Costs.

Labor h/y at $/h

Supplies: $/y

Outside Services: $/y

Total Cost $/y — $/

4.2._ Type: Floor Area: m^2, Throughput: /y

Charge Rate $/(m²·y),

Energy Use:				
Heating		/y at	$/	
Air Cond'g		/y at	$/	
Lighting		/y at	$/	

Maintenance Costs:

Labor: h/y at $/h

Supplies. $/y

Outside Services: $/y

Total Cost: $/y — $/

4.2 Subtotal Facilities.	0.052 $/m²
4.3 Equipment and Facilities Subtotal .	1.316 $/m²

Process No. 3 . 6 . 03 — 03

Revision 1 Date 2/81

7. Process Cost Computation

7.11 Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)	3.436 $/ m^2
7.22 Other Indirect Costs: ~~(0.059* 4.1 + 0.108* 4.2)~~ % of 7.11	0.080 $/ m^2
7.21 Total Operating Add-on Costs of Process·	3.516 $/ m^2
7.22 G & A ______% of 7.21	- $/
7.31 Total Gross Add-On Cost of Process	3.516 $/ m^2
7.32 Credit for Salvaged Material (5.8)	incl'd $/
7.33 Cost of Work-in-Process Lost (5.3)	- $/
7.34 Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	3.516 $/
7.35 Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	NA $/
7.36 Loading on Item 7.35 at Rate ______%	NA $/
7.37 Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)	NA $/

7 41 Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	1.0 m^2 / m^2
7.42 Practical Yield	99 %
7.43 Effective Yield (7.41 x 7.42)	0.99 /
7.44 Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	0.99 m^2 / m^2

7.51 Cost of Unit of Good Output Work-in-Process (7.37 ÷ 7.44)	$/
7.52 Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	3.552 $/ m^2

8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation

0.9274* 1.264 $/ m^2 from Subtotal 4.1 = 1.172 $/ m^2

1.946* 0.052 $/ m^2 from Subtotal 4.2 = 0.101 $/ m^2

Subtotal = 1.273 $/ m^2

8.22 Costs of Amortization of the One-Time Cost:

0.192* 1.825 $/ m^2 from Subtotal 2.7 = 0.350 $/ m^2

0.192* 0.295 $/ m^2 from Subtotal 3.5 = 0.057 $/ m^2

0.2958* 1.264 $/ m^2 from Subtotal 4.1 = 0.374 $/ m^2

2.77* 0.052 $/ m^2 from Subtotal 4.2 = 0.144 $/ m^2

Subtotal = 0.925 $/ m^2

8.23 Total Net Cost of Equity (8.21 + 8.22): 2.198 $/ m^2

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process
(Divide Subtotal 8.23 by 0.99 m^2 / m^2 from 7.44)

2.220 $/ m^2

8.25 Price of Process (7.52 + 8.24) 5.772 $/ m^2
3.85 ¢/W(peak)

8.26 Price of Work-in-Process (7.51 + 8.24) $/

Process No 3 . 6 . 03 - 03

WORKSHEET TO ITEM Process Descrip., FORM 2 PAGE 3

Machine throughput is nominally 48 m^2/h. The uptime fraction is 0.85, for an effective throughput rate of 41 m^2/h. Nickel thickness is 0.1 µm and copper layer is 10 µm thick. Approximately 1 h/shift is required for cleaning the vacuum chamber of metal deposits. Vacuum deposition machine is proposed by Airco Temescal, based on similar machines built by them (John L. Hughes).

With use of a common shadow mask for barrier layer and conduction layer deposition, some deposition of scattered copper atoms outside of an adequate barrier layer may not be avoidable. Even without heat treatment subsequent to metallization, this spurious copper deposit may reduce the effective operating life of the cells. This may be an additional reason, besides the impracticality of using shadow masks for thick deposits with fine line patterns, for the selection of competing processes over physical vapor deposition.

WORKSHEET TO ITEM Process Descript. , FORM 2 PAGE

Length of machine ∿ 50 ft ≃ 15 m;

Approximate breakdown of lengths:

Airlock in	2 m
batch disassembler	2 m
evaporation station 1	2.5 m
turn-over	2 m
evaporation station 2	2.5 m
batch re-assembler	2 m
airlock out	2 m
total length of machine	15 m

Throughput 48 m^2 = 48 m long x 1 m wide, means 0.8 m/min travel speed.
Boat width ∿ 12" ≃ 30 cm, means exposure ∿ 0.4 m: evaporation speed Cu ∿ 20 µm/min.
Assume airlock cycle time 15 min; batch size 12 m^2.
To calculate time at station:

Assemble batch for machine:	(1/2 batch)	6 m^2
In airlock in (pump-down ∿ 2/3 of airlock cycle)	(2/3 batch)	8 m^2
Dis-assemble batch in machine:	(1/2 batch)	6 m^2
Moving through process (∿ 8 m long)		8 m^2
Re-assemble batch	(1/2 batch)	6 m^2
In airlock out (air admission ∿ 1/3 of airlock cycle)	(1/3 batch)	4 m^2
Dis-assemble batch for further processing	(1/2 batch)	6 m^2
	Total	44 m^2

Result: Time at station: 55 min.

WORKSHEET TO ITEM 2.11 & 2.12, FORM 3 & 4 PAGE 1 ea.

Mass evaporated from boat:

$$M_{evap} = \frac{A_{mask}/f_{hold}}{\eta_{dep}} (d_F + d_R)\ \rho_{Met} = \frac{1\cdot 10^4\ cm^2/0.71}{0.7} \cdot 2\cdot 10^{-3}\ cm\cdot 8.96\ g/cm^3 = \underline{\underline{360\ g/m^2}}$$

Mass on cell:

$$M_{subs} = A_{mask}(f_{mask,F}d_F + f_{mask,R}d_R)\ \rho_{Met} = 1\cdot 10^4\ cm\ (0.034 + 1.00) \cdot 1\cdot 10^{-3}\cdot 8.94 = \underline{\underline{92.6\ g/m^2}}$$

Net metal used:

$$M_{net} = \frac{A_{mask}}{f_{hold}}\ \rho_{Met}\left\{\left[\frac{1-\eta_{dep}}{\eta_{dep}}(1-r_{wall}) + (1-f_{hold})(1-r_{hold})\right](d_F + d_R) + f_{hold}\left[(1-f_{mask,F})\ d_F + (1-f_{mask,R})\ d_R\right]\cdot(1-r_{mask})\right\} + M_{subs}\ ;$$

WORKSHEET TO ITEM 2.11 & 2.12, cont'd FORM ________ PAGE ______

$$M_{net} = \frac{1 \cdot 10^4\ cm^2}{0.71}\ 8.96\ g/cm^3 \left\{ \left[\frac{0.3}{0.7} \cdot 0.25 + 0.29 \cdot 0.25 \right] \cdot 2 \cdot 10^{-3}\ cm + 0.71 \left[(0.966 + 0) \cdot 1 \cdot 10^{-3}\ cm\ 0.5 \right\} + 92.6\ g/m^2 ;$$

$$\underline{\underline{M_{net} = 181.2\ g/m^2}}$$

The following quantities were used:

$A_{mask} = 1\ m^2 = 1 \cdot 10^4\ cm^2$; $\rho_{Met} = 8.96\ g/cm^3$; $d_F = d_R = 1 \cdot 10^{-3}\ cm \cdot r_{wall} = r_{hold} = 0.75$;

$r_{mask} = 0.5$

$\eta_{dep} = 0.7$; $f_{hold} = 0.71$; $f_{mask,F} = 0.034 \cdot f_{mask,R} = 1.0$;

Process No. 3 . 6 . 0 3 - 0 2 Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Device Fabrication

Subprocess: Contact Metallization (front and rear)

Option: Electroless Ni Plating of Strike or Barrier Layer

INDEX

Form	Pages	Rev.	Date	Remarks
1		1	2-81	
2	1 to 2	1	2-81	
3	1 to 1	1	2-81	
4	1 to 2	1	2-81	
5	1 to 1		12-79	
6	1 to	1	12-79	
7	1 to 1	1	2-81	
8	1 to 1		12-79	
9-1	1 to -			
9-2	1 to -			
9-3	1 to -			
10	1 to -			
11	1 to -			
12	1 to 1	1	2-81	
13-1	1 to -			
13-2	1 to 1	1	2-81	
14	1 to -			
15	1 to -			
16	1 to -			

Revision 1 Date 2-81

Process No. 3 . 6 . 0 3 - 0 2

0.1 Value Added:	\$/

Process Description: Wafers with contact mask are dipped in electroless nickel solution at 80 to 90°C for 5 min, and are then rinsed and dried. Two flow hoods are used for processing. Cycle time is 20 min and Wafers are carried in 50 wafer cassettes, which are moved automatically through the system. The plating tank is large enough to hold 5 cassettes. Plating occurs on both sides simultaneously.

Throughput rate is 3,000 wafers/h and machine utilization is 88%. Surface coverage is 3.4% front, 100% rear. Plating thickness is 0.5 µm. Plating effeciency is assumed to be 90%.

(Continued on Form 2, page 2)

1. Input Specification:

Name of Item: $N^{+}PP^{+}$ silicon wafer with contact mask

Dimensions: 10-cm square

Material:

Other Specifications:

1.1 Quantity Required: / Unit Cost: \$/

1.2 Input Value:	\$/
1.3 Input Cost:	\$/

Note to Item 1.3: Use price, if input produced in own plant.

Revision 1 Date 2-81

Process No. 3 . 6 . 0 3 - 0 2

0.1 Value Added:	\$/

Process Description One liter of Ni electroless plating solution consists of: 875 mℓ H_2O; 30 g of $NiCl_2 \cdot 6H_2O$; 50 g of NH_4Cl; 84 g of $Na_3C_6H_5O_7 \cdot 2H_2O$; 10 g of $NaH_2PO_2 \cdot H_2O$ and 125 mℓ of NH_4OH (58%).

1. Input Specification:

Name of Item:

Dimensions:

Material

Other Specifications:

1.1 Quantity Required: / Unit Cost: \$/

1.2 Input Value:	\$/
1.3 Input Cost:	\$/

Note to Item 1.3: Use price, if input produced in own plant.

Process No. 3 . 6 . 0 3 - 0 2

Form 3

Page 1 of 1

Revision 1 Date 2-81

2.1 Direct Materials:

2.1_ Type: $NiCl_2 \cdot 6H_2O$, reagent grade crystals, $\rho = 7.77\ g/cm^3$;

Specification. Coating thickness is 0.5 µm.

$NiCl_2 = (0.05) \cdot (0.5) \cdot (7.77) \cdot (237.71/58.71) \cdot (1/0.9) = 0.87\ g/m^2$. One liter of solution will plate 1.7 m^2 of cells. Cost of $NiCl_2 \cdot 6H_2O$ is $7.29/lb (12/79; J.T. Baker)

Quantity Required: 18 g / m^2; Unit Cost: 16.07 $/ kg, Cost: 0.289 $/ m^2

2.1_ Type: ;

Specification. ,

Quantity Required. ___ /___, Unit Cost. ___ $/___, Cost: ___ $/___

2.1_ Type: ;

Specification.

;

Quantity Required ___ /___, Unit Cost: ___ $/___, Cost: ___ $/___

2.1 Subtotal Direct Materials: 0.289 $/ m^2

Process No. 3 . 6 . 0 3 – 0 2

Form 4

Page 1 of 2

Revision 1 Date 2-81

2.2 Indirect Materials (incl. supplies and non-energy utilities).

2.21 Type. Deionized water for plating solution

Specification: Need 875 ml of DIH_2O per liter of solution. Consumption is 620 mℓ for 1 m^2 of cells. Cost is \$660 for 100 m^3 (SAMICS C1128D)

Quantity Required 620 mℓ / m^2, Unit Cost 0.0066 \$/ ℓ, Cost 0.004 \$/ m^2

2.22 Type Ammonium Chloride (NH_4Cl), reagent grade, granular

Specification Need 50 g/ℓ of plating solution. Consumption is 35 g/m^2 of cells. Cost is \$1.15/lb (J.T. Baker, 12/79)

Quantity Required: 35 g / m^2, Unit Cost 2.535 \$/ kg, Cost 0.089 \$/ m^2

2.23 Type Sodium Citrate, reagent grade crystals

Specification Need 84 g/ℓ of plating solution. Consumption is 62 g/m^2 of cells. Cost is 1.88 \$/lb. (J.T. Baker, 12/79)

Quantity Required 62 g / m^2, Unit Cost 4.145 \$/ kg, Cost. 0.257 \$/ m^2

2.2 Subtotal Indirect Materials \$/

Process No. 3 . 6 . 0 3 - 0 2

Form 4

2.2 Indirect Materials (incl. supplies and non-energy utilities):

Revision 1 Date 2-81

2.24 Type Sodium hypophosphite ($NaH_2PO_2 \cdot 2H_2O$), reagent grade crystals;

Specification: Need 10 g/ℓ of plating solution. Consumption is 7.2 g per m^2 of cells. Cost is $4.22/lb (J.T. Baker, 12/79)

Quantity Required: 7.2 g / m^2; Unit Cost 9.304 $/ kg, Cost: 0.067 $/ m^2

2.25 Type Ammonium hydroxide (NH_4OH), 58% reagent grade

Specification Need 125 mℓ/ℓ of plating solution. Consumption is 89 mℓ per square m^2 of cells. Density of NH_4OH (58%) is 0.826 g/mℓ. Cost is $0.47/lb. (J.T. Baker, 12/79)

Quantity Required 89 mℓ/ m^2; Unit Cost 0.861 $/ ℓ, Cost: 0.077 $/ m^2

2.2_ Type

Specification

Quantity Required: ____ ____/____; Unit Cost: ____$/____, Cost ____$/____

2.2 Subtotal Indirect Materials: 0.494 $/ m^2

Process No. 3 . 6 . 0 3 – 0 2

Form 5

Revision ____ Date 12-79

2.3 Expendable Tooling:

2.3 _ Type. ____

____ Quantity Required: ____ ____/____ Unit Cost: ____ $/____ Cost: ____ $/____

2.3 _ Type ____

____ Quantity Required: ____ ____/____ Unit Cost: ____ $/____ Cost: ____ $/____

2.3 _ Type. ____

____ Quantity Required: ____ ____/____. Unit Cost: ____ $/____ Cost. ____ $/____

2.3 _ Type: ____

____ Quantity Required ____ ____/____: Unit Cost: ____ $/____ Cost: ____ $/____

2.3	Subtotal Expendable Tooling:	____ $/____

2.4 Energy

2.4 1 Type: Electricity for laminar flow hoods with strong exhaust, heater on plating tank, drier, various motors and instruments, name plate rating estimated to be 20 kW with 75% load factor.

____ Quantity Required: 0.5 kWh/m^2: Unit Cost. 0.05 $/kWh Cost: 0.025 $\$/m^2$

2.4 _ Type: ____

____ Quantity Required. ____ ____. Unit Cost. ____ $/____ Cost: ____ $/____

2.4 Subtotal Energy Costs:	0.025 $\$/m^2$
2.5 Subtotal 2.1 to 2.4:	0.808 $\$/m^2$
2.6 Handling Charge: 5.26 % of item 2.5	0.043 $\$/m^2$
2.7 Subtotal Materials and Supplies: (2.5 + 2.6)	0.851 $\$/m^2$

Process No. 3.6.03-02

Form 6
Page 1 of 1

Revision 1 Date 12-79

3.1 Direct Labor.

3.1 1 Category: Semiconductor Assembler (SAMICS B5464D) Activity: Hood operation

Amount Required: 1 h/ h ; Rate: $ 5.65 /h, Load 113* %; Cost: 0.456 $/ m^2

3.1_ Category: ______ Activity: ______

Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.1_ Category: ______ Activity: ______

Amount Required ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost ______ $/ ______

3.1 Direct Labor Subtotal: ______ $/ ______

3.2 Indirect Labor Taken as 25% of direct

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2 Indirect Labor Subtotal: 0.114 $/ m^2

3.3 Subtotal 3.1 and 3.2	0.570	$/ m^2
3.4 Overhead on Labor: 5.26%	0.030	$/ m^2
3.5 Subtotal Labor	0.600	$/ m^2

*Includes cost of replacement personnel and benefits.

Process No. 3 . 6 . 0 3 - 0 2

Form 7
Page 1 of 1
Revision 1 Date 2-81

4.1 Equipment

4.1 1 Type: Two 6-foot laminar flow exhaust hoods (IAS type LU6-30x)

Cost: 9,000 $, Installation Cost: ______ $, Throughput 30 m^2 /h;

Plant Oper'g Time 8280 h/y, Machine Avail'ty 88 %, Machine Oper'g Time 7286 h/y

Servicing Costs Labor ______ h/y at ______ $/h, Parts or Outside Service ______ $/y

Useful Life. 7 y; Charge Rate 21.35 % of Cost/y, Capital Cost 1920 $/y | 0.009 $/$m^2$

4.1 2 Type Two chemical recirculating systems (fluorocarbon No. 5000)

Cost 15,000 $, Installation Cost ______ $, Throughput 30 m^2 /h,

Plant Oper'g Time 8200 h/y, Machine Avail'ty ______ %, Machine Oper'g Time 7286 h/y

Servicing Costs Labor ______ h/y at ______ $/h, Parts or Outside Service ______ $/y

Useful Life: 7 y, Charge Rate 21.35 % of Cost/y, Capital Cost. 3200 $/y | 0.015 $/$m^2$

4.1 3 Type: Drying station and cassette transport system

Cost: 20,000 $, Installation Cost 10,000 $; Throughput 30 m^2 /h,

Plant Oper'g Time ______ h/y, Machine Avail'ty. ______ %, Machine Oper'g Time 7286 h/y

Servicing Costs Labor ______ h/y at ______ $/h; Parts or Outside Service ______ $/y

Useful Life. 7 y; Charge Rate. 21.35 % of Cost/y, Capital Cost 6400 $/y | 0.029 $/$m^2$

4.1 Subtotal Equipment Cost	0.053 $/$m^2$

Process No. 3 . 6 . 03 - 02

Form 8
Page 1 of 1
Revision ____ Date 12-79

4 2 Facilities

4.21 Type Hood Area Floor Area 8.36 m^2, Throughput: 218,600 m^2 /y

Charge Rate: 179.13* $/($m^2$·y);

Maintenance Costs:

Labor. ____ h/y at ____ $/h

Supplies: ____ $/y

Outside Services: ____ $/y

Energy Use.

Heating ____ ____/y at ____ $/____

Air Cond'g ____ ____/y at ____ $/____

Lighting ____ ____/y at ____ $/____

Total Cost 1500 $/y 0.007 $/ m^2

4.2_ Type ____ Floor Area. ____ m^2; Throughput: ____ ____/y

Charge Rate. ____ $/($m^2$·y),

Maintenance Costs

Labor: ____ h/y at ____ $/h

Supplies: ____ $/y

Outside Services ____ $/y

Energy Use:

Heating ____ ____/y at ____ $/____

Air Cond'g ____ ____/y at ____ $/____

Lighting ____ ____/y at ____ $/____

Total Cost ____ $/y ____ $/____

4 2_ Type: ____ Floor Area: ____ m^2; Throughput ____ ____/y

Charge Rate. ____ $/($m^2$·y);

Maintenance Costs:

Labor: ____ h/y at ____ $/h

Supplies ____ $/y

Outside Services: ____ $/y

Energy Use:

Heating ____ ____/y at ____ $/____

Air Cond'g ____ ____/y at ____ $/____

Lighting ____ ____/y at ____ $/____

Total Cost. ____ $/y ____ $/____

4 2 Subtotal Facilities.	0.007 $/ m^2
4.3 Equipment and Facilities Subtotal :	0.060 $/ m^2

*Includes energy use

Form 12
Page 1 of 1

Process No. 3 . 6 . 0 3 – 0 2

Revision 1 Date 2-81

7. Process Cost Computation

Item	Value
7.11 Manufacturing Add-On Costs (sum of 2 7, 3.5, 4.3, 6.)	1.511 $/ m^2
7.22 Other Indirect Costs: (0.059 x 4.1 + ~~0.108 x 4.2~~) % of 7.11	0.004 $/ m^2
7.21 Total Operating Add-on Costs of Process:	1.515 $/ m^2
7.22 G & A ______% of 7.21	– $/
7.31 Total Gross Add-On Cost of Process	1.515 $/ m^2
7.32 Credit for Salvaged Material (5.8)	NA $/
7.33 Cost of Work-in-Process Lost (5.3)	NA $/
7.34 Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	1.515 $/ m^2
7 35 Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	NA $/
7.36 Loading on Item 7.35 at Rate ______%	NA $/
7.37 Cost of Output Work-in-Process (7 34 + 7.35 + 7.36)	NA $/

Item	Value
7.41 Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	1 m^2 / m^2
7.42 Practical Yield	99 %
7.43 Effective Yield (7.41 x 7.42)	0.99% /
7.44 Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	0.99 m^2 / m^2

Item	Value
7.51 Cost of Unit of Good Output Work-in-Process (7.37 ÷ 7.44)	– $/
7.52 Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	1.530 $/ m^2

Process No. 3.6.03-02

Form 13-2
Page 1 of 1

Revision 1 Date 2-81

8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation:

0.9274* 0.053 $/ m^2 from Subtotal 4.1 = 0.049 $/ m^2

1.946* 0.007 $/ m^2 from Subtotal 4.2 = 0.013 $/ m^2

Subtotal = 0.062 $/ m^2

8.22 Costs of Amortization of the One-Time Cost

0.192* 0.851 $/ m^2 from Subtotal 2.7 = 0.163 $/ m^2

0.192* 0.600 $/ m^2 from Subtotal 3.5 = 0.115 $/ m^2

0.2958* 0.053 $/ m^2 from Subtotal 4.1 = 0.016 $/ m^2

2.77* 0.007 $/ m^2 from Subtotal 4.2 = 0.019 $/ m^2

Subtotal = 0.313 $/ m^2

8.23 Total Net Cost of Equity (8.21 + 8.22): 0.375 $/ m^2

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process.
(Divide Subtotal 8.23 by 0.99 m^2 / m^2 from 7.44)

0.378 $/

8.25 Price of Process (7.52 + 8.24) 1.908 $/ m^2

or 1.3 ¢/W(peak)

8.26 Price of Work-in-Process (7.51 + 8.24) $/

Process No. 3 . 6 . 0 4 — 0 2 Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Device Fabrication

Subprocess: Contact Metallization (Front and Rear)

Option: Solder Dip

INDEX

Form	Pages	Rev.	Date	Remarks
1		1	2-81	
2	1 to 1		11-78	
3	1 to 1		11-78	
4	1 to 1	1	2-81	
5	1 to 1	1	2-81	
6	1 to 1		11-78	
7	1 to 1		11-78	
8	1 to 1		11-78	
9-1	1 to -			
9-2	1 to -			
9-3	1 to -			
10	1 to -			
11	1 to -			
12	1 to 1	1	2-81	
13-1	1 to -			
13-2	1 to 1	1	2-81	
14	1 to -			
15	1 to -			
16	1 to -			

Form 2

Revision ____ Date 11-78

Process No. 3 . 6 . 04 - 02

0.1 Value Added: ________ $/ ________

Process Description: Steps include flux application, pre-heating, soldering, cleaning and drying. Surface coverage is 6.2% on front (127 μm line width), and 100% on back. Throughout rates is 3,000 wafers/h, and up-time is 88% for an effective throughput rate of 26.4 m^2/h. Average coating thickness is 55 μm.

1. Input Specification:

Name of Item: n^+np^+ silicon solar cells with nickel (or other solderable metal) plated, ∿ 0.5 μm thick metallization

Dimensions: 10 cm square

Material: ________

Other Specifications: ________

1.1 Quantity Required: ____ ____ / ____ Unit Cost: ____ $/ ____

1.2 Input Value: ________ $/ ________

1.3 Input Cost: ________ $/ ________

Note to Item 1.3: Use price, if input produced in own plant.

Process No. 3 . 6 . 0 4 - 0 2

Form 3

Page 1 of 1

2.1 Direct Materials:

Revision ______ Date 11-78

2.11 Type. Tin Lead Solder (60:40), $\rho = 8.9\ g/cm^3$;

Specification. Solder thickness is 55 μm, area coverage is 106.2%. Coating efficiency is 95%. Cost is $10/kg.

Quantity Required. 547.4 g / m^2, Unit Cost. 10 $/kg; Cost: 5.474 $/$m^2$

2.1_ Type: ______;

Specification: ______,

Quantity Required. ______ __/__, Unit Cost ______ $/______, Cost: ______ $/______

2.1_ Type ______;

Specification: ______;

Quantity Required: ______ __/__, Unit Cost: ______ $/______, Cost: ______ $/______

2.1 Subtotal Direct Materials:	5.474 $/ m^2

Process No. 3 . 6 . 04 - 0 2

Form 4

Page 1 of 1

Revision 1 Date 2-81

2.2 Indirect Materials (incl. supplies and non-energy utilities).

2.2.1 Type: Flux, water-soluble

Specification One gallon of flux can coat 18.5 m^2 of cells. When bought in 53 gallon drums, cost is \$6.75/gal (1978).

Quantity Required: 0.054 gal / m^2; Unit Cost 6.75 \$/gal, Cost: 0.363 \$/ m^2

2.2.2 Type: Deionized water

Specification: Used continuously for flux residue removal at flow rate of 1 gal/min.

Cost is \$660 for 100 m^3 (SAMICS C1128D)

Quantity Required: 8 1 / m^2, Unit Cost 0.0066 \$/ 1; Cost 0.053 \$/ m^2

2.2._ Type:

Specification

Quantity Required ___ / ___, Unit Cost: ___ \$/ ___; Cost. ___ \$/ ___

2.2 Subtotal Indirect Materials: 0.416 \$/ m^2

rocess No. 3 . 6 . 0 4 — 0 2

.3 Expendable Tooling:

2.3 _ Type:				
Quantity Required:	/ :	Unit Cost: $/	Cost:	$/
2.3 _ Type:				
Quantity Required:	/ :	Unit Cost $/	Cost:	$/
2.3 _ Type:				
Quantity Required:	/ :	Unit Cost: $/	Cost:	$/
2.3 _ Type:				
Quantity Required:	/ :	Unit Cost: $/	Cost:	$/
		2.3 Subtotal Expendable Tooling:		- $/ m^2

.4 Energy

2.4 1 Type: Electricity, utilization is 95% and name plate rating is 15kW				
Quantity Required: 0.27	kWh/m^2	Unit Cost 0.05 $/ kWh	Cost:	0.013 $/ m^2
2.4 _ Type:				
Quantity Required:		Unit Cost: $/	Cost:	$/
		2.4 Subtotal Energy Costs:		0.013 $/ m^2
		2.5 Subtotal 2.1 to 2.4:		5.903 $/ m^2
		2.6 Handling Charge: 5.26 % of item 2.5		0.310 $/ m^2
		2.7 Subtotal Materials and Supplies: (2.5 + 2.6)		6.213 $/ m^2

Process No. 3.6.04-02

Form 6
Page 1 of 1

Revision ______ Date 11-78

3.1 Direct Labor:

3.11 Category: Semiconductor Assembler (SAMICS B5464D) Activity: Solder System Operator

Amount Required: 1 h/ h, Rate: $ 5.65 /h; Load 113 %*; Cost: 0.456 $/ m^2

3 1_ Category: ______ Activity: ______

Amount Required: ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.1_ Category: ______ Activity: ______

Amount Required ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.1 Direct Labor Subtotal 0.456 $/ m^2

3.2 Indirect Labor. Taken as 25% of direct

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2 Indirect Labor Subtotal:	0.114 $/ m^2
3.3 Subtotal 3.1 and 3.2	0.570 $/ m^2
3.4 Overhead on Labor: ______ %	0.030 $/ m^2
3.5 Subtotal Labor	0.600 $/ m^2

*Includes labor replacement costs and benefits.

Form 7
Page 1 of 1
Revision ____ Date 11-78

Process No. 3.6.04-02

4.1 Equipment

4.11 Type. Solder system (flux appliction, cell pre-heater, solder dipping, flux removal, drying stations with automatic cell handling)

Cost: 50,000 \$; Installation Cost - \$, Throughput 30 m^2/h,

Plant Oper'g Time 8280 h/y, Machine Avail'ty. 88 %; Machine Oper'g Time 7286 h/y

Servicing Costs: Labor ____ h/y at ____ \$/h;Parts or Outside Service: ____ \$/y

Useful Life 7 y, Charge Rate 21.35 % of Cost/y, Capital Cost: 10,675 \$/y | 0.049 \$/m^2

4.1_ Type: ____

Cost. ____ \$, Installation Cost. ____ \$, Throughput ____ /h;

Plant Oper'g Time ____ h/y, Machine Avail'ty: ____ %, Machine Oper'g Time ____ h/y

Servicing Costs: Labor ____ h/y at ____ \$/h,Parts or Outside Service ____ \$/y

Useful Life. ____ y, Charge Rate. ____ % of Cost/y, Capital Cost: ____ \$/y | ____ \$/____

4.1_ Type: ____

Cost ____ \$; Installation Cost. ____ \$, Throughput ____ /h,

Plant Oper'g Time ____ h/y, Machine Avail'ty: ____ %, Machine Oper'g Time ____ h/y

Servicing Costs. Labor ____ h/y at ____ \$/h;Parts or Outside Service: ____ \$/y

Useful Life ____ y; Charge Rate. ____ % of Cost/y; Capital Cost: ____ \$/y | ____ \$/____

4.1 Subtotal Equipment Cost | 0.049 \$/m^2

Process No. 3 . 6 . 04 - 02

Form 8
Page 1 of 1
Revision ____ Date 11-78

4.2 Facilities:

4.21 Type: Ventilated process area Floor Area: 9.3 m^2; Throughput: 218,600 m^2/y

Charge Rate: 179.13* \$/(m^2·y);

Energy Use:

Heating ____ ____/y at ____ \$/____

Air Cond'g ____ ____/y at ____ \$/____

Lighting ____ ____/y at ____ \$/____

Maintenance Costs:

Labor: ____ h/y at ____ \$/h

Supplies: ____ \$/y

Outside Services: ____ \$/y

Total Cost: 1665 \$/y — 0.022 \$/m^2

4.2_ Type ____ Floor Area: ____ m^2; Throughput: ____ ____/y

Charge Rate: ____ \$/(m^2·y);

Energy Use:

Heating ____ ____/y at ____ \$/____

Air Cond'g ____ ____/y at ____ \$/____

Lighting ____ ____/y at ____ \$/____

Maintenance Costs:

Labor ____ h/y at ____ \$/h

Supplies: ____ \$/y

Outside Services: ____ \$/y

Total Cost: ____ \$/y — ____ \$/____

4.2_ Type: ____ Floor Area: ____ m^2; Throughput: ____ ____/y

Charge Rate: ____ \$/(m^2·y);

Energy Use

Heating ____ ____/y at ____ \$/____

Air Cond'g ____ ____/y at ____ \$/____

Lighting ____ ____/y at ____ \$/____

Maintenance Costs:

Labor: ____ h/y at ____ \$/h

Supplies: ____ \$/y

Outside Services: ____ \$/y

Total Cost: ____ \$/y — ____ \$/____

4.2 Subtotal Facilities	0.022 \$/m^2
4.3 Equipment and Facilities Subtotal	0.071 \$/m^2

*Includes energy use

Process No. 3 . 6 . 0 4 – 0 2 Revision 1 Date 2-81

7. Process Cost Computation

7.11	Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)	6.883 $/ m^2
7.22	Other Indirect Costs: ~~(0.059 x 4.1 + 0.108 x 4.2)~~ % of 7.11	0.006 $/ m^2
7.21	Total Operating Add-on Costs of Process:	6.889 $/ m^2
7.22	G & A ______ % of 7.21	- $/
7.31	Total Gross Add-On Cost of Process	6.889 $/ m^2
7.32	Credit for Salvaged Material (5.8)	- $/
7.33	Cost of Work-in-Process Lost (5.3)	- $/
7.34	Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	6.889 $/ m^2
7.35	Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	NA $/
7.36	Loading on Item 7.35 at Rate ______ %	NA $/
7.37	Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)	$/

7.41	Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	1 m^2 / m^2
7.42	Practical Yield	99.8 %
7.43	Effective Yield (7.41 x 7.42)	0.998 /
7.44	Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	0.998 m^2 / m^2

7.51	Cost of Unit of Good Output Work-in-Process (7.37 - 7.44)	$/
7.52	Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	6.903 $/ m^2

Process No. 3.6.04-02

Form 13-2
Page 1 of 1
Revision 1 Date 2-81

8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation:

0.9274* 0.049 $/ m^2	from Subtotal 4.1	= 0.045 $/ m^2	
1.946* 0.022 $/ m^2	from Subtotal 4.2	= 0.044 $/ m^2	
	Subtotal	= 0.089 $/ m^2	

8.22 Costs of Amortization of the One-Time Cost:

0.192* 6.213 $/ m^2	from Subtotal 2.7	= 1.193 $/ m^2	
0.192* 0.599 $/ m^2	from Subtotal 3.5	= 0.115 $/ m^2	
0.2958* 0.049 $/ m^2	from Subtotal 4.1	= 0.387 $/ m^2	
2.77* 0.022 $/ m^2	from Subtotal 4.2	= 0.062 $/ m^2	
	Subtotal	= 1.757 $/ m^2	

8.23 Total Net Cost of Equity (8.21 + 8.22): 1.846 $/ m^2

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process.
(Divide Subtotal 8.23 by 0.998 m^2 / m^2 from 7.44)

1.850 $/ m^2

8.25 Price of Process (7.52 + 8.24) 8.753 $/ m^2 or 5.84 ¢/W(peak)

8.26 Price of Work-in-Process (7.51 + 8.24) $/

Process No. 3 . 6 . 0 4 – 0 1

Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Device Fabrication

Subprocess: Contact Metallization (Front and Rear)

Option: Electrolytic Plating of Copper over a Nickel Strike Layer

INDEX

Form	Pages	Rev.	Date	Remarks
1		1	2-81	
2	1 to 2	1	2-81	
3	1 to 1	1	2-81	
4	1 to 1	1	2-81	
5	1 to 1	1	2-81	
6	1 to 1	1	1-81	
7	1 to 1	1	2-81	
8	1 to 1	1	2-81	
9-1	1 to -			
9-2	1 to -			
9-3	1 to -			
10	1 to -			
11	1 to -			
12	1 to 1	1	2-81	
13-1	1 to -			
13-2	1 to 1	1	2-81	
14	1 to -			
15	1 to -			
16	1 to -			

Process No. 3 . 6 . 0 4 - 0 1

0.1 Value Added:	$/

Process Description: Copper is electrolytically plated sequentially on both sides of the cells in an automatic plating system, including cassette unload and re-load. The equipment should be capable of of a current density of about 60 mA/cm^2 and a voltage between 4 and 8 volts (DC). The system may resemble a finger plating machine (Napco) with individual racking, or a carousel machine (4 cavity) with jig loading (Oxy Metal Industries). Throughput rate is 3,000 wafers/h (30 m^2/h) and availability

(Continuation on Form 2, page 2)

1. Input Specification:

Name of Item: Silicon wafer with N^+PP^+ junctions and 0.5 µm thick nickel strike layer in desired metallization pattern on front and back surfaces, possibly contact mask.

Dimensions: 10-cm square

Material:

Other Specifications:

1.1 Quantity Required: / Unit Cost: $/

1.2 Input Value:	$/
1.3 Input Cost:	$/

Note to Item 1.3: Use price, if input produced in own plant.

Revision 1 Date 2-81

Process No. 3 . 6 . 0 4 - 0 1

0.1 Value Added: $/

Process Description: is 95% for an effective output rate of 28.5 m^2/h. Area coverage is 3.4% front, 100% rear, metal thickness is 10 μm. Cycle time is 15 minutes.

1. Input Specification:

Name of Item:

Dimensions:

Material:

Other Specifications:

1.1 Quantity Required: /

Unit Cost: $/

1.2 Input Value: $/

1.3 Input Cost: $/

Note to Item 1.3: Use price, if input produced in own plant.

Process No. 3 . 6 . 0 4 - 01

Form 3

Page 1 of 1

2.1 Direct Materials:

Revision 1 Date 2-81

2.1 1 Type: Copper electrodes (99.9%);

Specification: Electrolytic Cu anodes. At 1.034 m^2/m^2 and 10 μm thickness, 10.34 cm^3/m^2 or 92.44 g/m^2 deposited on solar cells. Coating efficiency of 95% assumed.;

Quantity Required. 97.31 g/m^2, Unit Cost. ∿ 2.00 $/ kg; Cost. 0.195 $/ m^2

2.1_ Type: ;

Specification. ;

Quantity Required. ____ /____, Unit Cost: ____ $/____; Cost: ____ $/____

2.1_ Type: ;

Specification: ;

Quantity Required: ____ /____; Unit Cost: ____ $/____, Cost: ____ $/____

2.1 Subtotal Direct Materials:	0.195 $/ m^2

Process No. 3 . 6 . 0 4 - 0 1

Form 4

Page 1 of 1

Revision 1 Date 2-81

2.2 Indirect Materials (incl. supplies and non-energy utilities):

2.21 Type. Electrolytic Copper Replenisher Solution ;

Specification: Need 1 mℓ per amp-h. Volume of solution is 1 mℓ/amp-h x 1 amp-h/3600 coul x 96,500 coul/0.5 mole x 1 mole/63.54g x 97.31g/m^2.

Cost of solution is $13/gallon when bought in 54 gallon drums.

Quantity Required 82.1 mℓ / m^2; Unit Cost. 3.434 $/ ℓ ; Cost 0.282 $/ m^2

2.2_ Type

Specification

Quantity Required ____ /____; Unit Cost: ____ $/____, Cost ____ $/____

2.2_ Type:

Specification

Quantity Required ____ /____; Unit Cost ____ $/____; Cost ____ $/____

2.2 Subtotal Indirect Materials 0.282 $/ m^2

Process No. 3 . 6 . 0 4 – 0 1

Form 5

Page 1 of 1

Revision 1 Date 2-81

2.3 Expendable Tooling:

2.3 _ Type:					
Quantity Required:		/:	Unit Cost: $/	Cost:	$/
2.3 _ Type:					
Quantity Required:		/:	Unit Cost: $/	Cost:	$/
2.3 _ Type:					
Quantity Required:		/:	Unit Cost: $/	Cost:	$/
2.3 _ Type:					
Quantity Required:		/:	Unit Cost: $/	Cost:	$/
			2.3 Subtotal Expendable Tooling:		$/

2.4 Energy

2.4 1 Type: DC power: ∿ 60 mA/cm^2 and nominal voltage of 6V: ∿ 4 kWh/m^2 output. Rectifier efficiency assumed to be 80%.					
Quantity Required:	5	kWh/m^2:	Unit Cost: 0.05 $/kWh	Cost:	0.250 $/m^2
2.4 _ Type:					
Quantity Required:		:	Unit Cost: $/	Cost:	$/
			2 4 Subtotal Energy Costs:		0.250 $/m^2
			2.5 Subtotal 2.1 to 2.4:		0.727 $/m^2
			2.6 Handling Charge: 5.26 % of item 2.5		0.038 $/m^2
			2.7 Subtotal Materials and Supplies: (2.5 + 2 6)		0.765 $/m^2

Process No. 3 . 6 . 0 4 - 0 1

Form 6
Page 1 of 1
Revision 1 Date 1-81

3.1 Direct Labor:

3.1_ Category: Semiconductor Assembler (SAMICS B5464D) Activity: Loading, changing electrodes and monitoring
Amount Required: 1 h/ h ; Rate: $ 5.65 /h; Load 113 %*; Cost: 0.422 $/ m^2

3.1_ Category: ______ Activity: ______
Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.1_ Category: ______ Activity: ______
Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.1 Direct Labor Subtotal: 0.422 $/ m^2

3.2 Indirect Labor: Taken as 25% of direct

3.2_ Category: ______ Activity: ______
Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______
Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______
Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2 Indirect Labor Subtotal:	0.106	$/ m^2
3.3 Subtotal 3.1 and 3.2	0.528	$/ m^2
3.4 Overhead on Labor: 5.26 %	0.028	$/ m^2
3.5 Subtotal Labor	0.556	$/ m^2

*Includes benefits and replacement labor costs.

Process No. 3 . 6 . 0 4 - 0 1

4.1 Equipment

4.11 Type: Automatic plating machines, complete (2 required for plating 2 sides)

Cost: 400,000 for 2 $, Installation Cost: 200,000* $; Throughput: 30 m^2 /h;

Plant Oper'g Time 8280 h/y; Machine Avail'ty: 95 %; Machine Oper'g Time 7866 h/y

Servicing Costs: Labor ______ h/y at ______ $/h; Parts or Outside Service: ______ $/y

Useful Life: ______ y; Charge Rate: 21.35 % of Cost/y; Capital Cost 128,100 $/y | 0.543 $/$m^2$

*Includes waste treatment and byproduct recovery system.

4.1_ Type: ______

Cost ______ $, Installation Cost: ______ $, Throughput: ______ /h,

Plant Oper'g Time ______ h/y, Machine Avail'ty: ______ %, Machine Oper'g Time ______ h/y

Servicing Costs: Labor ______ h/y at ______ $/h; Parts or Outside Service: ______ $/y

Useful Life: ______ y; Charge Rate: ______ % of Cost/y, Capital Cost: ______ $/y | ______ $/______

4.1_ Type ______

Cost: ______ $, Installation Cost: ______ $; Throughput ______ /h,

Plant Oper'g Time ______ h/y; Machine Avail'ty: ______ %, Machine Oper'g Time ______ h/y

Servicing Costs: Labor ______ h/y at ______ $/h, Parts or Outside Service ______ $/y

Useful Life: ______ y, Charge Rate: ______ % of Cost/y, Capital Cost: ______ $/y | ______ $/______

4.1 Subtotal Equipment Cost	0.543 $/$m^2$

Process No. 3 . 6 . 0 4 – 0 1

4.2 Facilities:

4.21 Type: Ventilated process area Floor Area: 90 m^2, Throughput: 236,000 m^2/y

Charge Rate 179.13* $/($m^2$·y);

Energy Use:

Heating ____ ____/y at ____$/____

Air Cond'g ____ ____/y at ____$/____

Lighting ____ ____/y at ____$/____

Maintenance Costs:

Labor: ____h/y at ____$/h

Supplies: ____$/y

Outside Services: ____$/y

Total Cost: 16 122 $/y — 0.068 $/$m^2$

4.2_ Type: ____ Floor Area: ____ m^2; Throughput: ____ ____/y

Charge Rate ____$/($m^2$·y),

Energy Use:

Heating ____ ____/y at ____$/____

Air Cond'g ____ ____/y at ____$/____

Lighting ____ ____/y at ____$/____

Maintenance Costs:

Labor: ____h/y at ____$/h

Supplies: ____$/y

Outside Services: ____$/y

Total Cost: ____$/y — ____$/____

4.2_ Type: ____ Floor Area: ____ m^2, Throughput ____ ____/y

Charge Rate: ____$/($m^2$·y),

Energy Use:

Heating ____ ____/y at ____$/____

Air Cond'g ____ ____/y at ____$/____

Lighting ____ ____/y at ____$/____

Maintenance Costs:

Labor: ____h/y at ____$/h

Supplies: ____$/y

Outside Services: ____$/y

Total Cost: ____$/y — ____$/____

4.2 Subtotal Facilities: 0.068 $/$m^2$

4.3 Equipment and Facilities Subtotal: 0.611 $/$m^2$

*Includes energy use

Process No. 3 . 6 . 0 4 — 0 1

Revision 1 Date 2-81

7. Process Cost Computation

7.11	Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)	1.932 $/ m^2
7.22	Other Indirect Costs: (0.059 x 4.1 + 0.108 x 4.2) % of 7.11	0.039 $/ m^2
7.21	Total Operating Add-on Costs of Process:	1.971 $/ m^2
7.22	G & A ______% of 7.21	______ $/
7.31	Total Gross Add-On Cost of Process	1.971 $/ m^2
7.32	Credit for Salvaged Material (5.8)	- $/
7.33	Cost of Work-in-Process Lost (5.3)	- $/
7.34	Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	1.971 $/ m^2
7.35	Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	NA $/
7.36	Loading on Item 7.35 at Rate ______%	NA $/
7.37	Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)	NA $/

7.41	Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	1 m^2 / m^2
7.42	Practical Yield	99.8%
7 43	Effective Yield (7.41 x 7.42)	0.998 m^2/ m^2
7.44	Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	0.998 m^2 / m^2

7.51	Cost of Unit of Good Output Work-in-Process (7.37 ÷ 7.44)	NA $/
7.52	Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	1.975 $/ m^2

Process No. 3.6.04-01

Form 13-2
Page 1 of 1

Revision 1 Date 2-81

8.2 Alternate 2 (SAMICS Methodology)

8.21 Profit Computation:

0.9274* 0.543 $/m^2	from Subtotal 4.1	=	0.504 $/m^2
1.946* 0.068 $/m^2	from Subtotal 4.2	=	0.132 $/m^2
	Subtotal	=	0.636 $/m^2

8.22 Costs of Amortization of the One-Time Cost:

0.192* 0.765 $/m^2	from Subtotal 2.7	=	0.147 $/m^2
0.192* 0.556 $/m^2	from Subtotal 3.5	=	0.107 $/m^2
0.2958* 0.543 $/m^2	from Subtotal 4.1	=	0.161 $/m^2
2.77* 0.068 $/m^2	from Subtotal 4.2	=	0.188 $/m^2
	Subtotal	=	0.603 $/m^2

8.23 Total Net Cost of Equity (8.21 + 8.22): 1.239 $/m^2

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process:
(Divide Subtotal 8.23 by 0.998 m^2/m^2 from 7.44)

1.241 $/m^2

8.25 Price of Process (7.52 + 8.24) 3.216 $/m^2

2.14 ¢/W(peak)

8.26 Price of Work-in-Process (7.51 + 8.24) $/

Process No. 3 . 6 . 04 - 03

Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Devices Fabrication

Subprocess: Contact Formation (front and rear)

Option: Sputter Deposition of Copper conductor layer (projected process)

INDEX

Form	Pages	Rev.	Date	Remarks
1		1	2-81	
2	1 to 1	1	2-81	
3	1 to 2	1	2-81	
4	1 to 1	1	2-81	
5	1 to 1	1	2-81	
6	1 to 1	1	2-81	
7	1 to 1	1	2-81	
8	1 to 1	1	2-81	
9-1	1 to -			
9-2	1 to -			
9-3	1 to -			
10	1 to -			
11	1 to -			
12	1 to 1	1	2-81	
13-1	1 to -			
13-2	1 to 1	1	2-81	
14	1 to -			
15	1 to -			
16	1 to 1			

Revision 1 Date 2-81

0.1 Value Added:	$/

Process No. 3 . 6 . 0 4 - 0 3

Process Description: Copper is sputtered from target by Argon ions. Voltage between cathode and copper target is about 500 volts. Distance between target and solar cell is 5-8 cm. This is a continuous process but machine has to be shut down 1.5 hour every two shifts for replacement of copper and cleaning. The cells move past the target at a rate of 0.833 m/min. Gross output rate is 30 m^2/h. Since uptime fraction is 90%, net output rate is 27 m^2/h. The area coverage is 3.4% front, 100% rear; metal thickness is 10 µm. Deposition rate is 2-3 µm/min. Shadow mask used for pattern definition.

1. Input Specification:

Name of Item: n^+pp^+ silicon solar cells with barrier metal layer.

Dimensions: 10 cm square.

Material:

Other Specifications:

1.1 Quantity Required: / Unit Cost: $/

1.2 Input Value:	$/
1.3 Input Cost:	$/

Note to Item 1.3: Use price, if input produced in own plant.

Process No. 3 . 6 . 0 4 - 0 3

Form 3

Page 1 of 2

2.1 Direct Materials:

Revision 1 Date 2-81

2.1 1 Type. Copper sputter targets-electronic grade (virgin material);

Specification. Size is 90 cm x 45 x 2.5 cm (90.7 kg). Need 6 targets/machine, change every 2160 m^2 of cells, or 72 h. Efficiency of deposition on holder plus masks is 65%, mask area is 71% of holder and mask area. 75% of wall

(Continued on Form 3, page 2)

Quantity Required. 188 g/ m^2, Unit Cost: 3.30 $/ kg, Cost: 0.620 $/ m^2

2.1 2 Type: Copper sputter targets-electronic grade (recycled material);

Specification. same as 2.11;

200 g/m^2 of wall, holder, and mask deposits recycled, $\frac{188}{3}$ g/m^2 = 63 g/m^2 of target material recycled.

Quantity Required. 263 g/ m^2, Unit Cost: 1.50 $/ kg, Cost: 0.395 $/ m^2

2.1_ Type: ;

Specification: ;

Quantity Required: /, Unit Cost $/; Cost: $/

2.1 Subtotal Direct Materials: 1.015 $/ m^2

Process No. 3 . 6 . 0 4 – 0 3

Form 3

Page 2 of 2

Revision 1 Date 2-81

2.1 Direct Materials.

2.1.1 Type: ______________________;

Specification: and holder deposits can be recycled, 50% of deposit on mask. Only 75% of target material can be used, but remainder can be recycled.

______________________;

Quantity Required. ________ ___/___, Unit Cost. ______$/______, Cost: ______$/______

2.1_ Type: ______________________;

Specification. ______________________;

____

____

Quantity Required. ________ ___/___, Unit Cost: ______$/______, Cost: ______$/______

2.1_ Type: ______________________;

Specification. ______________________

____

______________________;

Quantity Required. ________ ___/___, Unit Cost: ______$/______, Cost. ______$/______

2.1 Subtotal Direct Materials:	______$/______

Process No. 3 . 6 . 0 4 - 0 3

Form 4

Page 1 of 1

2.2 Indirect Materials (incl. supplies and non-energy utilities):

Revision 1 Date 2-81

2.2 1 Type: Argon gas

Specification Gas is used to maintain chamber pressure at 5 Torr for sputtering copper off the target. Flow rate is 1 ℓ/min. Cost of T-size cylinder (332 ft^3) is $100.00 (Linde, 3/79)

Quantity Required 4.44 ℓ / m^2, Unit Cost 0.011 $/ℓ, Cost 0.049 $/ m^2

2.2 2 Type Pump Oil

Specification

Quantity Required ___ / ___; Unit Cost ___ $/ ___, Cost 0.017 $/ m^2

2 2_ Type

Specification

Quantity Required: ___ / ___; Unit Cost ___ $/ ___, Cost ___ $/ ___

2 2 Subtotal Indirect Materials:	0.066 $/ m^2

Process No. 3 . 6 . 04 - 03

Form 5

Page 1 of 1

Revision 1 Date 2-81

2.3 Expendable Tooling:

2.3_ Type: ____

____ Quantity Required: ____ ____/____: Unit Cost: ____$/____ Cost: ____$/____

2.3_ Type: ____

____ Quantity Required: ____ ____/____: Unit Cost: ____$/____ Cost: ____$/____

2.3_ Type: ____

____ Quantity Required: ____ ____/____: Unit Cost: ____$/____ Cost: ____$/____

2.3_ Type. ____

____ Quantity Required: ____ ____/____. Unit Cost: ____$/____ Cost: ____$/____

2.3	Subtotal Expendable Tooling:	____$/____

2.4 Energy

2.4 1 Type. Electricity, name plate rating is 20 kW for sputter units, (75 % duty cycle) 45 kW for pumps (30% duty cycle)

____ Quantity Required: 1.06 kWh/m^2: Unit Cost. 0.05 \$/kWh Cost: 0.053 $\$/m^2$

2.4_ Type: ____

____ Quantity Required. ____ ____ Unit Cost: ____$/____ Cost: ____ $\$/m^2$

2 4 Subtotal Energy Costs:	0.053 $\$/m^2$
2.5 Subtotal 2.1 to 2.4:	1.134 $\$/m^2$
2.6 Handling Charge: 5.26 % of item 2.5	0.060 $\$/m^2$
2.7 Subtotal Materials and Supplies: (2 5 + 2.6)	1.194 $\$/m^2$

Process No. 3 . 6 . 0 4 - 0 3

Form 6
Page 1 of 1
Revision 1 Date 2-81

3.1 Direct Labor:

3.11 Category: Semiconductor Assembler (SAMICS B5464D) Activity loading, unloading, & monitoring
Amount Required: 1.0 h/ h , Rate: $ 5.65 /h; Load 113 %*; Cost: 0.446 $/ m^2

3.12 Category Maintenance Mechanic (SAMICS B5224D) Activity: Service and repair
Amount Required: 0.1 h/ h ; Rate: $ 7.95 /h, Load 113 %*; Cost: 0.063 $/ m^2

3.13 Category: Electronics Technician (SAMICS B5176D) Activity: Electronics repair
Amount Required: 0.1 h/ h ; Rate: $ 7.40 /h; Load 113 %*; Cost: 0.058 $/ m^2

3.1 Direct Labor Subtotal 0.567 $/ m^2

3.2 Indirect Labor: Taken as 25% of direct

3.2_ Category: ______ Activity: ______
Amount Required ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______
Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______
Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2 Indirect Labor Subtotal: 0.142 $/ m^2

3.3 Subtotal 3.1 and 3.2	0.709 $/ m^2
3.4 Overhead on Labor: 5.26 %	0.037 $/ m^2
3.5 Subtotal Labor	0.746 $/ m^2

*Includes benefits and replacement personnel costs.

Process No 3.6.04-03

4.1 Equipment

4.1.1 Type: Vacuum sputtering machine; 2 to 6 targets; 60-cm workpiece width

Cost: 2,500,000 \$, Installation Cost: 500,000 \$; Throughput: 30 m^2/h;

Plant Oper'g Time 8280 h/y, Machine Avail'ty: 90 %, Machine Oper'g Time 7452 h/y

Servicing Costs: Labor ____ h/y at ____ \$/h, Parts or Outside Service: ____ \$/y

Useful Life: 7 y; Charge Rate 21.35 % of Cost/y, Capital Cost 640,500 \$/y — 2,865 \$/m^2

4.1_ Type: ____

Cost: ____ \$, Installation Cost: ____ \$, Throughput ____ /h,

Plant Oper'g Time ____ h/y, Machine Avail'ty ____ %, Machine Oper'g Time ____ h/y

Servicing Costs: Labor ____ h/y at ____ \$/h; Parts or Outside Service ____ \$/y

Useful Life: ____ y; Charge Rate: ____ % of Cost/y, Capital Cost ____ \$/y — ____ \$/____

4.1_ Type: ____

Cost ____ \$, Installation Cost: ____ \$, Throughput: ____ /h;

Plant Oper'g Time ____ h/y, Machine Avail'ty ____ %; Machine Oper'g Time ____ h/y

Servicing Costs: Labor ____ h/y at ____ \$/h, Parts or Outside Service ____ \$/y

Useful Life: ____ y, Charge Rate: ____ % of Cost/y; Capital Cost ____ \$/y — ____ \$/____

4.1 Subtotal Equipment Cost	2,865 \$/m^2

Process No. 3 . 6 . 0 4 — 0 3

Revision 1 Date 2-81

7. Process Cost Computation

7.11 Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)	4.852 $/m^2$
7.22 Other Indirect Costs: (0.059 x 4.1 + 0.108 x 4.2) % of 7.11	0.174 $/m^2$
7.21 Total Operating Add-on Costs of Process	5.026 $/m^2$
7.22 G & A ______ % of 7.21	- $/
7.31 Total Gross Add-On Cost of Process	5.026 $/m^2$
7.32 Credit for Salvaged Material (5.8)	incl'd $/
7.33 Cost of Work-in-Process Lost (5.3)	- $/
7.34 Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	5.026 $/m^2$
7.35 Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	NA $/
7.36 Loading on Item 7.35 at Rate ______ %	NA $/
7.37 Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)	NA $/

7.41 Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units) 1 m^2 / m^2

7.42 Practical Yield 99 %

7.43 Effective Yield (7.41 x 7.42) 0.99 /

7.44 Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35 0.99 m^2 / m^2

7.51 Cost of Unit of Good Output Work-in-Process (7.37 ÷ 7.44)	$/
7.52 Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	5.077 $/m^2$

Process No. 3 . 6 . 04 - 03

Form 8
Page 1 of 1
Revision 1 Date 2-81

4.2 Facilities:

4.2.1 Type: Equipment Area Floor Area 60 m^2; Throughput: 223,560 m^2/y

Charge Rate: 179.13* $/(m^2·y),

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost 10,750 $/y — 0.048 $/$m^2$

4.2._ Type ______ Floor Area ______ m^2; Throughput ______ ______/y

Charge Rate ______ $/(m^2·y);

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost: ______$/y — ______$/______

4.2._ Type: ______ Floor Area: ______ m^2; Throughput: ______ ______/y

Charge Rate: ______ $/(m^2·y);

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies ______$/y

Outside Services. ______$/y

Total Cost. ______$/y — ______$/______

4.2 Subtotal Facilities.	0.048 $/$m^2$
4.3 Equipment and Facilities Subtotal	2.913 $/$m^2$

*Includes energy use

Process No. 3.6.04-03

Form 13-2
Page 1 of 1

Revision 1 Date 2-81

8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation:

0.9274* 2.865 \$/m^2	from Subtotal 4.1 =	2.657	\$/m^2
1.946* 0.048 \$/m^2	from Subtotal 4.2 =	0.093	\$/m^2
	Subtotal =	2.750	\$/m^2

8.22 Costs of Amortization of the One-Time Cost

0.192* 1.194 \$/m^2	from Subtotal 2.7 =	0.229	\$/m^2
0.192* 0.745 \$/m^2	from Subtotal 3.5 =	0.143	\$/m^2
0.2958* 2.865 \$/m^2	from Subtotal 4.1 =	0.847	\$/m^2
2.77* 0.048 \$/m^2	from Subtotal 4.2 =	0.133	\$/m^2
	Subtotal =	1.352	\$/m^2

8.23 Total Net Cost of Equity (8.21 + 8.22): 4.102 \$/m^2

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process:
(Divide Subtotal 8.23 by 0.99 m^2 / m^2 from 7.44)

4.144 \$/m^2

8.25 Price of Process (7.52 + 8.24) 9.221 \$/m^2

8.26 Price of Work-in-Process (7.51 + 8.24) 6.15 ¢/W (peak) \$/

Process No 3 . 6 . 0 4 - 0 3

Form 16

WORKSHEET TO ITEM ____________, FORM 3 PAGE 1

Mass evaporated from target:

$$M_{evap} = \frac{1.10^4\ cm^2/0.71}{0.65} \cdot 2 \cdot 10^{-3} \cdot 8.96\ g/cm^3 = 388.3\ g/m^2$$

Mass on cell: As in 3.6-01-05: $M_{subs} = 92.6\ g/cm^3$

Net metal used:

$$M_{net} = \frac{1 \cdot 10^4\ cm^2}{0.71} \cdot 8.96\ g/cm^3 \left\{ \left[\frac{0.35}{0.65} \cdot 0.25 + 0.29 \cdot 0.25 \right] 2 \cdot 10^{-3}\ cm + 0.71 \left[0.96 \cdot 1 \cdot 10^{-3}\ cm \cdot 0.5 \right] \right\}$$

$$+ 92.6\ g/cm^3;$$

$$= 188.2\ g/m^2$$

$\eta_{dep} = 0.65$; all other data as in 3.6-01-05.

Metal recycled:

$$M_{recl} = \frac{1 \cdot 10^4\ cm^2}{0.71} \cdot 8.9\ g/cm^3 \left\{ \left[\frac{0.35}{0.65}\ 0.75 + 0.29 \cdot 0.75 \right] \cdot 2 \cdot 10^{-3}\ cm + 0.71 \left[0.966 \cdot 1 \cdot 10^{-3}\ cm \cdot 0.5 \right] \right\}$$

$$= 200.1\ g/m^2$$

APPENDIX II

SAMIC FORMAT A

FOR THE

SIX GENERIC METALLIZATION PROCESSES

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr / Pasadena Calif 91103

PROCESS DESCRIPTION

Note Names given in brackets [ ] are the names of process attributes requested by the SAMICS III computer program

A1 Process [Referent] METLESNI

A2 [Descriptive Name] Electroless plating of Ni strike or barrier layer

PART 1 – PRODUCT DESCRIPTION

A3 [Product Referent] METCEL 4

A4 Descriptive Name [Product Name] Cell with Ni strike layer

A5 Unit Of Measure [Product Units] m^2 (100 cells)

PART 2 – PROCESS CHARACTERISTICS

A6 [Output Rate] (Not Thruput) 0.495 Units (given on line A5) Per Operating Minute

A7 Average Time at Station [Processing Time] 20 Calendar Minutes (Used only to compute in-process inventory)

A8 Machine "Up" Time Fraction [Usage Fraction] 0.88 Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS [Machine Description]

A9	Component [Referent]			
A9a	Component [Descriptive Name] (Optional)	2 Laminar Flow hoods	2 chemical recirculating systems	Drying, statio
A10	Base Year For Equipment Prices [Price Year]	1979	1979	1979
A11	Purchase Price ($ Per Component) [Purchase Cost]	9,000	15,000	20,000
A12	Anticipated Useful Life (Years) [Useful Life]	7	7	7
A13	[Salvage Value] ($ Per Component)	-	-	-
A14	[Removal and Installation Cost] ($/Component)	-	-	10,000

Note The SAMICS III computer program also prompts for the [payment float interval], the [inflation rate table], the [equipment tax depreciation method], and the [equipment book depreciation method] In the LSA SAMICS context, use 0 0, (1975, 4 0), DDB, and SL

Format A Process Description (Continued)

A15 Process Referent (From Page 1 Line A1) METLESNI

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel) [Facilities and Personnel Requirements]

A16 Catalog Number [Expense Item Referent]	A18 Amount Required Per Machine (Per Shift) [Amount per Machine]	A19 Units	A17 Requirement Description
A 3016D	84	sq ft	Manuf'g Space Type A
B 5464D	1	person/shift	Semicond. Assembler

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE [Byproduct Outputs] and [Utilities and Commodities Requirements]

A20 Catalog Number [Expense Item Referent]	A22 Amount Required Per Machine Per Minute [Amount per Cycle]	A23 Units	A21 Requirement Description
E	9	g/min	$NiCl_2 \cdot 6H_2O$, reagent gr. ($16.07/kg)
E	17.5	g/min	Ammonium chloride, reagent ($2.535/kg)
E 4416D	31	g/min	Sodium Citrate, reagent
E 4432D	3.6	g/min	Sodium Hypophosphite, reagent
E	45.	mℓ/min	Ammonium Hydroxide, reagent 58% ($0.861/ℓ)
C 1128D	310	mℓ/min	DI Water
C 1016B	0.25	kWh/min	Electricity

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED [Required Products]

A24 [Product Reference]	A26 Usable Output Per Unit of Input Product	A27 Units	A25 Product Name
	0.99	m^2 / m^2	cells with contact mask

Prepared by M. Wolf Date 3-16-81

Format A Process Description (Continued)

A15 Process Referent (From Page 1 Line A1) METEVAP

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)
[Facilities and Personnel Requirements]

A16 Catalog Number [Expense Item Referent]	A18 Amount Required Per Machine (Per Shift) [Amount per Machine]	A19 Units	A17 Requirement Description
A 3016D	480	sq ft	Manuf'g Space Type A
B 5464D	0.5	persons/shift	Semicond. Assembler
B 5176D	0.2	dto	Maintenance Person

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE
[Byproduct Outputs] and [Utilities and Commodities Requirements]

A20 Catalog Number [Expense Item Referent]	A22 Amount Required Per Machine Per Minute [Amount per Cycle]	A23 Units	A21 Requirement Description
E	145.2	g/min	Rod, 99.9% Cu, oxygen free, 1/8" dia. ($3/kg)
E	142.8	g/min	dto., but recycled Cu. ($1.30/kg)
E	1.44	g/min	Wire, 99.9% Ni.($11/kg)
E	$4.64\ 10^{-4}$	qt/min	Vacuum pump oil Convoil 20 ($30/qt)
E	$6.4\ 10^{-4}$	crucible/min	graphite crucible ($1000/cruc.)
C 1016B	1.92	kWh/min	electricity

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED [Required Products]

A24 [Product Reference]	A26 Usable Output Per Unit of Input Product	A27 Units	A25 Product Name
	0.99	m^2 / m^2	Wafer with pn junction
		/	
		/	

Prepared by M. Wolf Date 3-16-81

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr / Pasadena, Calif 91103

Note Names given in brackets [ ] are the names of process attributes requested by the SAMICS III computer program

A1 Process [Referent] METEVAP

A2 [Descriptive Name] Metallization front and back by Ni and 10 μm Cu by vacuum evaporation

PART 1 – PRODUCT DESCRIPTION

A3 [Product Referent] METCEL 1

A4 Descriptive Name [Product Name] Metallized solar cell

A5 Unit Of Measure [Product Units] 1 m^2 (= 100 cells)

PART 2 – PROCESS CHARACTERISTICS

A6 [Output Rate] (Not Thruput) 0.792 Units (given on line A5) Per Operating Minute

A7 Average Time at Station [Processing Time] 55 Calendar Minutes (Used only to compute in-process inventory)

A8 Machine "Up" Time Fraction [Usage Fraction] 0.85 Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS [Machine Description]

A9	Component [Referent]			
A9a	Component [Descriptive Name] (Optional)	Automatic Vacuum System		
A10	Base Year For Equipment Prices [Price Year]	1980		
A11	Purchase Price ($ Per Component) [Purchase Cost]	2 Mill		
A12	Anticipated Useful Life (Years) [Useful Life]	7y		
A13	[Salvage Value] ($ Per Component)	0		
A14	[Removal and Installation Cost] ($/Component)	–		

Note The SAMICS III computer program also prompts for the [payment float interval], the [inflation rate table], the [equipment tax depreciation method], and the [equipment book depreciation method] In the LSA SAMICS context, use 0 0, (1975, 4 0), DDB, and SL

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr / Pasadena, Calif 91103

Note Names given in brackets [ ] are the names of process attributes requested by the SAMICS III computer program

A1 Process [Referent] METTFAG

A2 [Descriptive Name] Metallization, front only, by thick film screen printing of silver

PART 1 – PRODUCT DESCRIPTION

A3 [Product Referent] METCEL 3

A4 Descriptive Name [Product Name] Metallized solar cell

A5 Unit Of Measure [Product Units] 1 m^2 (100 cells)

PART 2 – PROCESS CHARACTERISTICS

A6 [Output Rate] (Not Thruput) 0.198 Units (given on line A5) Per Operating Minute

A7 Average Time at Station [Processing Time] ______ Calendar Minutes (Used only to compute in-process inventory)

A8 Machine "Up" Time Fraction [Usage Fraction] 0.95 Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS [Machine Description]

A9	Component [Referent]			
A9a	Component [Descriptive Name] (Optional)	Screen printer	Ink drier	Belt Furnace
A10	Base Year For Equipment Prices [Price Year]	1979	1979	1979
A11	Purchase Price ($ Per Component) [Purchase Cost]	50,000	20,000	35,000
A12	Anticipated Useful Life (Years) [Useful Life]	7	7	7
A13	[Salvage Value] ($ Per Component)	–	–	–
A14	[Removal and Installation Cost] ($/Component)	–	–	–

Note The SAMICS III computer program also prompts for the [payment float interval], the [inflation rate table], the [equipment tax depreciation method], and the [equipment book depreciation method] In the LSA SAMICS context, use 0 0, (1975, 4 0), DDB, and SL

Format A Process Description (Continued)

A15 Process Referent (From Page 1 Line A1) METTFAG

PART 4 — DIRECT REQUIREMENTS PER MACHINE (Facilities) **OR PER MACHINE PER SHIFT** (Personnel)
[Facilities and Personnel Requirements]

A16 Catalog Number [Expense Item Referent]	A18 Amount Required Per Machine (Per Shift) [Amount per Machine]	A19 Units	A17 Requirement Description
A 3016D	400	sq ft	Manuf'g Space Type A
B 5464D	0.25	persons/shift	Semicond. Assembler
B 5176D	0.25	dto	Maintenance Person

PART 5 — DIRECT REQUIREMENTS PER MACHINE PER MINUTE
[Byproduct Outputs] and [Utilities and Commodities Requirements]

A20 Catalog Number [Expense Item Referent]	A22 Amount Required Per Machine Per Minute [Amount per Cycle]	A23 Units	A21 Requirement Description
E	2.4	g/min	Ag ink ($0.70/g)
E	5.2	g/min	Xylene ($0.52/lb)
E	0.0022	screens/min	print screen ($25.-/ screen)
E	0.0176	squeegees/ min	squeegee ($0.40/ squeegee)
G 1016B	0.3	kWh/min	Electricity

PART 6 — INTRA-INDUSTRY PRODUCT(S) REQUIRED [Required Products]

A24 [Product Reference]	A26 Usable Output Per Unit of Input Product	A27 Units	A25 Product Name
	0.99	m^2/m^2	Wafer with pn junction
		/	
		/	

Prepared by M. Wolf Date 3-16-81

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr / Pasadena Calif 91103

Note Names given in brackets [ ] are the names of process attributes requested by the SAMICS III computer program

A1 Process [Referent] METLYTCU

A2 [Descriptive Name] Electrolytic plating of copper over a Ni strike layer, front and rear.

PART 1 — PRODUCT DESCRIPTION

A3 [Product Referent] METCEL 1

A4 Descriptive Name [Product Name] Metallized solar cell, possibly having a contact mask attached.

A5 Unit Of Measure [Product Units] m^2 (100 cells)

PART 2 — PROCESS CHARACTERISTICS

A6 [Output Rate] (Not Thruput) 29.94 Units (given on line A5) Per Operating Minute

A7 Average Time at Station [Processing Time] 15 Calendar Minutes (Used only to compute in-process inventory)

A8 Machine "Up" Time Fraction [Usage Fraction] 0.95 Operating Minutes Per Minute

PART 3 — EQUIPMENT COST FACTORS [Machine Description]

A9	Component [Referent]			
A9a	Component [Descriptive Name] (Optional)	2 automatic plating machines		
A10	Base Year For Equipment Prices [Price Year]	1979		
A11	Purchase Price ($ Per Component) [Purchase Cost]	400,000		
A12	Anticipated Useful Life (Years) [Useful Life]	7		
A13	[Salvage Value] ($ Per Component)	-		
A14	[Removal and Installation Cost] ($/Component)	200,000		

Note The SAMICS III computer program also prompts for the [payment float interval], the [inflation rate table], the [equipment tax depreciation method], and the [equipment book depreciation method] In the LSA SAMICS context, use 0 0, (1975, 4 0), DDB, and SL

Format A Process Description (Continued)

A15 Process Referent (From Page 1 Line A1) METLYTCU

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) **OR PER MACHINE PER SHIFT** (Personnel)
[Facilities and Personnel Requirements]

A16 Catalog Number [Expense Item Referent]	A18 Amount Required Per Machine (Per Shift) [Amount per Machine]	A19 Units	A17 Requirement Description
A 3016D	900	sq ft	Manuf'g Space Type A
B 5464D	1	person/shift	Semiconductor Assembler

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE
[Byproduct Outputs] and [Utilities and Commodities Requirements]

A20 Catalog Number [Expense Item Referent]	A22 Amount Required Per Machine Per Minute [Amount per Cycle]	A23 Units	A21 Requirement Description
E	48.37	g/min	Cu anodes ($2.00/kg)
E	41.	mℓ/min	Replenisher solut'n
			($3.43/ℓ)
C 1016B	2.5	kWh/min	Electricity

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED [Required Products]

A24 [Product Reference]	A26 Usable Output Per Unit of Input Product	A27 Units	A25 Product Name
	0.998	m^2 / m^2	Cell with strike metal

Prepared by M. Wolf Date 3-16-81

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr / Pasadena, Calif 91103

PROCESS DESCRIPTION

Note Names given in brackets [ ] are the names of process attributes requested by the SAMICS III computer program

A1 Process [Referent] METSOLD

A2 [Descriptive Name] Solder dipping of solar cell with plated metal

PART 1 – PRODUCT DESCRIPTION

A3 [Product Referent] METCEL 2

A4 Descriptive Name [Product Name] Solder dipped solar cell

A5 Unit Of Measure [Product Units] m^2 (100 cells)

PART 2 – PROCESS CHARACTERISTICS

A6 [Output Rate] (Not Thruput) 29.94 Units (given on line A5) Per Operating Minute

A7 Average Time at Station [Processing Time] ______ Calendar Minutes (Used only to compute in-process inventory)

A8 Machine "Up" Time Fraction [Usage Fraction] 0.88 Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS [Machine Description]

A9	Component [Referent]			
A9a	Component [Descriptive Name] (Optional)	Solder Dip System		
A10	Base Year For Equipment Prices [Price Year]	1978		
A11	Purchase Price ($ Per Component) [Purchase Cost]	50,000		
A12	Anticipated Useful Life (Years) [Useful Life]	7		
A13	[Salvage Value] ($ Per Component)	–		
A14	[Removal and Installation Cost] ($/Component)	–		

Note The SAMICS III computer program also prompts for the [payment float interval], the [inflation rate table], the [equipment tax depreciation method], and the [equipment book depreciation method] In the LSA SAMICS context, use 0 0, (1975, 4 0), DDB, and SL

Format A Process Description (Continued)

A15 Process Referent (From Page 1 Line A1) METSOLD

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) **OR PER MACHINE PER SHIFT** (Personnel)
[Facilities and Personnel Requirements]

A16 Catalog Number [Expense Item Referent]	A18 Amount Required Per Machine (Per Shift) [Amount per Machine]	A19 Units	A17 Requirement Description
A 3016D	93	sq ft.	Manuf'g Space Type A
B 5464D	1	person/shift	Semiconductor Assembler

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE
[Byproduct Outputs] and [Utilities and Commodities Requirements]

A20 Catalog Number [Expense Item Referent]	A22 Amount Required Per Machine Per Minute [Amount per Cycle]	A23 Units	A21 Requirement Description
E	113	g/min	60/40 Sn/Pb Solder
			(10.-/kg)
E	0.027	gal/min	Flux, water soluble
			(6.75/gal)
C 1128D	4	ℓ/min	DI Water
C 1016B	0.135	kWh/min	Electricity

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED [Required Products]

A24 [Product Reference]	A26 Usable Output Per Unit of Input Product	A27 Units	A25 Product Name
	0.998	m^2 / m^2	metallized cell

Prepared by M. Wolf Date 3-16-81

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr / Pasadena Calif 91103

PROCESS DESCRIPTION

Note Names given in brackets [ ] are the names of process attributes requested by the SAMICS III computer program

A1 Process [Referent] METSPUT

A2 [Descriptive Name] Sputter deposition of Cu (front and rear)

PART 1 – PRODUCT DESCRIPTION

A3 [Product Referent] METCEL 1

A4 Descriptive Name [Product Name] Metallized solar cell

A5 Unit Of Measure [Product Units] m^2 (100 cells)

PART 2 – PROCESS CHARACTERISTICS

A6 [Output Rate] (Not Thruput) 0.495 Units (given on line A5) Per Operating Minute

A7 Average Time at Station [Processing Time] ______ Calendar Minutes (Used only to compute in-process inventory)

A8 Machine "Up" Time Fraction [Usage Fraction] 0.875 Operating Minutes Per Minute

PART 3 – EQUIPMENT COST FACTORS [Machine Description]

A9	Component [Referent]			
A9a	Component [Descriptive Name] (Optional)	Vacuum Sputtering System		
A10	Base Year For Equipment Prices [Price Year]	1979		
A11	Purchase Price ($ Per Component) [Purchase Cost]	2.5 Mill		
A12	Anticipated Useful Life (Years) [Useful Life]	7		
A13	[Salvage Value] ($ Per Component)	-		
A14	[Removal and Installation Cost] ($/Component)	0.5 Mill		

Note The SAMICS III computer program also prompts for the [payment float interval], the [inflation rate table], the [equipment tax depreciation method], and the [equipment book depreciation method] In the LSA SAMICS context, use 0 0, (1975, 4 0), DDB, and SL

Format A Process Description (Continued)

A15 Process Referent (From Page 1 Line A1) METSPUT

PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) **OR PER MACHINE PER SHIFT** (Personnel)
[Facilities and Personnel Requirements]

A16 Catalog Number [Expense Item Referent]	A18 Amount Required Per Machine (Per Shift) [Amount per Machine]	A19 Units	A17 Requirement Description
B 5464D	1	pers/stat'n	Semiconductor Assembler
B 5224D	0.1	dto	Maintenance Mechanic
B 5176D	0.1	dto	Electronics Technician
A 3016D	600	squ. ft.	Manuf'g Space Type A

PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE
[Byproduct Outputs] and [Utilities and Commodities Requirements]

A20 Catalog Number [Expense Item Referent]	A22 Amount Required Per Machine Per Minute [Amount per Cycle]	A23 Units	A21 Requirement Description
E	93	g/min	Copper sputter targets

PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED [Required Products]

A24 [Product Reference]	A26 Usable Output Per Unit of Input Product	A27 Units	A25 Product Name
		/	Wafer with pn junction
		/	
		/	

Prepared by M. Wolf Date 3-16-81

APPENDIX III

SAMPLE SET OF FORMS

FOR THE

UNIVERSITY OF PENNSYLVANIA PROCESS CHARACTERIZATION (UPPC)

Process No. ☐.☐.☐☐-☐☐

Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: ____________________

Subprocess: ____________________

Option: ____________________

____

INDEX

Form	Pages	Rev.	Date	Remarks
1		___	___	___
2	1 to ___	___	___	___
3	1 to ___	___	___	___
4	1 to ___	___	___	___
5	1 to ___	___	___	___
6	1 to ___	___	___	___
7	1 to ___	___	___	___
8	1 to ___	___	___	___
9-1	1 to ___	___	___	___
9-2	1 to ___	___	___	___
9-3	1 to ___	___	___	___
10	1 to ___	___	___	___
11	1 to ___	___	___	___
12	1 to ___	___	___	___
13-1	1 to ___	___	___	___
13-2	1 to ___	___	___	___
14	1 to ___	___	___	___
15	1 to ___	___	___	___
16	1 to ___	___	___	___

Form 2

Page ____ of _____

Revision ______ Date _________

Process No. ☐ . ☐ . ☐☐ - ☐☐

0.1 Value Added:	__________ $/_______

Process Description: ____

1. Input Specification:

Name of Item: ______________________________________

Dimensions: ______________________________________

Material: ______________________________________

Other Specifications: ______________________________________

1.1 Quantity Required: ______ _____ / ______ Unit Cost: _______ $/ _______

1.2 Input Value:	__________ $/_______
1.3 Input Cost:	__________ $/_______

Note to Item 1.3: Use price, if input produced in own plant.

Process No. ☐ . ☐ . ☐☐ - ☐☐

2.1 Direct Materials:

2.1_ Type ________________________________;

Specification: ________________________________

____

________________________________,

Quantity Required. ____________ ___/___, Unit Cost: ______$/______; Cost ______$/______

2.1_ Type ________________________________;

Specification: ________________________________,

____

____

Quantity Required. ____________ ___/___; Unit Cost: ______$/______, Cost: ______$/______

2.1_ Type ________________________________;

Specification: ________________________________

____

________________________________;

Quantity Required. ____________ ___/___, Unit Cost. ______$/______; Cost: ______$/______

2.1 Subtotal Direct Materials:	______$/______

Process No. ☐ . ☐ . ☐☐ - ☐☐

Form 4

Page __ of __

Revision ______ Date ______

2.2 Indirect Materials (incl. supplies and non-energy utilities):

2 2_ Type: ______________________________

Specification: ______________________________

____

____

Quantity Required: ______________ ___/____, Unit Cost ______$/______; Cost: ______$/____

2.2_ Type ______________________________

Specification: ______________________________

____

____

Quantity Required: ______________ ___/____, Unit Cost ______$/______; Cost: ______$/____

2.2_ Type: ______________________________

Specification ______________________________

____

____

Quantity Required ______________ ___/____, Unit Cost: ______$/______, Cost: ______$/____

2.2 Subtotal Indirect Materials:	______$/____

Process No. ☐.☐.☐☐-☐☐

Form 5

Page __ of __

Revision_____ Date______

2.3 Expendable Tooling.

2.3 _ Type: ______________________

______ Quantity Required: ______ ____/____ Unit Cost: ____$/____ Cost: ______$/_____

2.3 _ Type. ______________________

______ Quantity Required. ______ ____/____ Unit Cost: ____$/____ Cost: ______$/_____

2.3 _ Type: ______________________

______ Quantity Required: ______ ____/____: Unit Cost: ____$/____ Cost: ______$/_____

2.3 _ Type. ______________________

______ Quantity Required ______ ____/____: Unit Cost ____$/____ Cost. ______$/_____

2.3 Subtotal Expendable Tooling:	______$/_____

2.4 Energy

2.4 _ Type. ______________________

______ Quantity Required: ______ ______ Unit Cost. ____$/____ Cost: ______$/_____

2.4 _ Type: ______________________

______ Quantity Required. ______ ______: Unit Cost. ____$/____ Cost: ______$/_____

2.4 Subtotal Energy Costs:	______$/_____
2.5 Subtotal 2.1 to 2.4:	______$/_____
2.6 Handling Charge: _____% of item 2.5	______$/_____
2.7 Subtotal Materials and Supplies. (2.5 + 2.6)	______$/_____

Process No. ☐.☐.☐☐-☐☐

Form 6
Page ___ of ___

Revision______ Date__________

3.1 Direct Labor:

3.1_ Category: ______________________ Activity: ______________________

Amount Required: ________h/________; Rate: $________/h; Load________%; Cost: ________$/______

3.1_ Category: ______________________ Activity: ______________________

Amount Required: ________h/________; Rate: $________/h; Load________%; Cost: ________$/______

3.1_ Category ______________________ Activity: ______________________

Amount Required: ________h/________, Rate: $________/h; Load________%; Cost. ________$/______

3.1 Direct Labor Subtotal ________$/______

3.2 Indirect Labor:

3.2_ Category: ______________________ Activity: ______________________

Amount Required: ________h/________; Rate. $________/h; Load________%; Cost: ________$/______

3.2_ Category: ______________________ Activity: ______________________

Amount Required: ________h/________; Rate: $________/h; Load________%; Cost: ________$/______

3.2_ Category: ______________________ Activity: ______________________

Amount Required: ________h/________; Rate: $________/h; Load________%; Cost: ________$/______

3.2 Indirect Labor Subtotal: ________$/______

3.3 Subtotal 3.1 and 3.2 ________$/______

3.4 Overhead on Labor: ______% ________$/______

3.5 Subtotal Labor ________$/______

Process No. ☐.☐.☐☐-☐☐

4.1 Equipment

4.1_ Type. ______________________________

Cost: ____________$, Installation Cost: ____________$, Throughput: ____________/h,

Plant Oper'g Time __________h/y, Machine Avail'ty: _____%, Machine Oper'g Time __________h/y

Servicing Costs Labor ________h/y at ________$/h; Parts or Outside Service: ________$/y

Useful Life ________y, Charge Rate ________% of Cost/y; Capital Cost ____________$/y ________$/___

4 1_ Type ______________________________

Cost ____________$, Installation Cost: ____________$, Throughput ____________/h,

Plant Oper'g Time __________h/y, Machine Avail'ty: _____%, Machine Oper'g Time __________h/y

Servicing Costs: Labor ________h/y at ________$/h, Parts or Outside Service ________$/y

Useful Life: ________y, Charge Rate: ________% of Cost/y, Capital Cost: ____________$/y ________$/___

4.1_ Type: ______________________________

Cost ____________$, Installation Cost: ____________$, Throughput ____________/h,

Plant Oper'g Time __________h/y; Machine Avail'ty. _____%; Machine Oper'g Time __________h/y

Servicing Costs: Labor ________h/y at ________$/h; Parts or Outside Service: ________$/y

Useful Life ________y, Charge Rate. ________% of Cost/y, Capital Cost. ____________$/y ________$/___

4.1 Subtotal Equipment Cost	________$/___

Process No. ☐.☐.☐☐-☐☐

Form 8
Page ___ of _
Revision _____ Date ______

4.2 Facilities·

4.2_ Type: ________________ Floor Area: ________ m^2; Throughput ________ ________/y

Charge Rate ________________ $/($m^2$·y),

Energy Use:

Heating ________ ______/y at ______$/_____

Air Cond'g ________ ______/y at ______$/_____

Lighting ________ ______/y at ______$/_____

Maintenance Costs:

Labor ________h/y at ________$/h

Supplies: ________$/y

Outside Services: ________$/y

Total Cost. ________$/y ________$/_____

4.2_ Type ________________ Floor Area ________ m^2; Throughput. ________ ________/y

Charge Rate: ________________ $/($m^2$·y),

Energy Use:

Heating ________ ______/y at ______$/_____

Air Cond'g ________ ______/y at ______$/_____

Lighting ________ ______/y at ______$/_____

Maintenance Costs:

Labor: ________h/y at ________$/h

Supplies: ________$/y

Outside Services: ________$/y

Total Cost: ________$/y ________$/_____

4.2_ Type: ________________ Floor Area: ________ m^2, Throughput ________ ________/y

Charge Rate. ________________ $/($m^2$·y),

Energy Use:

Heating ________ ______/y at ______$/_____

Air Cond'g ________ ______/y at ______$/_____

Lighting ________ ______/y at ______$/_____

Maintenance Costs:

Labor· ________h/y at ________$/h

Supplies ________$/y

Outside Services: ________$/y

Total Cost. ________$/y ________$/_____

4 2 Subtotal Facilities: ________$/_____

4.3 Equipment and Facilities Subtotal : ________$/_____

Revision ________ Date ________

Process No. ☐ . ☐ . ☐☐ - ☐☐

5. Salvaged Material (Work-in-process)

5 1	Quantity of Work-in-Process 1. Contained in Good Output Work-in-Process (per Computation Unit)	______ ______/______	
5 21	Input Work-in-process 1. Not Contained in Good Output Work-in-Process ("Amount Required" from 1.1 minus 5 1)	______ ______/______	
5.22	Net Amount of 5.21 which is sold for Credit As-Is or After Applying Re-Process ☐ . ☐ . ☐☐ - ☐☐	______ ______/______	
5 23	Credit for 5.22 at the Market Value of ______$/______.	______$/______	
5 24	Cost of Reprocessing Material of 5 22 at the Average Reprocessing Cost of ______$/______:	______$/______	
5 25	Net Credit for 5.22 (5.23 minus 5 24):		______$/______
5.26	Material of Type 1. Lost in Process (5.21 minus 5.22)	______ ______/______	
5 3	Cost of Work-in-Process Not Contained in Good Output Work-in-Process (Amount 5.21 Times Unit Cost 1.1)		______$/______
5.4	Cost of Work-in-Process Contained in Good Output Work-in-Process (Amount 5.1 Times Unit Cost from 1.1)		______$/______

Salvaged Materials Summary:

5 8	Total Net Credits for All Salvaged Materials (5.25 + 5.67 + 5.76)	______$/______

Process No. ☐ . ☐ . ☐☐ - ☐☐ Revision_____ Date__________

5. Salvaged Material (Direct)

5.5	Quantity of Direct Material 2.1_ Contained in Good Output Work-in Process (per Computation Unit)	________ _____/______	
5.61_	Input Material of Type 2.1_ Not Contained in Good Work-in-Process ("Amount Required" from 2.1_ minus 5.5_)	________ _____/______	
5.62_1	Net Amount of 5.61_ which is sold for Credit As-Is or After Applying Re-Process ☐ . ☐ . ☐☐ - ☐☐	________ _____/______	
5.63_1	Credit for 5.62_1 at the Market Value of _____$/_____:	____________$/______	
5.64_1	Cost of Reprocessing Material of 5.62_1 at the Average Reprocessing Cost of _____$/_____:	____________$/______	
5.65_1	Net Credit for 5.62_1 (5.63_1 minus 5.64_1):	____________$/______	
5.62_2	Net Amount of 5.61_ which is sold for Credit As-Is or After Applying Re-Process ☐ . ☐ . ☐☐ - ☐☐	________ _____/______	
5.63_2	Credit for 5.62_2 at the Market Value of _____$/_____:	____________$/______	
5.64_2	Cost of Reprocessing Material of 5.62_2 at the Average Reprocessing Cost of _____$/_____:	____________$/______	
5.65_2	Net Credit for 5.62_2 (5.63_2 minus 5.64_2):	____________$/______	
5.66_	Total Net Amount of Material of Type 2.1_ Salvaged (Σ 5.62_i)	________ _____/______	
5.67_	Total Net Credits for Salvaged Material of Type 2.1_ (Σ 5.45_i)		________$/________

Process No ☐ . ☐ . ☐☐ - ☐☐

Form 9-3

Page ___ of ___

Revision ______ Date __________

5 Salvaged Material (Indirect)

5.7_ Quantity of Indirect Material 2 2_ Entered into Process (per Computation Unit) __________ ______/________

5.71_1 Net Amount of 5.71_ which is sold for Credit As-Is or After Applying Re-Process ☐ . ☐ . ☐☐ - ☐☐ __________ ______/________

5.72_1 Credit for 5.71_1 at the Market Value of ________$/______:

5.73_1 Cost of Reprocessing Material of 5.71_1 at the Average Reprocessing Cost of ________$/______: ______________$/________

5.74_1 Net Credit for 5.71_1 (5.72_1 minus 5.73_1): ______________$/________

5.71_2 Net Amount of 5.71_ which is sold for Credit As-Is or After Applying Re-Process ☐ . ☐ . ☐☐ - ☐☐ __________ ______/________

5.72_2 Credit for %.71_2 at the Market Value of ________$/______. ______________$/________

5.73_2 Cost of Reprocessing Material of 5.71_2 at the Average Reprocessing Cost of ________$/______ ______________$/________

5.74_2 Net Credit for 5.71_2 (5.72_2 minus 5.73_2)" ______________$/________

5.75_ Total Net Amount of Material of Type 2.2_ Salvaged (Σ 5.71_i) ________$/________

Process No. ☐ . ☐ . ☐☐ - ☐☐

6 Byproducts and Wastes

Revision ________ Date ________

6 1 Solid Byproducts/Wastes

6.1_ Type (Composition) ____________________ Quantity Produced: ________/________

Physical Shape/Size· ____________________ Energy Content· __________ kWh/________

Density:__________g/cm^3, Water Solubility·__________g/l at __________°C. pH __________

Toxicity:__________ Biodegradable:__________ Other Remarks· ____________________

____

Type of Disposal: ____

Input Material for:____________________ Cost/(Credit)______$/______; Cost: ______$/______

6.2 Liquid Byproducts/Wastes (inorganic)

6.2_ Type (Composition).____________________ Quantity Produced.______/______

Density.____g/cm^3; Suspended Solids:__________ Amount:______mg/l pH:______

Toxicity·______________ Heavy Metal Content:_____mg/l Other Remarks __________

____

Type of Disposal ____

Input Material for:____________________Cost/(Credit)_____$/________ Cost ______$/______

Carry ______$/______

Process No. ☐☐.☐☐.☐☐☐☐-☐☐☐☐

Revision____ Date ________

Carry from Form 10	______$/______

6.3 Liquid Byproducts/Wastes (organic)

6 3_ Type (Composition) ______________________ Quantity Produced: ______/______

Density. ________ g/cm^3; Toxicity __________ COD __________ mg/1, BOD: ________ mg/1

Ignition Point _____ ^oC, Explosive Mixture in Air: ___% to ___%, Other Remarks. _______

____

Type of Disposal ____

Input Material for ______________________ Cost(Credit) ____$/_____; Cost ______$/______

6.4 Fumes, Gaseous Byproducts/Wastes

6.4_ Type (Composition) ______________________ Quantity Produced ______/______

Energy Content (Combustion): ______ kWh/______, Explosive Mixture in Air ___% to ___%.

Ignition Point _____ ^oC, Aerosol ☐ Precipitates in _____ minutes pH______

Toxicity ____________ Requires Scrubbing ☐ Type of Scrubber: ____________

(enter scrubber under 4.1, 4.2, scrubber effluent under 6.1 to 6.3)

Other remarks: ____

____

Type of Disposal ____

Operating Costs: __________$/________, Cost: ______$/______

6. Subtotal Byproduct/Waste Disposal Cost.	

Process No. ☐.☐.☐☐-☐☐

Revision ______ Date________

7. Process Cost Computation

7.11 Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)		________$/________
7.22 Other Indirect Costs: ________% of 7.11		________$/________
7.21 Total Operating Add-on Costs of Process:		________$/________
7.22 G & A ________% of 7.21		________$/________
7.31 Total Gross Add-On Cost of Process		________$/________
7.32 Credit for Salvaged Material (5.8)		________$/________
7.33 Cost of Work-in-Process Lost (5.3)		________$/________
7.34 Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)		________$/________
7.35 Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)		________$/________
7.36 Loading on Item 7.35 at Rate ________%		________$/________
7.37 Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)		________$/________
7.41 Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	__________ _____/______	
7.42 Practical Yield	______%	
7.43 Effective Yield (7.41 x 7.42)	__________/__________	
7.44 Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	______________/________	
7.51 Cost of Unit of Good Output Work-in-Process (7.37 ÷ 7.44)		________$/________
7.52 Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)		________$/________

Process No ☐.☐.☐☐-☐☐

Form 13-1
Page ___ of ___

Revision_____ Date__________

8. Price Computation

8.1 Alternate 1

8 11 Profit at Expected Rate of _____%· __________$/__________
(Profit before income taxes; applied to 7.52)

8 12 Price of Process (7.52 + 8.11) __________$/__________

8.13 Price of Work-in-Process (7.51 + 8.11) __________$/__________

Process No. □.□.□□-□□

Form 13-2
Page ___ of ___

Revision ________ Date ____________

8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation:

0.9274* __________ \$/ ______________ from Subtotal 4.1 = __________ \$/ ____________

1.946* __________ \$/ ______________ from Subtotal 4.2 = __________ \$/ ____________

Subtotal = __________ \$/ ____________

8.22 Costs of Amortization of the One-Time Cost:

0.192* __________ \$/ ______________ from Subtotal 2.7 = __________ \$/ ____________

0.192* __________ \$/ ______________ from Subtotal 3.5 = __________ \$/ ____________

0.2958* __________ \$/ ______________ from Subtotal 4.1 = __________ \$/ ____________

2.77* __________ \$/ ______________ from Subtotal 4.2 = __________ \$/ ____________

Subtotal = __________ \$/ ____________

8.23 Total Net Cost of Equity (8.21 + 8.22): ____________ \$/ ________

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process:
(Divide Subtotal 8.23 by ____________ __________ / ________ from 7.44)

__________ \$/ ____________

8.25 Price of Process (7.52 + 8.24) ____________ \$/ ________

8.26 Price of Work-in-Process (7.51 + 8.24) ____________ \$/ ________

Process No. ☐.☐.☐☐-☐☐

Form 14
Page ___ of ___

9. Process Economic Evaluation.

Revision_____ Date_________

9.1	Process Cost Balance (7.52 - 0.1)	________$/________
9.2	Relative Process Performance (9.1 - 0 1)	____________
9 3	Output Cost (7 51)	________$/________
9.4	Output Value (0.2 + 0.1)	________$/________
9.5	Relative Excess Cost [(9 3 - 9 4) - 9 4]	____________

Process No. ☐.☐.☐☐-☐☐

Form 15
Page ____ of ____

Revision ______ Date __________

0. Output Specification:

Name of item: ______________________________

Dimensions ______________________________

Material. ______________________________

Other Specifications: ______________________________

Form 16

Page ____ of ____

Process No ☐ . ☐ . ☐☐ - ☐☐

WORKSHEET TO ITEM ____________________, FORM __________ PAGE ______