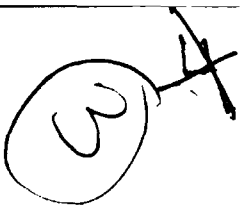
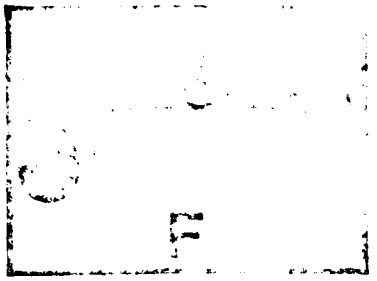
AD-A286 119





94-34506

Quarterly Report

Technical Cost Modeling Applied to CVD Diamond Deposition

Contract Number: N00014-93-C2044

Distribution Statement A:
Approved for Public Release:
Distribution is Unlimited.

IBIS

Third Quarter 1994

IBIS Associates, Inc.
55 William Street, Suite 220
Wellesley, MA 02181
Tel: 617-239-0666
Fax: 617-239-0852

94 11 1 177

Best
Available
Copy

Table of Contents

Executive Summary 1

CVD Diamond Wafer Fabrication Layout 2

Surface Preparation 2
Deposition 3
Etching 3
Laser Trimming 3
Lapping 3
Inspection 4

Deposition Rate Calculations 5

DC Arcjet 5
Microwave 6
Combustion Flame 8

Technical Cost Modeling Results 12

Three Technology Comparison 12
Baseline Costs in the Long Term 13
Long Term Cost vs Thermal Conductivity 15
DC Arcjet 16
Cost vs Reactor Power and Substrate Diameter 16
Cost vs Reactor Power and Gas Temperature 17
Cost vs Reactor Power and Thermal Conductivity 18
Microwave 19
Cost vs Reactor Power 19
Cost vs Reactor Power and Thermal Conductivity 19
Combustion Flame 19
Cost vs Acetylene:Oxygen Gas Ratio and Substrate Diameter 21
Cost vs Substrate Diameter and Thermal Conductivity 21

Summary 23

Appendix A - The DC Arcjet Model . . . . . A

Appendix B - The Microwave Model . . . . . B

Appendix C - The Combustion Flame Model C

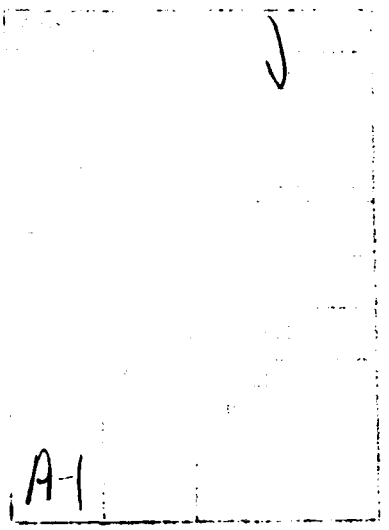
Executive Summary

IBIS Associates has completed its predictive spreadsheet models of chemical vapor deposition (CVD) diamond film fabrication. This report details the capabilities of the models, and shows cost sensitivities to product and process input parameters.

The DC arcjet, microwave, and combustion flame CVD diamond deposition models, in addition to the CVD diamond finishing model, have been developed to maximize cost estimation flexibility. In doing so for deposition, inputs such as thermal conductivity, machine power, gas concentration, gas temperature, and reactor pressure have been provided in the model to predict the deposition growth rate, which is critical to the cost calculation. For the finishing model, inputs such as laser power, laser spot size, and laser frequency have been provided in the model to predict the diamond removal rate, which is also critical to the final cost calculation.

For this report and the results contained herein, it is assumed that the transport theory model which predicts growth rates in the CVD diamond technical cost models closely predicts actual growth rates for the deposition technologies and that the input values for variables such as the gas flow rate and substrate diameter are physically achievable.

To be investigated further is the market value issue. IBIS will contact potential users of CVD diamond substrates to determine the price at which they would be willing to pay for specific performance improvements.



CVD Diamond Wafer Fabrication Layout

The three CVD diamond deposition models have the process flow shown in Figure 1, and full printouts of these models are included in the appendices. This process flow has been determined from the CVD diamond literature and from interviews with industry experts. Since the finishing steps were documented in the fourth quarter report of 1993 and have not changed, this report shows the final form of the deposition models and illuminates the economics of the processes.

The unit operations are described in the following sections.

Surface Preparation

A substrate, usually silicon or molybdenum, is critical for the nucleation phase of CVD diamond deposition. Wafers made of different materials at varying thicknesses and diameters are listed in the spreadsheet's material database. These substrates are assumed to be lapped, or abrasively polished, to create a mirror quality finish. The model assumes that the same type of lapping equipment is used for silicon as is used for the diamond wafers.

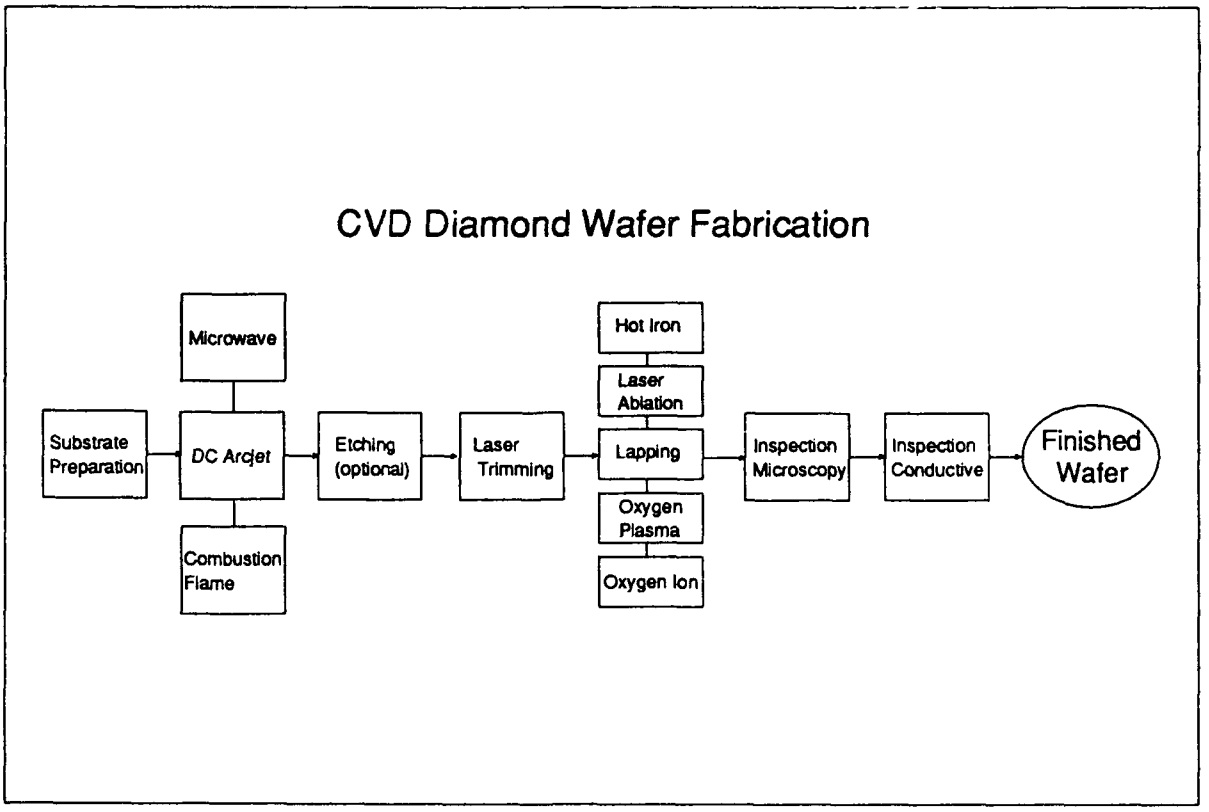


Figure 1

The capital costs for lapping equipment are predicted based on a statistical relationship derived from the analysis of collected industry data.

Deposition

The cost of forming of CVD diamond is calculated in this step. As CVD diamond deposition is a process requiring hundreds of hours, hundreds of thousands of dollars of deposition equipment, tens to hundreds of kilowatts, and large quantities of expensive process gases to form a one millimeter thick wafer, this is the most costly step is the series of operations modeled. Consequently each of the three technologies studied for CVD diamond (DC arcjet, microwave, and combustion flame) have been subjected to numerous iterations of expert scrutiny. The end result is a model that will predict diamond linear growth rate as a function of such product and process characteristics as desired thermal conductivity, machine power and pressure, gas flow rates and concentrations, desired diameter, and gas temperature.

Etching

The third step in the baseline process, as modeled, is etching to remove the silicon substrate, if one is used. The substrate/diamond wafers are placed in a cassette, then placed in a 5:1:1 bath of water, hydrofluoric acid, and nitric acid, designed to completely etch away the substrate. After the etching has been completed, the cassette is placed in a rinse bath. The entire process must be performed under a hood in order to draw away noxious gases. Disposal costs associated with waste liquids, which range from four to eight dollars per liter, are included in the model.

Substrate etching is only applicable when the substrate is not reusable, as in the case of silicon. For other materials, the substrate is mechanically separated from the diamond film and reconditioned for reuse.

Laser Trimming

Due to the formation of undesirable quality diamond on the periphery of the intended area, the fourth step, laser trimming, is necessary to cut a clean edge encircling an area of uniform quality CVD diamond. A CO_2 laser is the assumed equipment required to perform this task. The cost for such a system is estimated at $6,000 and requires a full-time operator. The rate at which CVD diamond is trimmed is set at one centimeter per second.

Lapping

The fifth step is the lapping of the diamond film. This step can either be a one sided or two sided process. (In other instances, depending on the end use application, lapping may be unnecessary.) In the lapping operation, diamond wafers are placed in carriers or holders, and lapped by the abrasive action of diamond grit. Diamond wafers (typically three to five

per batch), are held in place by the holders and travel in an elliptical pattern on the surface of a rotating, "O" shaped plate. During this process, a diamond grit slurry flows through grooves in the plate, lapping the surface of the diamond films. The size of the grit chosen depends on the initial and desired surface roughness.

Other techniques for lapping or polishing have been reviewed in previous quarterly reports for this contract as well as in the technical literature, including chemical and ablative techniques for surface reduction. However, according to most experts surveyed, conventional abrasive lapping remains the technology of choice. This operation is second to deposition in cost due to the difficult nature of removing diamond material.

Inspection

The last two steps are the inspection of the finished diamond films. The first is a visual inspection using a microscope while the second involves thermal conductivity testing. Neither step appears to have a significant cost, other than the accrued cost of product rejections which occur at these steps.

The preceding paragraphs briefly describe each operation in the fabrication of CVD diamond wafers. As mentioned, efforts have primarily been focused on the deposition step, with secondary efforts involving the finishing of CVD diamond films. Since the finishing model was documented in the fourth quarter report of 1993 and has not changed, this report shows the final form of the deposition models and illuminates the economics of the processes.

Deposition Rate Calculations

The incorporation of CVD diamond deposition theory allows the cost models to predict the deposition rate as a function of the reactor input variables, as if the model user had access to an actual CVD diamond reactor. For the DC arcjet, microwave, and combustion flame technologies, industry experts were consulted to provide modeling support ranging from overall strategy to the details of the deposition rate equations. The strategy aspect included the identification of input variables, definition of process conditions, and structure of the logic of the equations; while the detailed modeling included the actual equations, chemical reaction constants, and output trend verification.

In all three technologies, Professor David Goodwin of the California Institute of Technology was the key theorist consulted for both overall strategy and detailed modeling. In addition, Professor David Dandy from Colorado State University and Dr. Michael Coltrin from Sandia National Laboratories provided detailed modeling support regarding the thermal conductivity input to all three cost models. Dr. James Butler has also been involved in all three technologies, providing expert review of the cost models. Other deposition theorists and the strategies employed are described in the following sections.

DC Arcjet

The deposition modeling assumptions for the DC arcjet model are depicted in Figure 2, with the equation logic flow shown in Figure 3. In addition to Professor David Goodwin, Dr. Richard Woodin, formerly of Norton Diamond Film, was consulted for the deposition rate calculation. The experts who reviewed the approach and outputs from this model include Professor Goodwin, Dr. Woodin, Dr. Butler, Drs. Young and Partlow from Westinghouse, Professor Angus from Case Western Reserve University, Professor Cappelli from Stanford University, and Mr. White from Olin Aerospace Co.

Figure 2 is a diagram of the overall modeling strategy for the DC arcjet model. The gas jet exiting the nozzle forms the first regime; the chemistry in this region is a function of the reactor's input parameters and is assumed to be uniform. The second region is the boundary layer, where the chemistry varies with the distance from the growth surface. This goal of this approach is to calculate the atomic hydrogen concentration at the growth surface which, along with the CH_3 (methyl) concentration, determines the CVD diamond growth rate. Because of the interrelationships that exist among such variables as reactor power, gas concentrations, reactor pressure, gas temperature, wafer diameter, and thermal conductivity, the calculation path to deposition rate is complex.

Figure 3 shows the equation logic flow for the DC arcjet model. Important calculations include the atomic hydrogen mole fraction in the gas jet (H Mole Frac. (Jet)), gas jet Mach Number (Mach Number), gas pressure at the substrate surface (Gas Pressure (Sub)), atomic

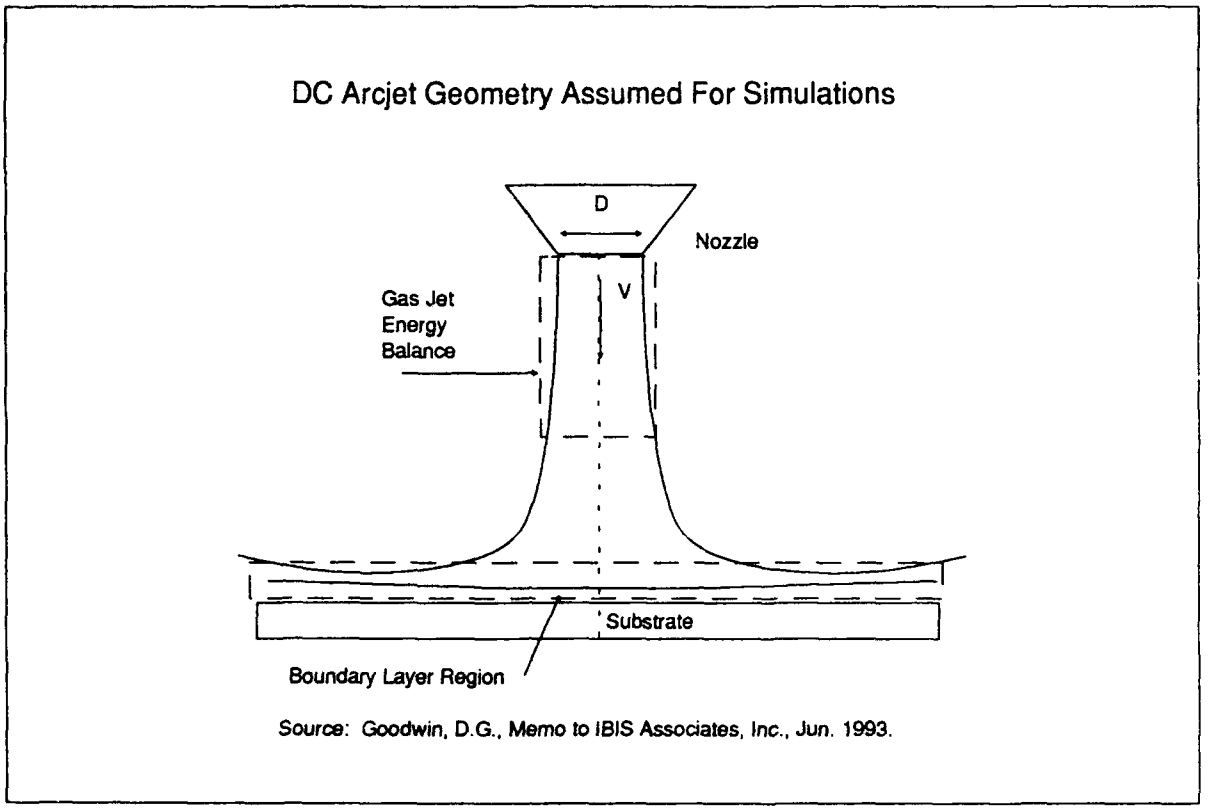


Figure 2

hydrogen concentration at the substrate (H Concentr. (Sub)), and the linear deposition rate (Linear Dep. Rate). For an explanation of the logic and actual equations, see an article on this subject by Professor Goodwin (Goodwin, D.G., J. Appl. Phys. 74, 6888 (1993)) and the third quarter report of 1993 for this contract.

Updated results from this model are shown later in this report. The next section details the microwave CVD diamond cost model.

Microwave

The deposition modeling assumptions for the microwave model are depicted in Figure 4, with the equation logic flow shown in Figure 5. In addition to Professor Goodwin, Dr. Jeff Casey of ASTeX was consulted for the deposition rate calculation. The experts who reviewed the approach and outputs from this model include Professor Goodwin, Dr. Casey, Dr. Butler, Drs. Young and Partlow from Westinghouse, Dr. Buckley-Golder from AEA (Britain), and Dr. Dahimene of Wavemat.

Figure 4 is a diagram of the overall modeling strategy for the microwave model. The model assumes atomic hydrogen is generated roughly in the middle of the plasma at a distance "L" from the substrate. This goal of this approach is to calculate the atomic hydrogen concentration at the growth surface through the characterization of both the

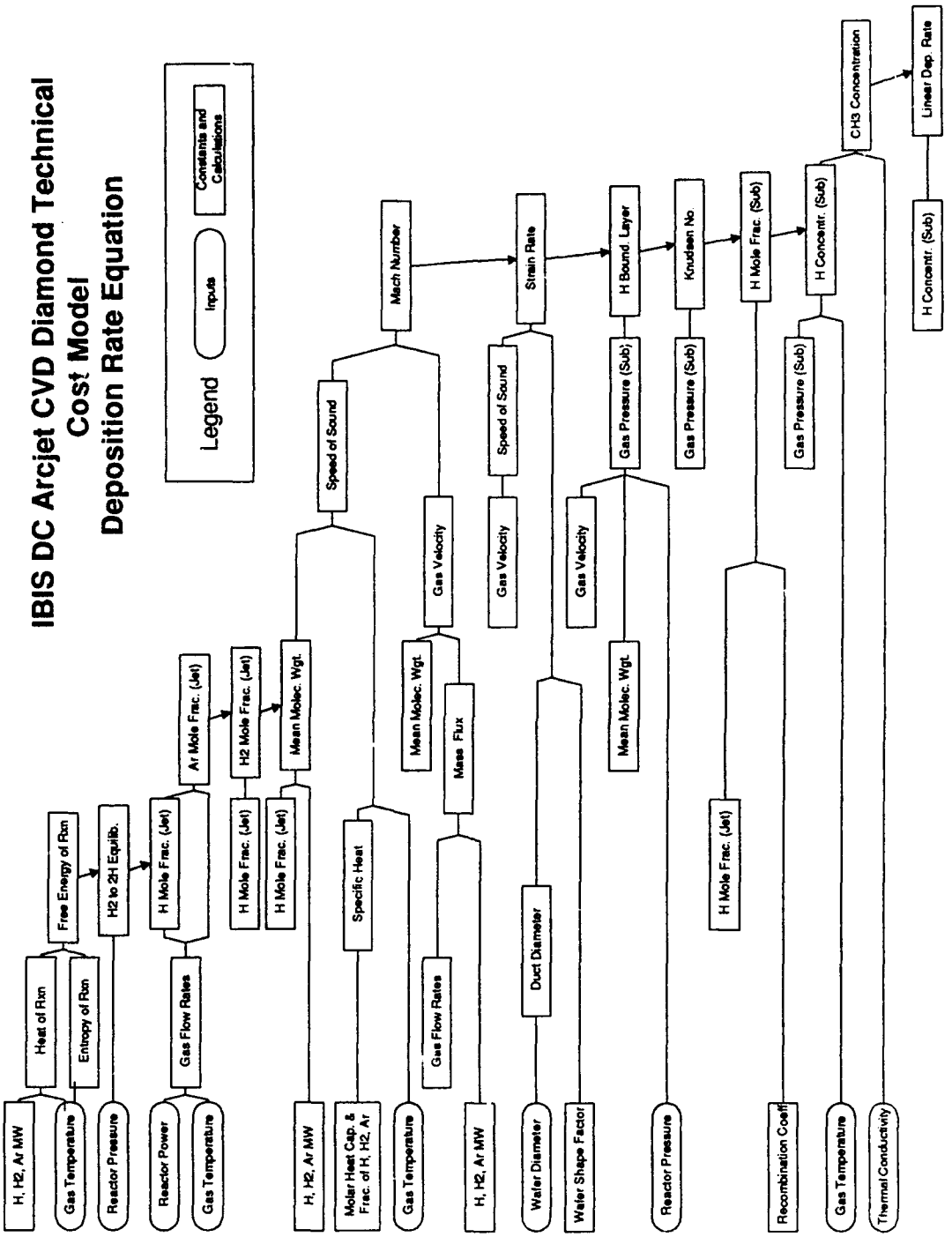

IBIS DC Arcjet CVD Diamond Technical Cost Model
Deposition Rate Equation
Legend
Inputs
Constants and Calculations
H, H2, Ar MW
Heat of Rxn
Free Energy of Rxn
Entropy of Rxn
Gas Temperature
H2 to 2H Equilib.
Reactor Pressure
H Mole Frac. (Jet)
Ar Mole Frac. (Jet)
Gas Flow Rates
Reactor Power
Gas Temperature
H2 Mole Frac. (Jet)
H Mole Frac. (Jet)
H Mole Frac. (Jet)
Mean Molec. Wgt.
H, H2, Ar MW
Speed of Sound
Molar Heat Cap. & Frac. of H, H2, Ar
Specific Heat
Gas Temperature
Mach Number
Mean Molec. Wgt.
Gas Velocity
Gas Flow Rates
Mass Flux
H, H2, Ar MW
Speed of Sound
Gas Velocity
Duct Diameter
Wafer Diameter
Strain Rate
Gas Velocity
Wafer Shape Factor
Mean Molec. Wgt.
Gas Pressure (Sub)
H Bound. Layer
Reactor Pressure
Gas Pressure (Sub)
Knudsen No.
H Mole Frac. (Jet)
Recombination Coeff
Gas Pressure (Sub)
H Mole Frac. (Sub)
Gas Temperature
H Concentr. (Sub)
CH3 Concentration
Thermal Conductivity
H Concentr. (Sub)
Linear Dep. Rate

Figure 3

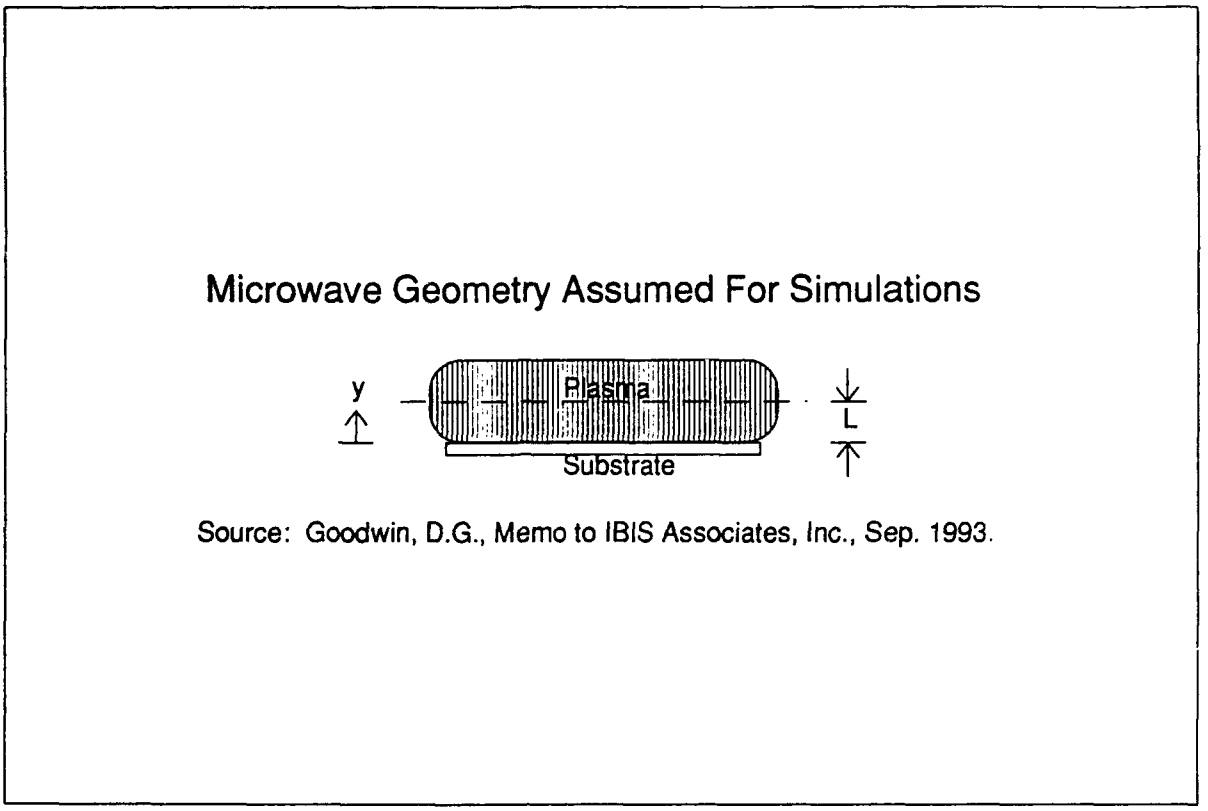


Figure 4

diffusion of atomic hydrogen toward the surface and its recombination into H_2. Along with the CH_3 (methyl) concentration, the atomic hydrogen concentration at the surface determines the CVD diamond growth rate. Due to such variables as reactor power, reactor pressure, and thermal conductivity, the calculation path to deposition rate is fairly complex.

Figure 5 shows the equation logic flow for the microwave model. Important calculations include the plasma ball diameter, atomic hydrogen generation rate (H Generation Rate), atomic hydrogen concentration at the substrate (H Concentr. @ Substrate), and the mass deposition rate. For an explanation of the logic and actual equations, see an article on this subject by Professor Goodwin (Goodwin, D.G., J. Appl. Phys. 74, 6888 (1993)) and the third quarter report of 1993 for this contract.

Updated results from this model are shown later in this report. The next section details the combustion flame CVD diamond cost model.

Combustion Flame

The deposition modeling assumptions for the combustion flame model are depicted in Figure 6, with the equation logic flow shown in Figure 7. Professor Goodwin was the sole source for the deposition rate calculation. The experts who reviewed the approach and outputs from this model include Professor Goodwin; Dr. Butler; Drs. Kee, Meeks, McCarty,

IBIS Microwave CVD Diamond Technical Cost Model
Deposition Rate Equation

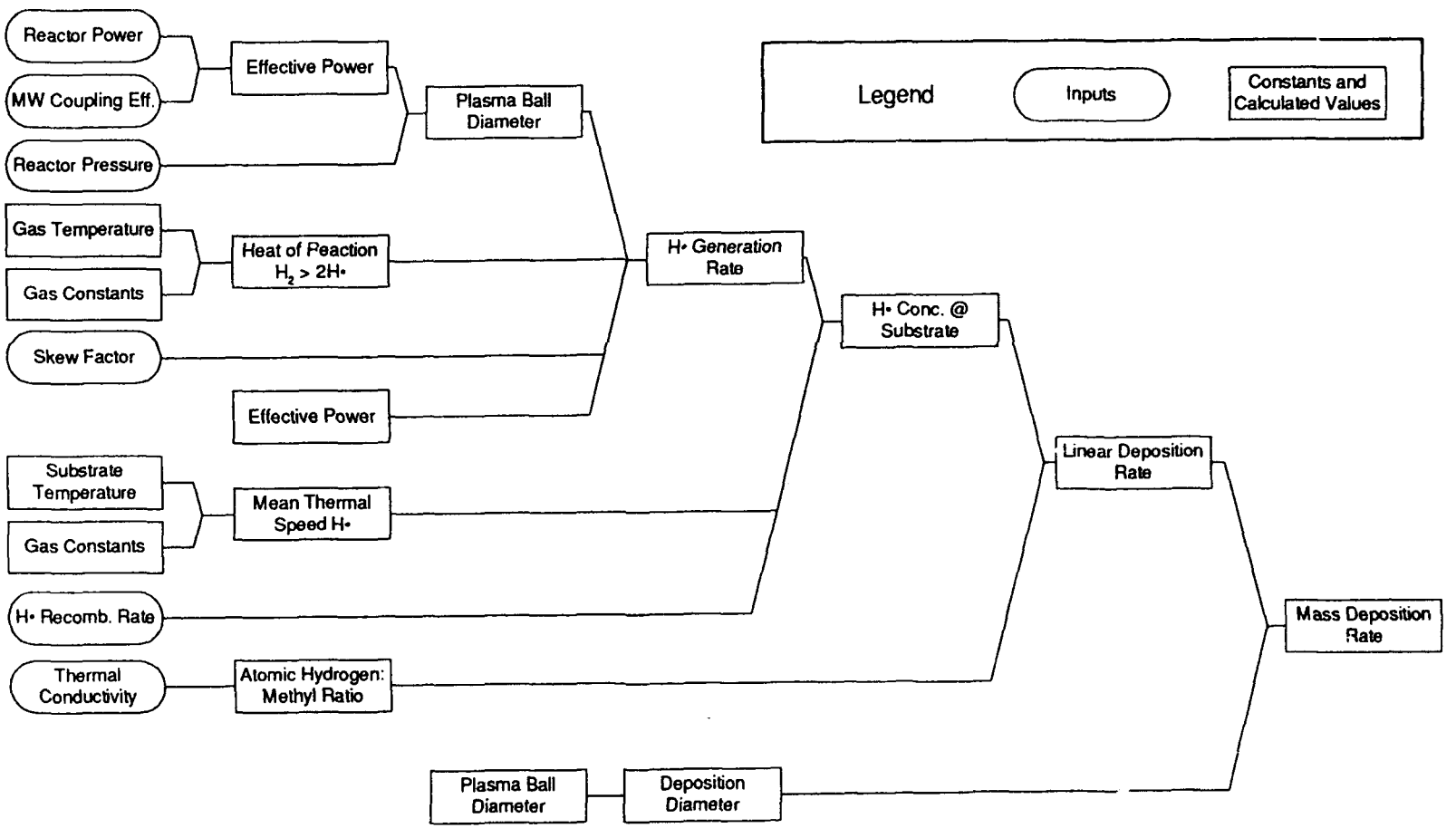


Figure 5

and Coltrin from Sandia National Laboratories; Professor Cappelli from Stanford, and Dr. K.V. Ravi from Lockheed.

Figure 6 is a diagram of the overall modeling strategy for the combustion flame model. For numerical simulations that were generated by Professor Goodwin, it is assumed that the process gases are mixed and combust previous to accelerating through the nozzle. The resulting combustion jet is assumed to have uniform chemistry and velocity. Impinging on the substrate creates a boundary layer, through which atomic hydrogen and methyl radicals diffuse. The goal of this approach is to calculate the atomic hydrogen concentration at the growth surface which, along with the CH_3 (methyl) concentration, determines the CVD diamond growth rate. Due to such variables as gas concentration and thermal conductivity, the calculation path to deposition rate warrants an explanatory diagram.

Figure 7 shows the equation logic flow for the combustion flame model. Important calculations include the strain rate, atomic hydrogen concentration at the substrate, and the linear deposition rate. For an explanation of the logic and actual equations, see an article on this subject by Professor Goodwin (Goodwin, D.G., J. Appl. Phys. 74, 6888 (1993)) and the first quarter report of 1994 for this contract.

Updated results from the three deposition models are shown in the upcoming section.

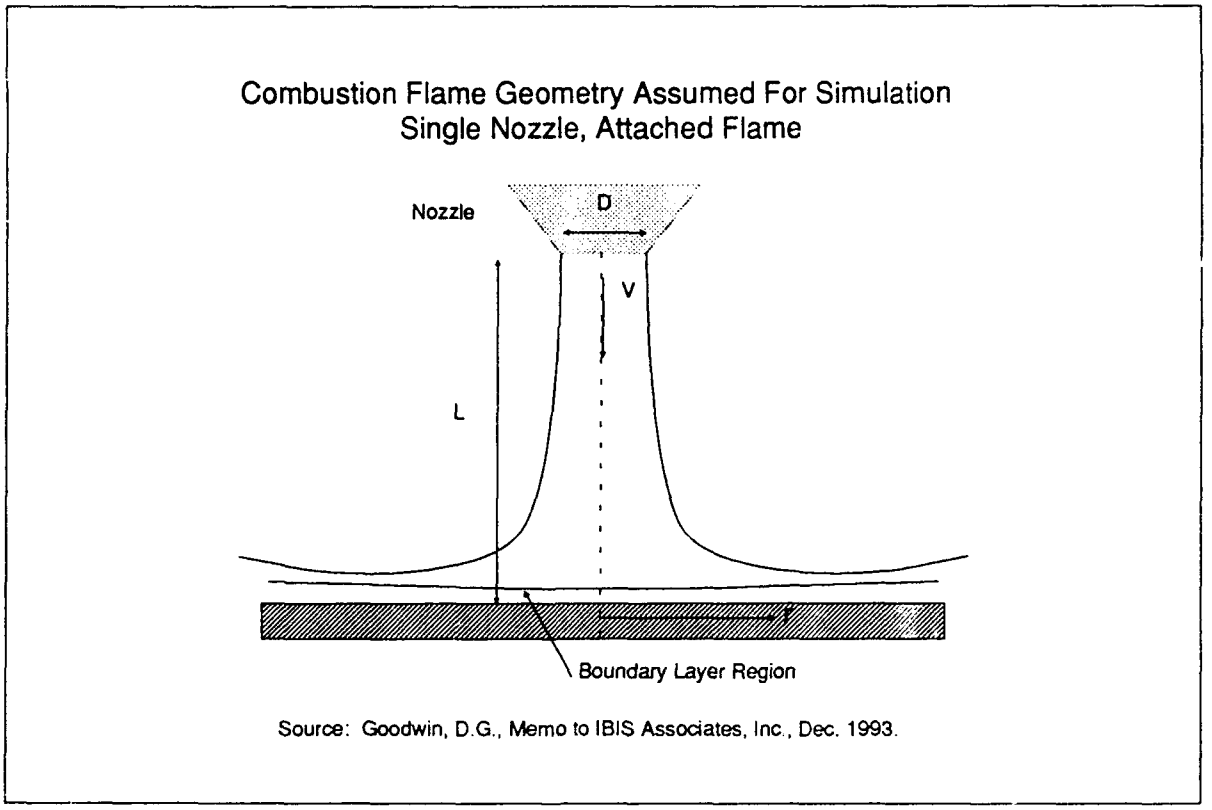


Figure 6

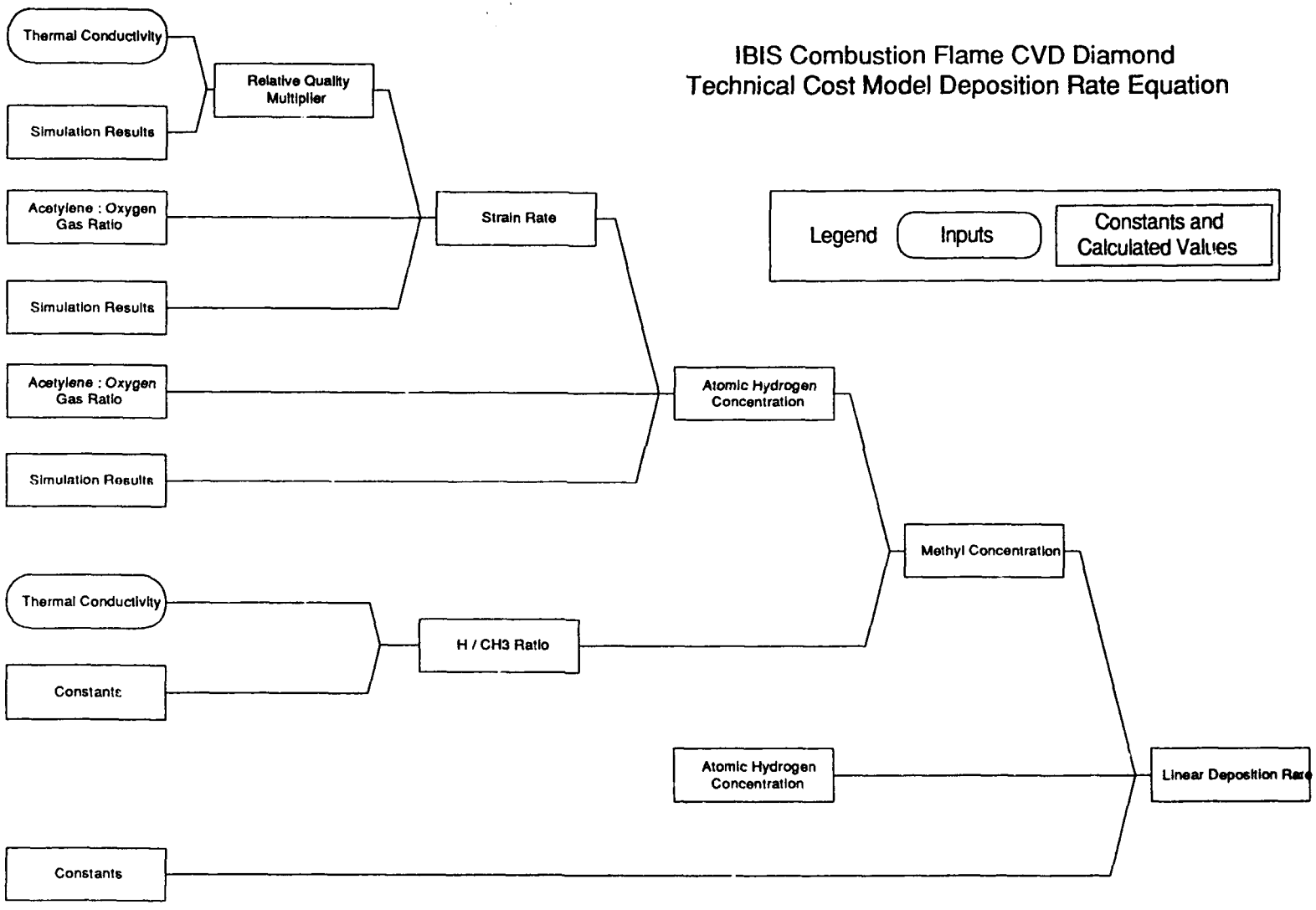

IBIS Combustion Flame CVD Diamond
Technical Cost Model Deposition Rate Equation
Legend
Inputs
Constants and Calculated Values
Thermal Conductivity
Simulation Results
Relative Quality Multiplier
Acetylene : Oxygen Gas Ratio
Simulation Results
Strain Rate
Acetylene : Oxygen Gas Ratio
Simulation Results
Atomic Hydrogen Concentration
Methyl Concentration
Thermal Conductivity
Constants
H / CH3 Ratio
Atomic Hydrogen Concentration
Linear Deposition Rate
Constants

Figure 7

Technical Cost Modeling Results

Results from all three deposition models have been reported: the DC arcjet and microwave technologies were analyzed in the third quarter report of 1993 while the combustion flame technology was illuminated in the first quarter report of 1994. This section shows updated results and sensitivities for the long term modeling scenarios since the models have changed recently to incorporate thermal conductivity as an input to the models.

Technical Cost Modeling permits the flexibility of performing sensitivity analyses. Using sensitivity analyses, it is possible to explore the cost implications of changing key input variables such as gas composition, production volume, material prices, product dimensions, etc. As an R&D management tool, these analyses help set development goals for cost effective manufacturing. Further, they help in long term planning, by indicating the cost savings that may be realized through scale-up.

For the purpose of these analyses it is assumed that the transport theory model which is used to estimate the diamond growth rate closely predicts actual growth rates and that input values for variables such as gas flow rate and substrate temperature are physically achievable. Presented in the following sections are the following analyses:

- Three Technology Comparison
  - *Baseline Costs in the Long Term*
  - *Long Term Cost vs Thermal Conductivity*
- DC Arcjet
  - *Cost vs Reactor Power and Substrate Diameter*
  - *Cost vs Reactor Power and Gas Temperature*
  - *Cost vs Reactor Power and Thermal Conductivity*
- Microwave
  - *Cost vs Reactor Power and Pressure*
  - *Cost vs Reactor Power and Thermal Conductivity*
- Combustion Flame
  - *Cost vs Acetylene:Oxygen Gas Ratio and Substrate Diameter*
  - *Cost vs Substrate Diameter and Thermal Conductivity*

Three Technology Comparison

The long term scenario for the three technologies has been modeled, where "long term" is defined as the expected state of diamond deposition five to ten years from today. With the assistance of industry experts, plausible product and process conditions have been selected to represent the long term scenario. Unless stated otherwise, there are certain constant conditions: thermal conductivity of 1,000 W/mK, CVD diamond film final thickness of one

millimeter, one thousand parts per year, and deposition yield of 87.5%. Labor wages and other exogenous cost factors are held constant (within each model in the appendix), and non-dedicated equipment is assumed (as if machines are rented). Although this section compares the three technologies in the long term, the modeling assumptions should be understood before a decision is made which favors one technology over another. Some of these assumptions are presented in Figure 8.

Baseline Costs in the Long Term

Figure 9 shows the relative long term costs of the DC arcjet, microwave, and combustion flame technologies for the production of one millimeter thick CVD diamond wafers. The single nozzle combustion flame technology has the highest long term cost, at $47 per square centimeter. The DC arcjet and microwave technologies are at $3 and $13 per square centimeter respectively. The combustion flame technology is dominated by the material cost due to the high consumption rate of expensive process gases. The microwave technology has a significant equipment cost due to the low growth rates and high equipment investment requirement per machine. Lastly, the equipment cost is also significant to the DC arcjet technology, however, its high deposition rate effectively spreads this cost over more production units.

CVD Diamond Deposition Long Term Assumptions

	Microwave	DC Arcjet	Combustion	
Finished Wafer Thickness	1,000	1,000	1,000	microns
Thermal Conductivity	1,000	1,000	1,000	W/mK
Wafer Diameter	16	6	4.1	inches
Annual Production Volume	1,000	1,000	1,000	wafers
Dedicated Investment	No	No	No	
Operation Yield	90%	90%	90%	good wafers
Downtime	15%	15%	15%	
No. of Laborers / Station	0.1	0.4	0.4	
System Power	250	200	2 drawn / 172 generated	kW
System Pressure	127.9	50	760 (1 atmosphere)	torr
Power to Gas Efficiency	98%	40%	NA	
Machine Load Time	30	120	120	minutes
Operation Hours / Year	8,640	8,640	8,640	hours
Building Space Req.	400	1,500	1,500	square feet
Lapping Percentage	10%	10%	10%	of thickness
Percent Methane	10.0%	0.1%	NA	
Percent Acetylene	NA	NA	50.5%	
Percent Oxygen	1.3%	NA	49.5%	
Percent Hydrogen	88.7%	66.6%	NA	
Percent Argon	NA	33.3%	NA	

Figure 8

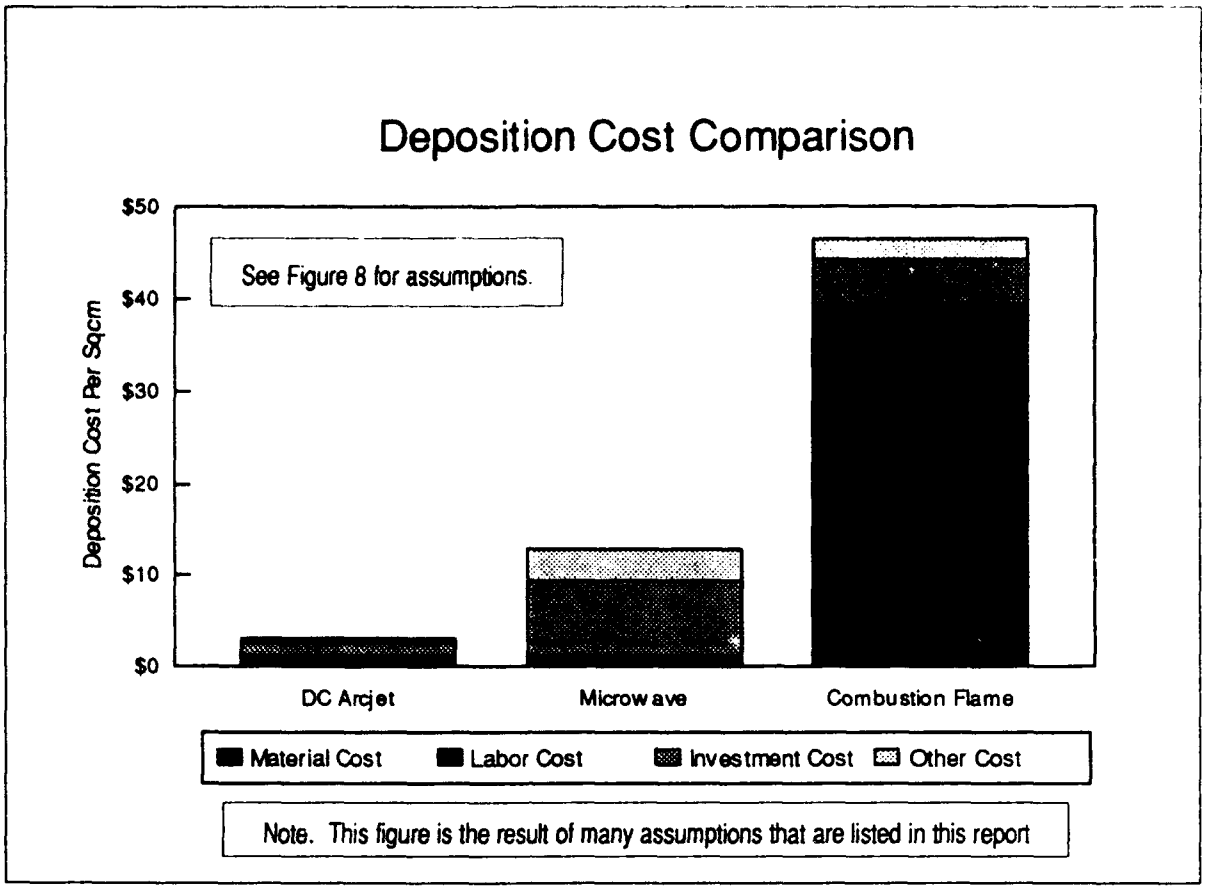

Deposition Cost Comparison
$50
$40
$30
$20
$10
$0
Deposition Cost Per Sqcm
See Figure 8 for assumptions.
DC Arcjet
Microwave
Combustion Flame
Material Cost
Labor Cost
Investment Cost
Other Cost
Note. This figure is the result of many assumptions that are listed in this report

Figure 9

Long Term Cost vs Thermal Conductivity

As described in the second quarter report of 1994, thermal conductivity as an input has been implemented in all three deposition models. Figure 10 shows the cost as a function of thermal conductivity for the three deposition models with long term input assumptions. In all cases the cost of CVD diamond increases dramatically with thermal conductivity. The rise in cost is steepest with the combustion flame technology, where a curve-fit of the data shows that cost is proportional to thermal conductivity to the exponent 2.79. In curve-fits for the microwave and DC arcjet technologies, this exponent is 2.71 and 1.97 respectively. The impact of this result is more apparent with the following example: if the thermal conductivity requirements double for a change such as a system improvement, the CVD diamond cost will increase for DC arcjet diamond by a factor of four, while combustion flame and microwave diamond experiences a cost increase of about a factor of . This high-quality/high-cost trend confirms that regardless of deposition technology, the minimum value of thermal conductivity for an application must be identified in order to produce the lowest cost diamond.

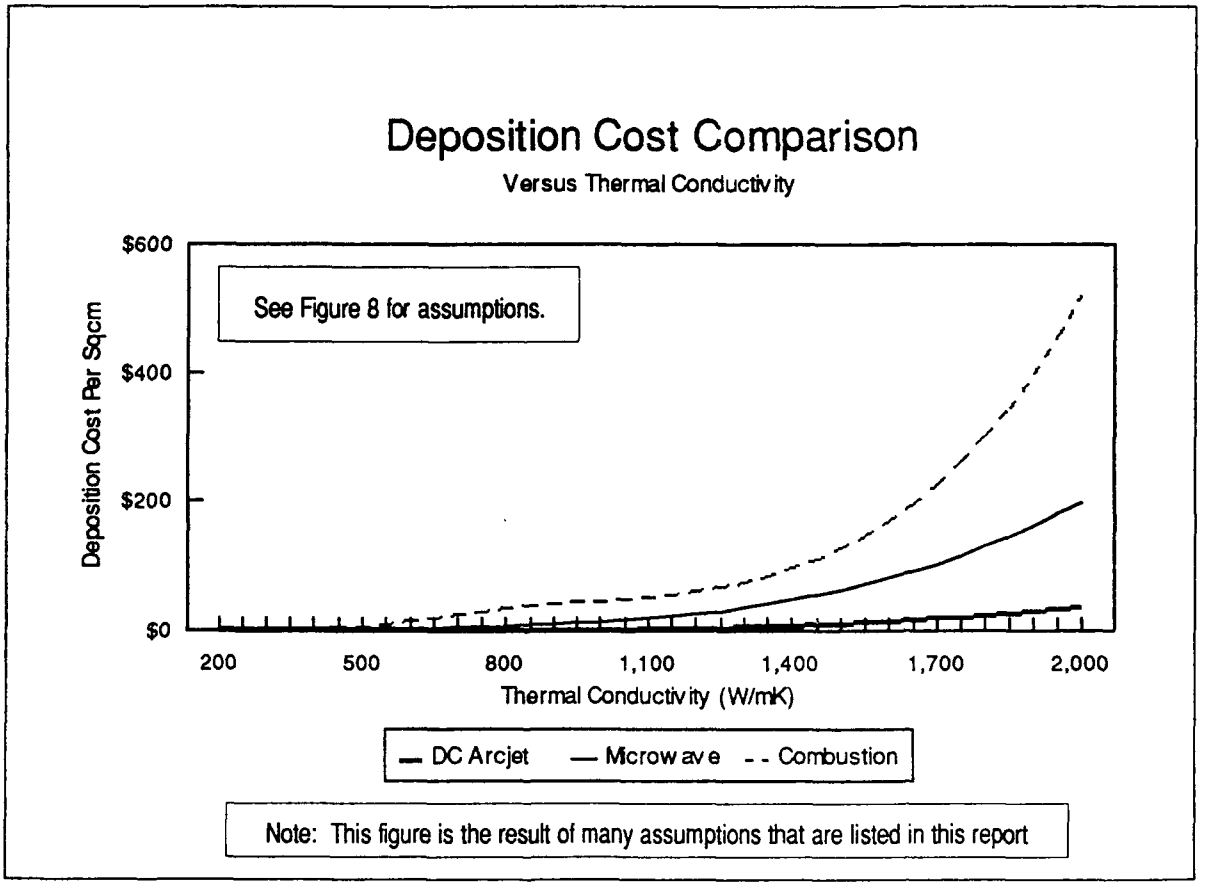


Figure 10

DC Arcjet

The DC arcjet technology is cost-sensitive to, among others, the three process parameters: the reactor power, the upper limit on gas jet temperature, and the diameter of the diamond wafer being deposited. The gas flow rate is another significant process parameter affecting the cost of diamond but is calculated based on the process variables above. The following sections provide insight into what can reduce the cost of CVD diamond produced by this technology.

Cost vs Reactor Power and Substrate Diameter

Figure 11 shows that deposition cost can be reduced by increasing the deposition diameter due to economies of scale, but that increasing the power into the range of hundreds of kilowatts does not appear to have a significant impact on cost. The reason for the cost optimum is because it is the sum of two effects of increasing the area of deposition: the gain in economy of scale and the loss in growth rate. The incentive to increase the deposition diameter is that investment costs will be distributed over a greater area, resulting in lower costs per square centimeter. The incentive to decrease the deposition diameter is the lower linear deposition rates that result from increasing the diameter without corresponding increases in reactor power and gas temperature.

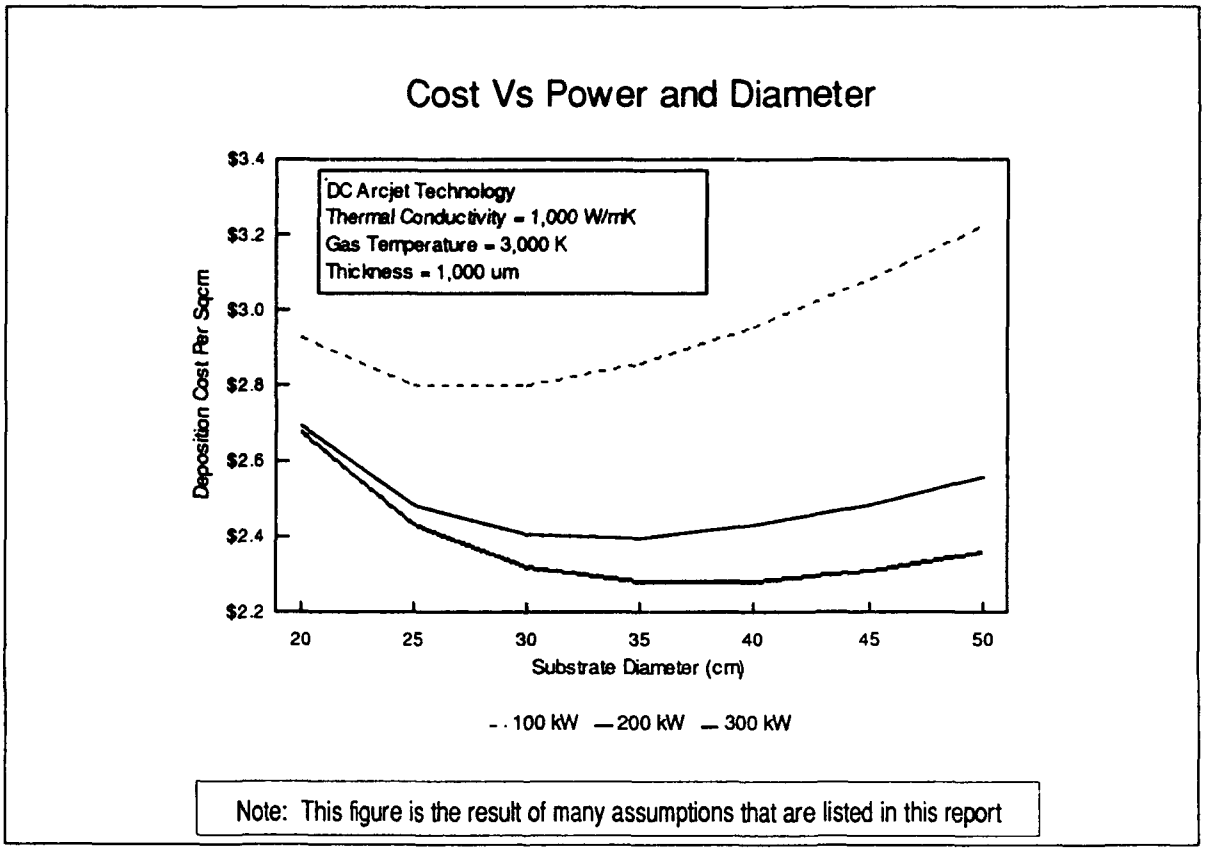


Figure 11

Figure 11 also indicates that there are diminishing returns on power increases. It does not, however, consider that there may be prohibitive engineering challenges when scaling up low powered reactors to high substrate diameters.

Cost vs Reactor Power and Gas Temperature

Figure 12 shows the CVD diamond deposition cost as a function of both the reactor power and the temperature of the gas jet. A higher gas temperature allows more atomic hydrogen to reach the substrate, creating a higher growth rate which translates to lower cost. From interviews with industry experts, the upper limit on gas jet temperature is determined by the limitations of the DC arcjet torch nozzle. Therefore, Figure 12 indicates that the maximum gas temperature must be determined in order to produce the lowest cost diamond. Fitting a curve to this data, the cost of diamond is inversely proportional to the gas temperature raised to the sixth power. This strong relationship means a gas temperature increase of just ten percent reduces the diamond cost by roughly forty percent.

In contrast to the influence of gas jet temperature is the seemingly weak effect of reactor power on deposition cost. However, this result is somewhat misleading since the graph was generated at a diameter of six inches and a thermal conductivity of 1,000 W/mK. In all probability, higher powered reactors will be used to create larger area wafers.

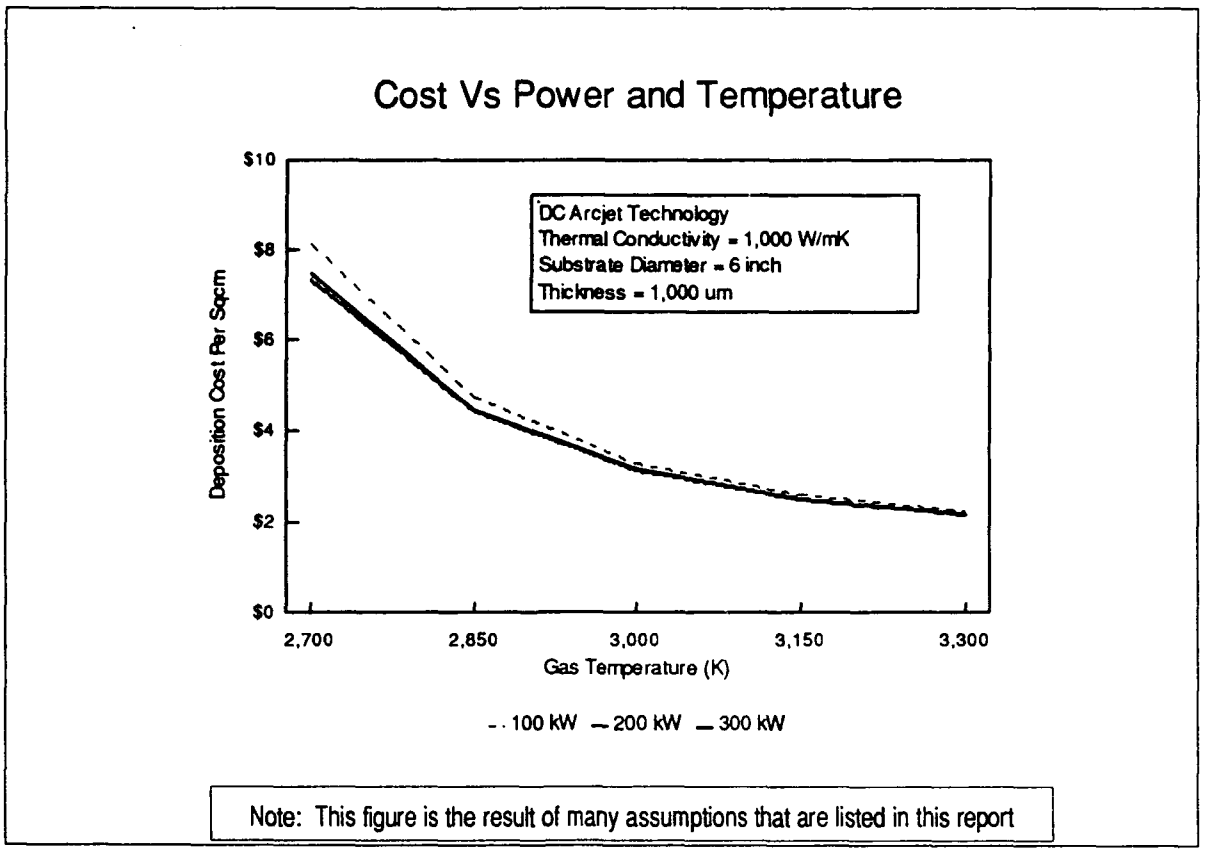


Figure 12

The same modeling methodology warning as for the last sensitivity must be given: both high gas temperature and large substrates require higher power reactors, therefore the lower powered reactors may not be able to realistically attain the higher gas temperatures and diameters.

Cost vs Reactor Power and Thermal Conductivity

A recent addition to the model is the incorporation of the thermal conductivity input. Figure 13 shows how the desired quality of the end product (meaning thermal conductivity) affects the cost of manufacturing using reactors of various powers. The cost of CVD diamond produced by the DC arcjet technology is proportional to thermal conductivity to the exponent 1.97, where a ten percent thermal conductivity reduction results in a twenty percent cost reduction. Since the relationship between thermal conductivity and deposition cost is strong, the minimum thermal conductivity for a given market must be identified. Competing materials for electronic thermal management applications range from as low as 200 W/mK (Aluminum) to as high as 800 W/mK (Copper/Carbon fiber composite). Industry experts believe the minimum CVD diamond film thermal conductivity would have to be higher than 1,000 W/mK in order to be competitive, depending on the selling price. Pure diamond has been measured at 2,000 W/mK and is the upper limit for CVD diamond thermal conductivity.

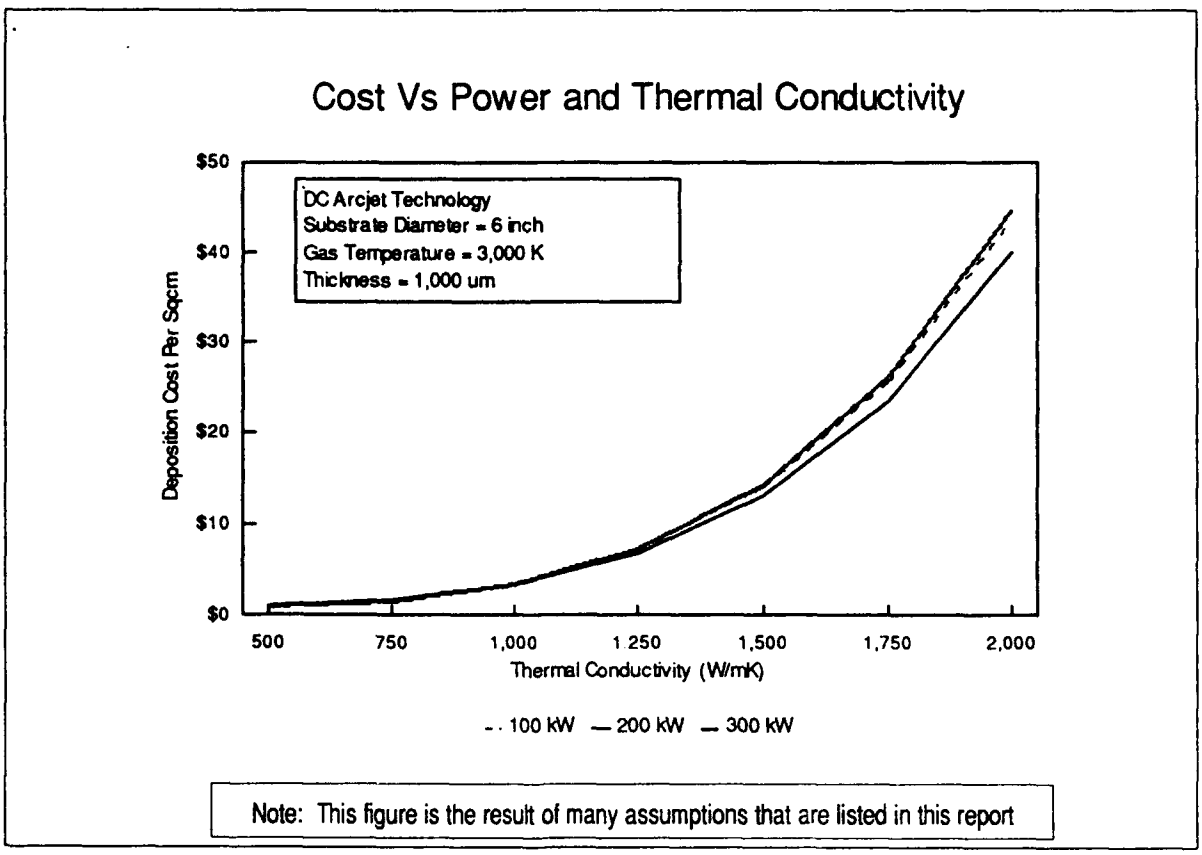


Figure 13

Microwave

The microwave technology is cost-sensitive, among others, to the reactor power. The reactor pressure and substrate diameter are other significant process parameters affecting the cost of diamond but are optimized to the reactor power. The following sections provide insight into what can reduce the cost of CVD diamond produced by this technology.

Cost vs Reactor Power

For this technology, process gases are excited into a plasma by the effect of microwave radiation. A plasma ball is formed in the reactor, its diameter proportional to the reactor power and inversely proportional to the reactor pressure. With the diameter and reactor power, the rate of atomic hydrogen generation is computed. This generation rate in conjunction with known characteristics of the plasma allows the atomic hydrogen concentration at the growth surface to be predicted. The calculated atomic hydrogen at the substrate surface and the thermal conductivity input then determine the linear growth rate of CVD diamond.

Figure 14 shows the cost per square centimeter of CVD diamond as a function of reactor power. As noted in the figure, both reactor pressure and deposition diameter are dependents of reactor power. Fitting a curve to the data reveals that cost is proportional to reactor power to the exponent -0.43, meaning a doubling of the power allows a twenty-five percent cost reduction. This sensitivity indicates there are cost savings and possibly new applications for scaling up this technology to higher powers and areas.

Cost vs Reactor Power and Thermal Conductivity

A recent addition to the model is the incorporation of the thermal conductivity input. Figure 15 shows how the desired thermal conductivity affects the cost of manufacturing using reactors of various powers. The cost of CVD diamond produced by the microwave technology is proportional to thermal conductivity to the exponent 2.71, where a ten percent thermal conductivity reduction results in a twenty-five percent cost reduction. Since the relationship between thermal conductivity and deposition cost is strong, the minimum thermal conductivity for a given market must be identified.

Combustion Flame

The combustion flame technology is cost-sensitive, among others, to the following two process parameters: the ratio of acetylene to oxygen and the substrate diameter. The gas flow rate is another significant process parameter affecting the cost of diamond but is calculated based on the process variables above and the thermal conductivity input. The following sections provide insight into what can reduce the cost of CVD diamond produced by this technology.

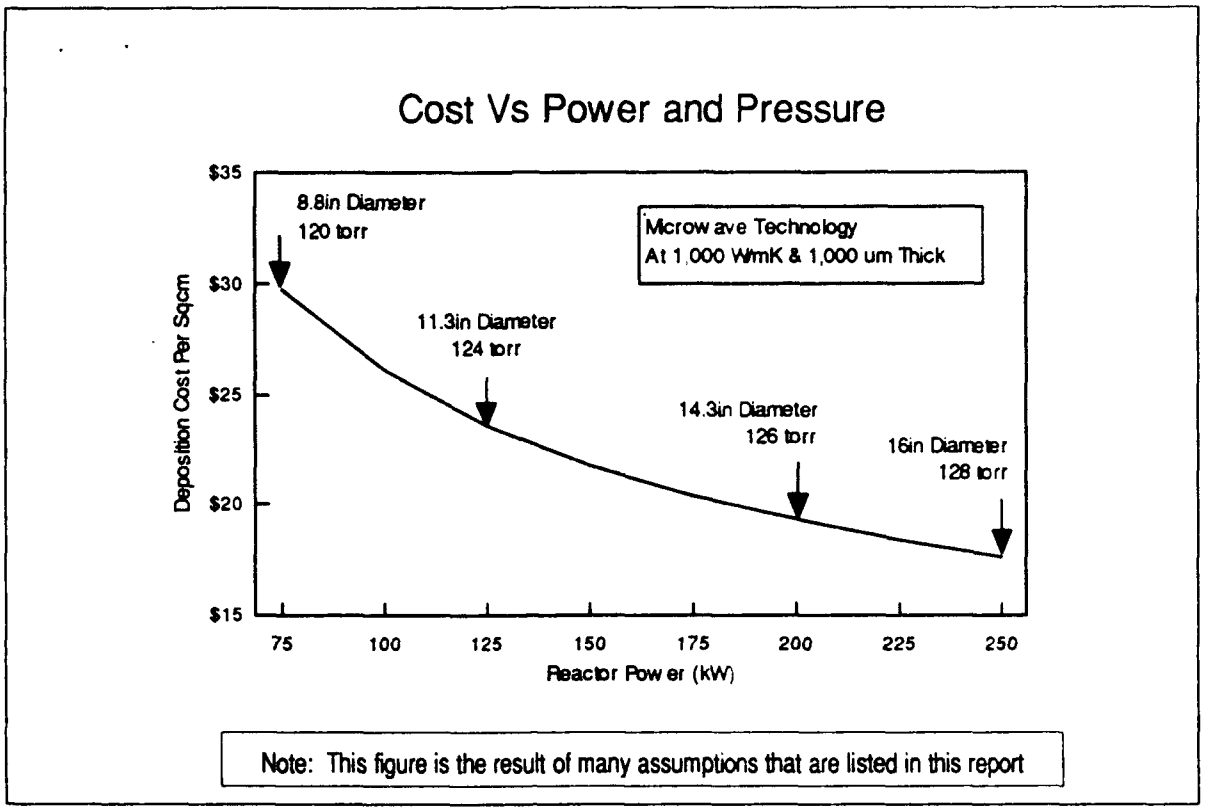


Figure 14

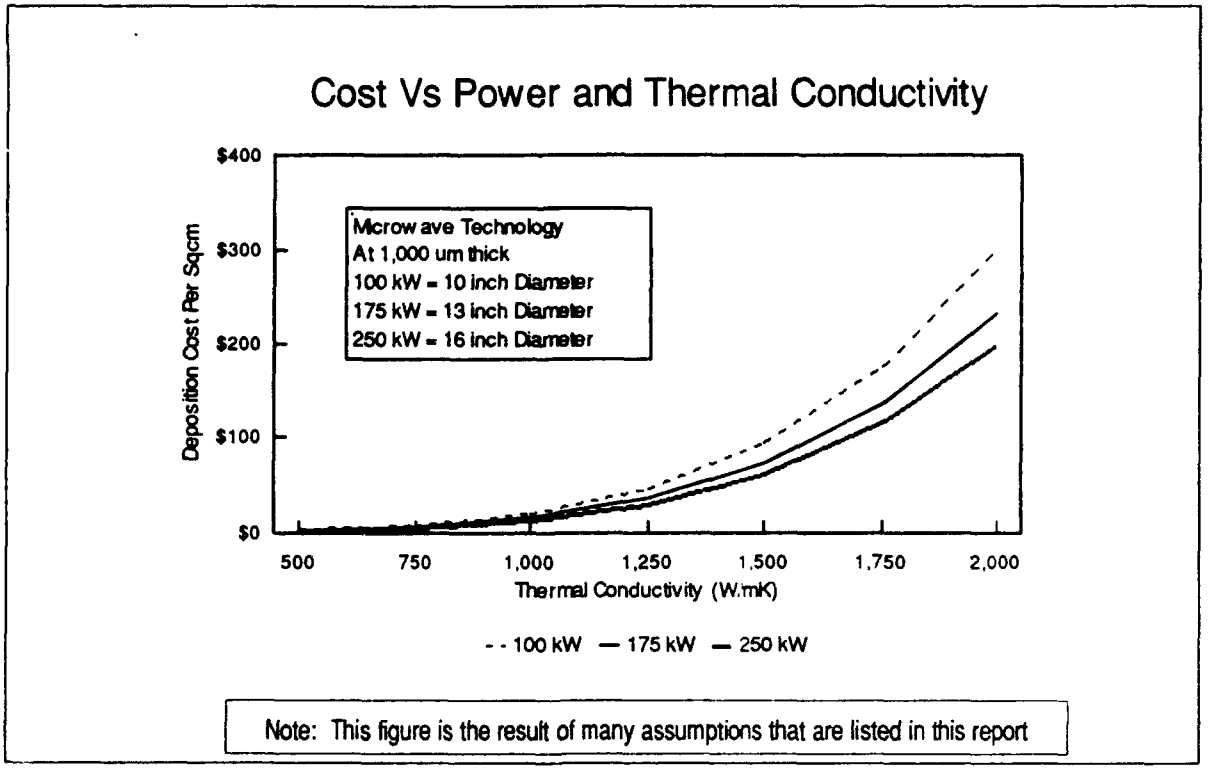


Figure 15

Cost vs Acetylene:Oxygen Gas Ratio and Substrate Diameter

As shown in Figure 16 and in the first quarter report of 1994, there is an optimal diameter for the combustion flame technology based on the single nozzle torch design assumed in the model. There exists an optimum due to the combination of two dynamics: one where increasing substrate diameter decreases the fixed costs (i.e., equipment investment) per square centimeter, and the dynamic where gas costs vary with the cube of substrate diameter. Depending on the ratio of incoming acetylene to oxygen, the optimal substrate diameter ranges from ten centimeters at a gas ratio of 1.02 to six centimeters at a gas ratio of 1.10. The optimal substrate diameter varies inversely with thermal conductivity; at higher thermal conductivities the flow rates must also be higher to deliver more atomic hydrogen to the growth surface. With higher flow rates, the material cost increases.

Cost vs Substrate Diameter and Thermal Conductivity

A recent addition to the model is the incorporation of the thermal conductivity input. Figure 17 shows how the desired thermal conductivity affects the cost of manufacturing at various substrate diameters. Also, as mentioned for Figure 16, Figure 17 shows how smaller substrate diameters are desirable with higher thermal conductivities. The cost of CVD diamond produced by the combustion flame technology is proportional to thermal conductivity to the exponent 2.79, where a ten percent thermal conductivity reduction

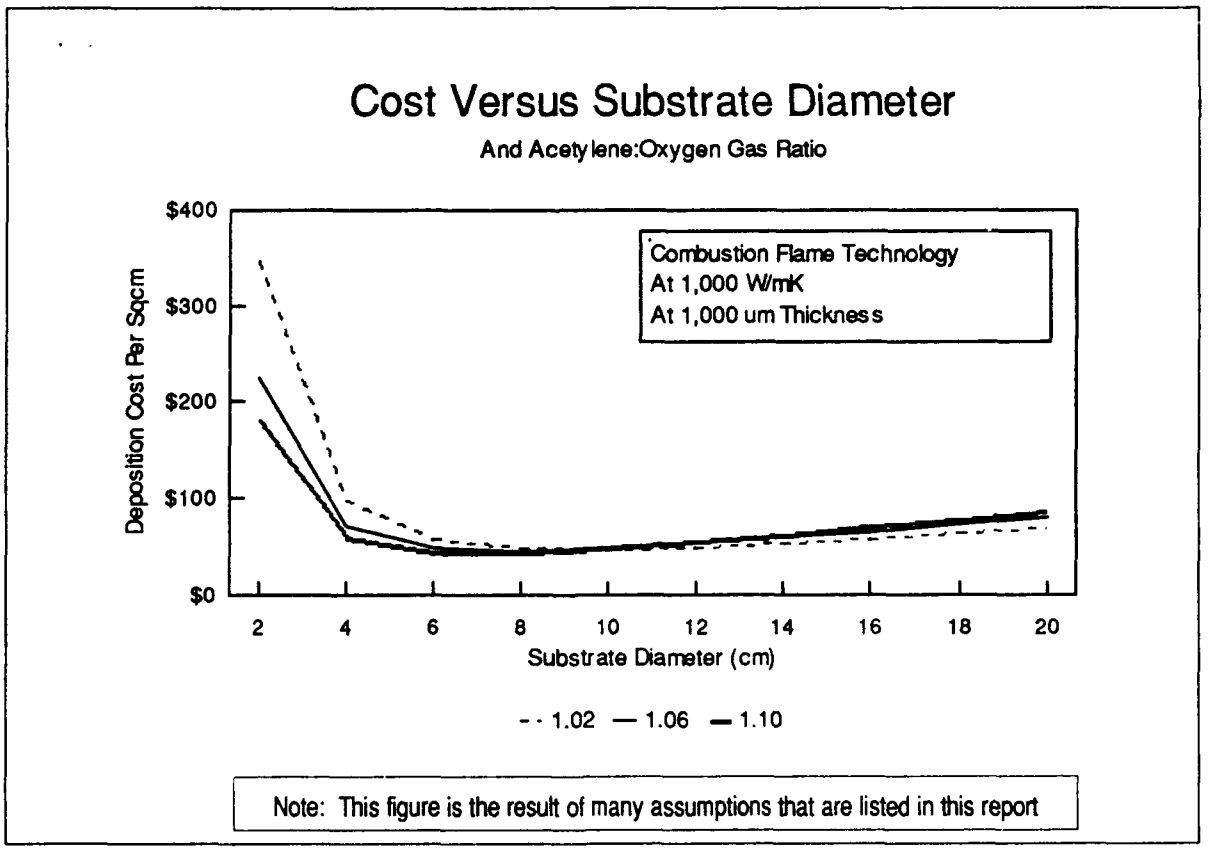


Figure 16

results in a twenty-five percent cost reduction. Since the relationship between thermal conductivity and deposition cost is strong, the minimum thermal conductivity for a given market must be identified.

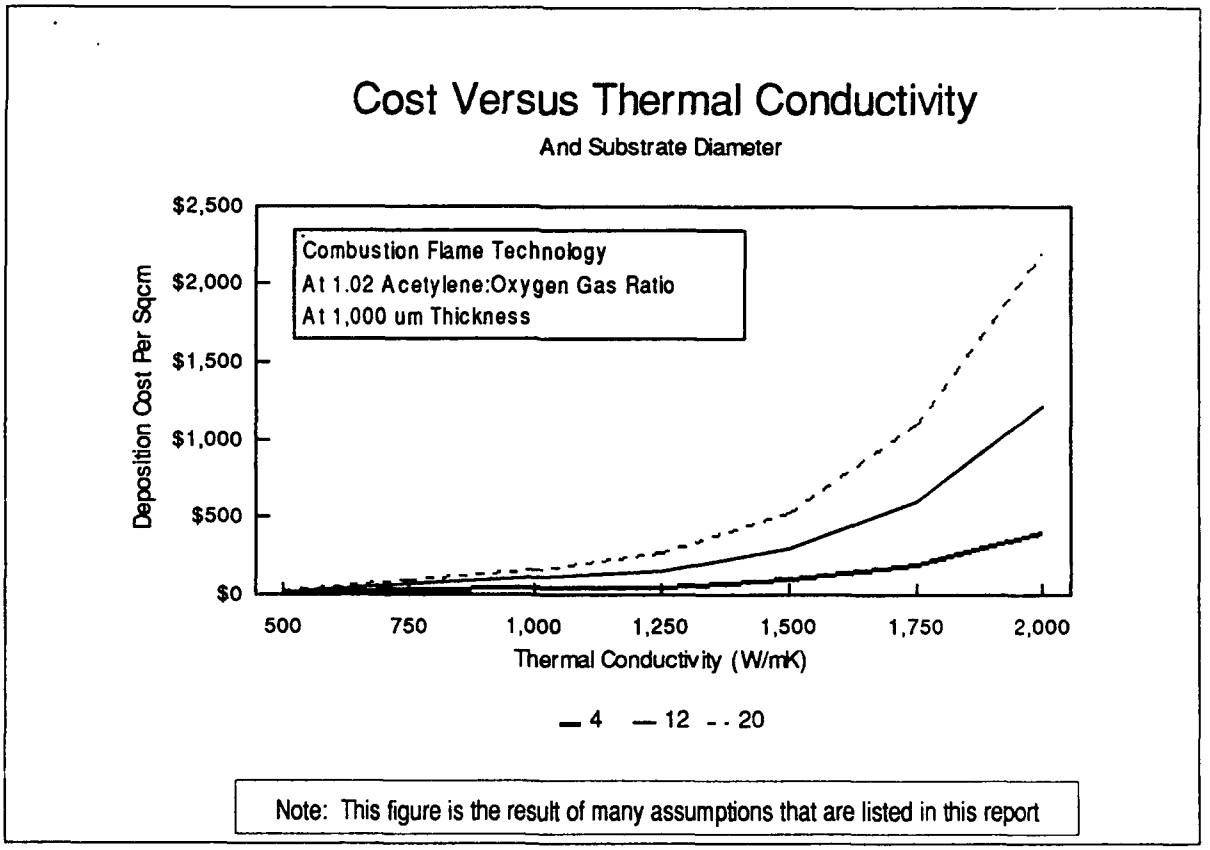


Figure 17

Summary

IBIS Associates has completed its predictive spreadsheet models of chemical vapor deposition (CVD) diamond film fabrication. This report details the capabilities of the models, and shows cost sensitivities to product and process input parameters.

The DC arcjet, microwave, and combustion flame CVD diamond deposition models, in addition to the CVD diamond finishing model, have been developed to maximize cost estimation flexibility. In doing so for deposition, inputs such as thermal conductivity, machine power, gas concentration, gas temperature, and reactor pressure have been provided in the model to predict the deposition growth rate, which is critical to the cost calculation. For the finishing model, inputs such as laser power, laser spot size, and laser frequency have been provided in the model to predict the diamond removal rate, which is also critical to the final cost calculation.

For this report and the results contained herein, it is assumed that the transport theory model which predicts growth rates in the CVD diamond technical cost models closely predicts actual growth rates for the deposition technologies and that the input values for variables such as the gas flow rate and substrate diameter are physically achievable.

To be investigated further is the market value issue. IBIS will contact potential users of CVD diamond substrates to determine the price at which they would be willing to pay for specific performance improvements.

Appendix A - The DC Arcjet Model

Revision Date: 9/94

PRODUCT SPECIFICATIONS

Part Name 6 in. substrate			NAME
Wafer Diameter	15.24	cm	DIAM
Finished Wafer Thickness	1,000	um	THIK
Thermal Conductivity	1,000	W/mK	THERMCON
Annual Production Volume	1.0	(000/yr)	NUM
Length of Production Run	5.00	yrs	PLIFE

PROCESS RELATED FACTORS - SURFACE PREPARATION

Process In Use?	1.00	[1=Y 0=N]	USE1
Dedicated Investment	0.00	[1=Y 0=N]	DED1
Process Yield	95.0%		YLD1
Average Equipment Downtime	20.0%		DOWN1
Direct Laborers Per Station	0.50		NLAB1
Substrate Material	11.00	[menu #]	MATL1
Pieces Per Batch	20.00	pcs/batch	PCS1
Process Time	60.00	min/batch	PTIME1
Building Space Requirement	250	sqft/sta	FLR1

PROCESS RELATED FACTORS - DEPOSITION

Process In Use?	1.00	[1=Y 0=N]	USE2
Dedicated Investment	0.00	[1=Y 0=N]	DED2
Process Yield	90.0%		YLD2
Average Equipment Downtime	15.0%		DOWN2
Direct Laborers	0.40	/sta	NLAB2
Machine Power	100	kW	POW2
Power to Gas Efficiency	0.40		P2GEFF
Machine Load/Unload Time	120.00	min/batch	PTIME2
Available Deposition Time	8,640	hrs/yr	DAYHR2
Coolant Temp. Rise	50.00	C	TEMP2
Heat Capacity of Coolant	1.0	cal/g/C	CP2
Building Space Requirement	1,500	sqft/sta	FLR2
Reactor Pressure	50.0	torr	RPRESS
Substrate Temperature	1,173	K	STEMP
Gas Temperature (>1000K)	3,000	K	GTEMP
Hydrogen Gas Flow Rate	197.4	slm	HFLOW
Carbon Fas Flow Rate	0.2	slm	CFLOW
Argon Gas Flow Rate	98.7	slm	ARFLOW
Other Gas Flow Rate	0.0	slm	OGFLOW
Total Gas Flow Rate	296.36	slm	

Menu #	vol%

DC ARC-JET CVD DIAMOND TECHNICAL COST MODEL - LONG TERM
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

GAS DATABASE

#	Gas	Source	Purity	Price $/SCM	No. of Carbons	Liq Gas	Tank gal	Price Update
0	None			$0.00	0.00	0.00		
1	Liq Hydrogen	Airco	99.998%	$0.34	0.00	1.00	6000	1/93
2	Liq Hydrogen	Airco	99.998%	$0.32	0.00	1.00	11000	1/93
3	Liq Hydrogen	Airco	99.998%	$0.30	0.00	1.00	20000	1/93
4	Liq Argon	Airco	99.998%	$1.41	0.00	1.00	3000	1/93
5	Liq Argon	Airco	99.998%	$1.32	0.00	1.00	6000	1/93
6	Liq Argon	Airco	99.998%	$1.29	0.00	1.00	11000	1/93
7	Hydrogen	MG Ind.	99.9999%	$29.86	0.00	0.00		1/93
8	Hydrogen	MG Ind.	99.9996%	$40.61	0.00	0.00		1/93
9	Hydrogen	MG Ind.	99.999%	$10.28	0.00	0.00		1/93
10	Hydrogen	Air Prod.	99.95%	$1.59	0.00	0.00		1/93
11	Argon	MG Ind.	99.9999%	$33.09	0.00	0.00		1/93
12	Argon	Air Prod.	99.9997%	$37.33	0.00	0.00		1/93
13	Argon	Air Prod.	99.999%	$11.74	0.00	0.00		1/93
14	Argon	Air Prod.	99.997%	$2.03	0.00	0.00		1/93
15	Methane	Air Prod.	99.99%	$21.99	1.00	0.00		1/93
16	Methane	Air Prod.	99%	$13.76	1.00	0.00		1/93
17	Methane	Air Prod.	93%	$4.93	1.00	0.00		1/93
18	Acetylene	Air Prod.	99.6%	$6.80	2.00	0.00		1/93
19	Acetylene	Air Prod.	98%	$5.85	2.00	0.00		1/93
20	Helium	Air Prod.	99.9995%	$15.90	0.00	0.00		1/93
21	Helium	Air Prod.	99.995%	$4.77	0.00	0.00		1/93
22	Nitrogen	Air Prod.	99.9996%	$45.50	0.00	0.00		1/93
23	Nitrogen	MG Ind.	99.999%	$9.23	0.00	0.00		1/93
24	Nitrogen	Air Prod.	99.998%	$1.24	0.00	0.00		1/93
25	Oxygen	Air Prod.	99.998%	$2.00	0.00	0.00		1/93
26								

SUBSTRATE DATABASE

#	Substrate	Source	Price $/ea	Thick um	Diam cm	Etch um/min	Life use#	Price Update
0	None		$0.00	1	1.00	1.00	1.00	
1	Silicon	Si-Tech	$2.65	1270.00	5.08	20.00	1	1/93
2	Silicon	Si-Tech	$3.50	1270.00	7.62	20.00	1	1/93
3	Silicon	Si-Tech	$6.25	1270.00	10.16	20.00	1	1/93
4	Silicon	Si-Tech	$9.70	1270.00	12.70	20.00	1	1/93
5	Silicon	Si-Tech	$18.60	1270.00	15.24	20.00	1	1/93
6	Silicon	Si-Tech	$57.95	1270.00	20.32	20.00	1	1/93
7	Silicon	Si-Tech	$4.35	3810.00	5.08	20.00	1	1/93
8	Silicon	Si-Tech	$8.15	3810.00	7.62	20.00	1	1/93
9	Silicon	Si-Tech	$14.50	3810.00	10.16	20.00	1	1/93
10	Silicon	Si-Tech	$22.65	3810.00	12.70	20.00	1	1/93

Hydrogen	1	66.6%	GASAVOLA
Carbon Containing Gas	15	0.1%	GASBVOLB
Carrier Gas	4	33.3%	GASCVOLC
Other Gas	0	0.0%	GASDVOLD
		100.0%	

Hydrogen Recycle Rate	0.0%		RECYC
Carrier Gas Recycle Rate	0.0%		RECYC2
Gas Recycle Equipment Cost	$250,000	total	MCH2A
Recombine Coef. (gammaH)	0.10		RECOMBX
Substrate:Duct Area Ratio	3.00		SUBDUCT
Substrate Shape Factor (c)	1.00		SHAPFAC
Diamond Density	3.51	g/cc	DENS
Ideal Gas Constant (R)	62,358	cc torr/K mol	IDEALG1
Ideal Gas Constant 2 (R)	8.31	J / mol K	IDEALG2

NASA Enthalpy Constants	H2	H	Ar
a1	2.99E+00	2.50E+00	2.50E+00
a2	7.00E-04	0.00E+00	0.00E+00
a3	-5.63E-08	0.00E+00	0.00E+00
a4	-9.23E-12	0.00E+00	0.00E+00
a5	1.58E-15	0.00E+00	0.00E+00
a6	-8.35E+02	2.55E+04	-7.45E+02
a7	-1.36	-0.46	4.37
MW	2.02	1.01	39.95

PROCESS RELATED FACTORS - ETCHING

Process In Use?	1.00	[1=Y 0=N]	USE3
Dedicated Investment	0.00	[1=Y 0=N]	DED3
Process Yield	99.0%		YLD3
Average Equipment Downtime	10.0%		DOWN3
Direct Laborers Per Station	1.00		NLAB3
Load/Unload and Rinse Time	30.00	min/batch	PTIME3
Pieces Per Batch	20.00		PCS3
Machine Cost	$6,000	/sta	MCH3
Etchant Cost	$70	/liter	ETCH3A
Etchant Disposal Cost	$30	/liter	ETCH3B
Machine Etchant Capacity	1.00	l/batch	CAP3
Machine Power	0.00	kW	POW3
Building Space Requirement	100	sqft/sta	FLR3

PROCESS RELATED FACTORS - LASER TRIMMING

Process In Use?	1.00	[1=Y 0=N]	USE4
Dedicated Investment	0.00	[1=Y 0=N]	DED4
Process Yield	99.0%		YLD4
Average Equipment Downtime	10.0%		DOWN4
Direct Laborers Per Station	1.00		NLAB4
Machine Cost	$6,000	/sta	MCH4
Trimming Rate	1.00	cm/s	RATE4

11	Silicon	Si-Tech	$43.45	3810.00	15.24	20.00	1	1/93
12	Silicon	Si-Tech	$135.20	3810.00	20.32	20.00	1	1/93
13	Silicon	Si-Tech	$6.85	6350.00	5.08	20.00	1	1/93
14	Silicon	Si-Tech	$12.80	6350.00	7.62	20.00	1	1/93
15	Silicon	Si-Tech	$22.75	6350.00	10.16	20.00	1	1/93
16	Silicon	Si-Tech	$35.55	6350.00	12.70	20.00	1	1/93
17	Silicon	Si-Tech	$68.30	6350.00	15.24	20.00	1	1/93
18	Silicon	Si-Tech	$212.45	6350.00	20.32	20.00	1	1/93
19	Molybdenum	Phil. Elmet	$3.90	254	5.08	10.00	1	1/93
20	Molybdenum	Phil. Elmet	$8.20	254	10.16	10.00	1.00	1/93
21	Molybdenum	Phil. Elmet	$14.50	254	15.24	10.00	1.00	1/93
22	MolybdenumSchwarzkopf Te		$25.35	254	20.32	10.00	1.00	1/93
23	MolybdenumSchwarzkopf Te		$4.80	508.00	5.08	10.00	4	1/93
24	MolybdenumSchwarzkopf Te		$14.75	508.00	10.16	10.00	4	1/93
25	MolybdenumSchwarzkopf Te		$24.30	508.00	15.24	10.00	4	1/93
26	MolybdenumSchwarzkopf Te		$37.10	508.00	20.32	10.00	4	1/93
27	Molybdenum	Phil. Elmet	$9.15	1524.00	5.08	10.00	20	1/93
28	MolybdenumSchwarzkopf Te		$27.60	1524.00	10.16	10.00	20	1/93
29	MolybdenumSchwarzkopf Te		$52.25	1524.00	15.24	10.00	20	1/93
30	MolybdenumSchwarzkopf Te		$85.25	1524.00	20.32	10.00	20	1/93
31	MolybdenumSchwarzkopf Te		$14.75	2286.00	5.08	10.00	32.00	1/93
32	MolybdenumSchwarzkopf Te		$36.00	2286.00	10.16	10.00	32.00	1/93
33	MolybdenumSchwarzkopf Te		$69.00	2286.00	15.24	10.00	32.00	1/93
34	MolybdenumSchwarzkopf Te		$113.50	2286.00	20.32	10.00	32.00	1/93
35	MolybdenumSchwarzkopf Te		$18.50	3175.00	5.08	10.00	46.00	1/93
36	MolybdenumSchwarzkopf Te		$46.75	3175.00	10.16	10.00	46.00	1/93
37	MolybdenumSchwarzkopf Te		$90.50	3175.00	15.24	10.00	46.00	1/93
38	MolybdenumSchwarzkopf Te		$149.00	3175.00	20.32	10.00	46.00	1/93
39	TungstenSchwarzkopf Te		$7.75	254	5.08	10.00	1	1/93
40	TungstenSchwarzkopf Te		$24.50	254	10.16	10.00	1.00	1/93
41	TungstenSchwarzkopf Te		$50.00	254	15.24	10.00	1.00	1/93
42	TungstenSchwarzkopf Te		$79.25	254	20.32	10.00	1.00	1/93
43	TungstenSchwarzkopf Te		$10.00	508.00	5.08	10.00	4.00	1/93
44	TungstenSchwarzkopf Te		$35.10	508.00	10.16	10.00	4.00	1/93
45	TungstenSchwarzkopf Te		$67.00	508.00	15.24	10.00	4.00	1/93
46	TungstenSchwarzkopf Te		$109.20	508.00	20.32	10.00	4.00	1/93
47	TungstenSchwarzkopf Te		$50.00	1524.00	5.08	10.00	20.00	1/93
48	TungstenSchwarzkopf Te		$112.00	1524.00	10.16	10.00	20.00	1/93
49	TungstenSchwarzkopf Te		$317.00	1524.00	15.24	10.00	20.00	1/93
50	TungstenSchwarzkopf Te		$422.00	1524.00	20.32	10.00	20.00	1/93
51	TungstenSchwarzkopf Te		$60.00	3175.00	5.08	10.00	46.00	1/93
52	TungstenSchwarzkopf Te		$161.25	3175.00	10.16	10.00	46.00	1/93
53	TungstenSchwarzkopf Te		$521.30	3175.00	15.24	10.00	46.00	1/93
54	TungstenSchwarzkopf Te		$687.00	3175.00	20.32	10.00	46.00	1/93
55								

##########

Machine Power	5.00	kW	POW4
Building Space Requirement	100	sqft/sta	FLR4
PROCESS RELATED FACTORS - LAPPING			
Process In Use?	1.00	[1=Y 0=N]	USE5
Dedicated Investment	0.00	[1=Y 0=N]	DED5
Process Yield	90.0%		YLD5
Average Equipment Downtime	15.0%		DOWN5
Direct Laborers Per Station	0.25		NLAB5
Lapped Material Removal	10.0%	by wgt	TLAP5
No of Lapping Steps	2.00		LAPS5
Pieces Per Batch	5.00		PCS5
Load/Unload and Clean Wafers	40.00	min/batch	PTIME5
Average Lapping Rate	1.0	um/hr	RATE5
Lapping Slurry Cost	$53	/liter	LAPSL5
Lapping Slurry Usage Rate	0.50	liter/hr	LAPR5
Lapping Plate Life	320.00	hrs	PLAL5
Available Lapping Time	8,640	hrs/yr	DAYHR5
Building Space Requirement	400	sqft/sta	FLR5
PROCESS RELATED FACTORS - INSPECTION - MICROSCOPY			
Process In Use?	1.00	[1=Y 0=N]	USE6
Dedicated Investment	0.00	[1=Y 0=N]	DED6
Process Yield	95.0%		YLD6
Average Equipment Downtime	5.0%		DOWN6
Direct Laborers Per Station	1.00		NLAB6
Average Inspection Time	15.00	min/batch	PTIME6
Percent Inspection	100%		INSP6
Machine Cost	$50,000	/sta	MCH6
Machine Power	0.10	kW	POW6
Building Space Requirement	50	sqft/sta	FLR6
PROCESS RELATED FACTORS - INSPECTION - THERMAL CONDUCTIVITY			
Process In Use?	1.00	[1=Y 0=N]	USE7
Dedicated Investment	0.00	[1=Y 0=N]	DED7
Process Yield	95.0%		YLD7
Average Equipment Downtime	5.0%		DOWN7
Direct Laborers Per Station	1.00		NLAB7
Average Inspection Time	15.00	min/batch	PTIME7
Percent Inspection	100%		INSP7
Machine Cost	$50,000	/sta	MCH7
Machine Power	0.10	kW	POW7
Building Space Requirement	50	sqft/sta	FLR7

OPTIONAL INPUTS

	override	estimate
Surface Preparation		

Machine Cost	$0	$65,774	/sta	OMCH1
Machine Power	0.0	19.2	kW	OPOW1
Deposition				
Duct Area	0.00	60.80	sqcm	ODAREA2
Deposition Rate	0.00	9.80	g/hr	ODRATE2
Deposition Equipment Cost	$0	$424	k$/sta	OMCH2
Etching				
Process Cycle Time	0.00	0.18	hrs	OCTIME3
Chemical Requirement	$0	$5.00	/pc	OCHEM3
Laser Trimming				
Process Cycle Time	0.00	0.01	hrs	OCTIME4
Lapping				
Lapping Time	0.00	111.11	hrs	OCTIME5
Lapping Plate Cost	$0	$869	/ea	OWHEEL5
Lapping Machine Cost	$0	$11,939	/sta	OMCH5
Lapping Machine Power	0.00	4.2	kW	OPWR5

EXOGENOUS COST FACTORS

Direct Wages	$13.33 /hr	WAGE	
Indirect Salary	$50,000 /yr	SALARY	* exc. dep. & lap
Indirect:Direct Labor Ratio	1.00	ILAB	
Benefits on Wage and Salary	35.0%	BENI	
Working Days per Year	360.00	DAYS	
Working Hours per Day (*)	8.00 /hr	HRS	
Capital Recovery Rate	10%	CRR	
Capital Recovery Period	5.00 yrs	ELIFE	
Building Recovery Life	20.00 yrs	BLIFE	
Working Capital Period	3.00 months	WCP	
Price of Electricity	$0.050 /kWh	ELEC	
Price of Natural Gas	$6.50 /MBTU	GAS	
Price of Building Space	$100 /sqft	PBLD	
Price of Cooling Water	$0.03 /100 gal	WATER	
Auxiliary Equipment Cost	15.0%	AUX	
Equipment Installation Cost	35.0%	INST	
Maintenance Cost	8.0%	MNT	

REGRESSION CONSTANTS, COEFFICIENTS, AND EXPONENTS

-Surface Preparation-		
Machine Cost Constant	1,334	MCH1A
Machine Cost Capacity Coef	3,222	MCH1B
Machine Power Constant	-0.75	PWR1A
Machine Power Capacity Coef	1.00	PWR1B
-Deposition-		
Deposition Rate Constant	0.009	CYC2
Machine Cost Power Coef	43,500	MCH2Y
Machine Cost Power Exponent	0.40	MCH2Z
Machine Cost Power Constant	150,000	MCH2X
H/CH3 Therm. Cond. Coeff.	0.00	TC2A
H/CH3 Therm. Cond. Exp.	4.07	TC2B
Growth Rate Coeff. 1	1.80E+11	GR2A

Growth Rate Coeff. 2	5.00E-09	GR2B
Tank 1 $ Capacity Constant	1,175	TANK2A
Tank 1 $ Capacity Coef	0.165	TANK2B
Tank 2 $ Capacity Constant	370.00	TANK2X
Tank 2 $ Capacity Coef	0.03	TANK2Y
-Etching-		
-Lapping-		
Machine Cost Constant	2,719	MCH5A
Machine Cost Capacity Coef	1,844	MCH5B
Machine Power Constant	-0.75	PWR5A
Machine Power Capacity Coef	1.00	PWR5B
Tool Cost Constant	771.00	TOOL5A
Tool Cost Capacity Coef	0.92	TOOL5B
Tool Cost Capacity Exponent	2.90	TOOL5C

##########

IBIS ASSOCIATES, INC.
TECHNICAL COST MODEL (C) 1993
RESTRICTED RIGHTS LEGEND

Use, duplication, or disclosure by the Government is subject to
restrictions as set forth in subparagraph (c)(1)(ii) of the Rights in
Technical Data and Computer Software clause at DFARS 252.227-7013

##########

DC ARC CVD TCM: SURFACE PREPARATION
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$63.84	$63,836	94.1%	
Direct Labor Cost	$0.83	$826	1.2%	
Utility Cost	$0.07	$70	0.1%	
FIXED COST ELEMENTS				
Equipment Cost	$0.63	$629	0.9%	$98,661
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.04	$40	0.1%	$25,000
Maintenance Cost	$0.32	$315	0.5%	
Overhead Labor Cost	$0.80	$797	1.2%	
Cost of Capital	$1.33	$1,326	2.0%	
TOTAL FABRICATION COST	$67.84	$67,840	100.0%	$123,661

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO1
Cumulative Yield	68.1%		CYLD1
Effective Production Volume	1,469	/yr	ENUM1
Substrate Area	182.4	sq cm	AREA1
New Substrate Cost	$43.45	/pc	SUB1
Substrate Useful Life	1.00	cycle	LIFE1
Process Cycle Time	3	min/pc	CTIME1
Runtime for One Station	3%		RTIME1
Number of Parallel Stations	0.03		NSTAT1
Energy Requirement	0.959	kWh/pc	ENERGY1
Building Space/Station	250	sqft	SPACE1
Machine Cost	$65,774	/sta	MCH1
Machine Power	19.2	kW	POW1
Installed Equipment Cost	$88,795	/sta	IEQUIP1
Auxiliary Equipment Cost	$9,866	/sta	AEQUIP1
Equipment Annuity	$802	/yr	EINT1
Tooling Annuity	$0	/yr	TINT1
Building Annuity	$92	/yr	BINT1
Working Annuity	$66,945	/yr	WINT1

##########

DC ARC CVD TCM: DEPOSITION
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$159.65	$159,651	20.2%	
Direct Labor Cost	$109.45	$109,452	13.8%	
Utility Cost	$52.03	$52,030	6.6%	
FIXED COST ELEMENTS				
Equipment Cost	$224.05	$224,048	28.3%	$1,273,399
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$13.20	$13,196	1.7%	$300,000
Maintenance Cost	$110.73	$110,733	14.0%	
Overhead Labor Cost	$35.19	$35,189	4.4%	
Cost of Capital	$86.75	$86,746	11.0%	
TOTAL FABRICATION COST	$791.04	$791,043	100.0%	$1,573,399
	$4.34			

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO2
Cumulative Yield	71.6%		CYLD2
Effective Production Volume	1,396	/yr	ENUM2

ENERGY BALANCE CALCULATIONS

	H2	H	Ar	
Enthalpy Per Unit Mass	44,019	271,987	1,406	J/g
Molar Enthalpy	88,734	274,136	56,160	J/mol
Molar Entropy	202.79	162.59	202.72	J/K mol
Molar Heat Capacity (Cp)	37.11	20.79	20.79	J/K mol

Heat of Reaction (H2==>2H)	459,538	J/mol	
Entropy of Rxn (H2==>2H)	122	J/K mol	
Free Energy of Rxn (H2==>2H)	92,362	J/mol	
Equilibr Const Kp (H2==>2H)	2.47E-02		
Mole Fraction H	36.75%		
Mole Fraction Argon	27.21%		
Mole Fraction H2	36.04%		
Total Molar Enthalpy	148,004	J/mole	
Mean Molecular Weight	11.97	g/mole	
Mean Specific Enthalpy	12,369	J/g	
Mean Molar Heat Capacity	26.67	J/K mol	
Deposition Arc Power	40	kW	DAPOW2
Duct Area (A inf.)	60.80	sqcm	DCTAREA
Duct Diameter	8.80		DCTDIAM
Mass Flux	3.23	g/s	
Gas Velocity (U inf.)	16,611	cm/s	
Specific Heat Ratio (gamma)	1.45		

Speed of Sound	174,029	cm/s
Mach Number	0.10	

Note: Adjust Input Temperature (cell B47) such that Temp. Solver = 0

Input Temperature	3,000	K
Temperature Solver	9.09E-13	

BOUNDARY LAYER CALCULATIONS

Strain Rate (a)	1,888	1/s
Gas Pressure at Substrate	50.33	torr
Hydrogen Boundary Layer	0.52	cm
Thermal Boundary Layer	0.45	cm
H Mean Free Path (lambda)	2.78E-03	cm
Knudsen Number	5.36E-03	
H Mole Fraction at Substrate	1.87%	
H Concentration at Substrate	1.29E-08	mol/cc
H/CH3 Ratio	10.89	
CH3 Concentration at Substr.	1.18E-09	mol/cc

DEPOSITION RATE CALCULATIONS

Mass of Diamond Deposited	71.14	g	MASS2
Linear Deposition Rate	153.1	um/hr	LINDEP2
Mass Deposition Rate	9.8	g/hr	*MASDEP2*
Deposition Time	7.26	hrs	CTIMEB2
Machine Setup Time	2.00	hrs	CTIMEA2
Runtime for One Station	176%		RTIME2
Number of Parallel Stations	1.76		NSTAT2
Total Hydrogen Gas Volume	85.98	SCM	HGAS2
Total Argon Gas Volume	42.99	SCM	ARGAS2
Total Carbon Gas Volume	0.09	SCM	CARGAS2
Total Gas Volume	129	SCM	TVOL2
Total Gas Flow Rate	296,358	sccm	FLOWR2
Carbon Capture Factor	168.60%		CCF2

	Consumption (SCM/pc)	Cost ($/pc)		
Hydrogen Consumption	85.98	$29.23	GASA2	COSTA2
Carbon Gas Consumption	0.09	$1.89	GASB2	COSTB2
Carrier Gas Consumption	42.99	$60.62	GASC2	COSTC2
Other Gas Consumption	0.00	$0.00	GASD2	COSTD2

Energy Requirement	726	kWh/pc	ENERGY2
Cooling Water Flow Rate	7.6	gal/min	WATER2
Cooling Water Requirement	3,297	gal/pc	COOL2
Building Space/Station	1,500	sqft	SPACE2

Recycle Equipment Cost	$0	/sta	REC2
Liquid Hydrogen Tank Rental	$2,165	/mo/tank	HYD2
Liq Carrier Gas Tank Rental	$469	/mo/tank	CAR2
Gas Storage Equipment Rent	$31,608	/year	GTANK2
Machine Cost	$424,466	/sta	MCH2B
Installed Equipment Cost	$573,030	/sta	IEQUIP2
Auxiliary Equipment Cost	$63,670	/sta	AEQUIP2
Equipment Annuity	$285,621	/yr	EINT2
Tooling Annuity	$0	/yr	TINT2
Building Annuity	$30,562	/yr	BINT2
Working Annuity	$474,860	/yr	WINT2

##########

DC ARC CVD TCM: ETCHING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$6.28	$6,281	39.1%	
Direct Labor Cost	$4.62	$4,616	28.8%	
Utility Cost	$0.00	$0	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$0.16	$160	1.0%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.04	$45	0.3%	$10,000
Maintenance Cost	$0.14	$135	0.8%	
Overhead Labor Cost	$4.45	$4,452	27.7%	
Cost of Capital	$0.36	$361	2.3%	
TOTAL FABRICATION COST	$16.05	$16,051	100.0%	$19,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00 [1=Y 0=N]	PRO3
Cumulative Yield	79.6%	CYLD3
Effective Production Volume	1,256 /yr	ENUM3
Total Etched Thickness	3,810 um	ETHIK3
Average Etchant Rate	20.00 um/min	ERATE3
Process Cycle Time	0.18 hrs/pc	CTIME3
Runtime for One Station	9%	RTIME3
Number of Parallel Stations	0.09	NSTAT3
Chemical Requirement	$5.00 /pc	CHEM3
Energy Requirement	0 kWh/pc	ENERGY3
Building Space/Station	100 sq ft	SPACE3
Installed Equipment Cost	$8,100 /sta	IEQUIP3
Auxiliary Equipment Cost	$900 /sta	AEQUIP3
Equipment Annuity	$204 /yr	EINT3
Tooling Annuity	$0 /yr	TINT3
Building Annuity	$103 /yr	BINT3
Working Annuity	$15,744 /yr	WINT3

##########

DC ARC CVD TCM: LASER TRIMMING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$0.33	$331	47.5%	
Utility Cost	$0.00	$4	0.6%	
FIXED COST ELEMENTS				
Equipment Cost	$0.01	$11	1.6%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.00	$3	0.5%	$10,000
Maintenance Cost	$0.01	$10	1.4%	
Overhead Labor Cost	$0.32	$319	45.8%	
Cost of Capital	$0.02	$18	2.6%	
TOTAL FABRICATION COST	$0.70	$697	100.0%	$19,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00 [1=Y 0=N]	PRO4
Cumulative Yield	80.4%	CYLD4
Effective Production Volume	1,244 /yr	ENUM4
Process Cycle Time	0.01 hrs/pc	CTIME4
Runtime for One Station	1%	RTIME4
Number of Parallel Stations	0.01	NSTAT4
Energy Requirement	0 kWh/pc	ENERGY4
Building Space/Station	100 sq ft	SPACE4
Installed Equipment Cost	$8,100 /sta	IEQUIP4
Auxiliary Equipment Cost	$900 /sta	AEQUIP4
Equipment Annuity	$15 /yr	EINT4
Tooling Annuity	$0 /yr	TINT4
Building Annuity	$7 /yr	BINT4
Working Annuity	$675 /yr	WINT4

##########

DC ARC CVD TCM: LAPPING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$725.01	$725,009	66.7%	
Direct Labor Cost	$146.58	$146,579	13.5%	
Utility Cost	$5.79	$5,786	0.5%	
FIXED COST ELEMENTS				
Equipment Cost	$13.50	$13,503	1.2%	$71,634
Tooling Cost	$74.41	$74,415	6.8%	$372,073
Building Cost	$7.54	$7,540	0.7%	$160,000
Maintenance Cost	$17.47	$17,465	1.6%	
Overhead Labor Cost	$47.13	$47,125	4.3%	
Cost of Capital	$49.83	$49,828	4.6%	
TOTAL FABRICATION COST	$1,087.25	$1,087,251	100.0%	$603,707

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO5
Cumulative Yield	81.2%		CYLD5
Effective Production Volume	1,231	/yr	ENUM5
Thickness of Material Lapped	111.11	um	HLAP5
Setup Time	1.33	hrs/batch	CTIME5A
Lapping Time	*111.11*	*hrs/batch*	*CTIME5B*
Runtime for One Station	377%		RTIME5
Number of Parallel Stations	3.77		NSTAT5
Lapping Plate Cost	$869	/ea	PLA5
Lapping Plate Life	14	pcs	WHEEL5
Number of Plates Required	428.00		PLAT5
Lapping Slurry Consumption	11.11	l/pc	GRIT5
Machine Power	4.2	kW	PWR5
Energy Requirement	94	kWh/pc	ENERGY5
Machine Cost	$11,939	/sta	MCH5
Building Space/Station	400	sq ft	SPACE5
Installed Equipment Cost	$16,118	/sta	IEQUIP5
Auxiliary Equipment Cost	$1,791	/sta	AEQUIP5
Equipment Annuity	$17,214	/yr	EINT5
Tooling Annuity	$94,865	/yr	TINT5
Building Annuity	$17,463	/yr	BINT5
Working Annuity	$957,709	/yr	WINT5

##########

DC ARC CVD TCM: INSPECTION - MICROSCOPY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$5.25	$5,249	39.9%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.52	$1,519	11.6%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.03	$25	0.2%	$5,000
Maintenance Cost	$0.65	$648	4.9%	
Overhead Labor Cost	$5.06	$5,062	38.5%	
Cost of Capital	$0.63	$634	4.8%	
TOTAL FABRICATION COST	$13.14	$13,138	100.0%	$80,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO6
Cumulative Yield	90.3%		CYLD6
Effective Production Volume	1,108	/yr	ENUM6
Process Cycle Time	0.25	hrs	CTIME6
Runtime for One Station	10%		RTIME6
Number of Parallel Stations	*0.10*		*NSTAT6*
Energy Requirement	0	kWh/pc	ENERGY6
Building Space/Station	50	sq ft	SPACE6
Installed Equipment Cost	$67,500	/sta	IEQUIP6
Auxiliary Equipment Cost	$7,500	/sta	AEQUIP6
Equipment Annuity	$1,936	/yr	EINT6
Tooling Annuity	$0	/yr	TINT6
Building Annuity	$59	/yr	BINT6
Working Annuity	$11,143	/yr	WINT6

##########

DC ARC CVD TCM: INSPECTION - THERMAL CONDUCTIVITY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$4.99	$4,986	38.7%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.52	$1,519	11.8%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.03	$25	0.2%	$5,000
Maintenance Cost	$0.65	$648	5.0%	
Overhead Labor Cost	$5.06	$5,062	39.3%	
Cost of Capital	$0.63	$629	4.9%	
TOTAL FABRICATION COST	$12.87	$12,871	100.0%	$80,000

DC ARC CVD TCM: COST SUMMARY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$954.78	$954,776	48.0%	
Direct Labor Cost	$272.04	$272,039	13.7%	
Utility Cost	$57.89	$57,894	2.9%	
FIXED COST ELEMENTS				
Equipment Cost	$241.39	$241,389	12.1%	$1,611,694
Tooling Cost	$74.41	$74,415	3.7%	$372,073
Building Cost	$20.87	$20,874	1.0%	$515,000
Maintenance Cost	$129.95	$129,954	6.5%	
Overhead Labor Cost	$98.01	$98,008	4.9%	
Cost of Capital	$139.54	$139,542	7.0%	
TOTAL FABRICATION COST	$1,988.89	$1,988,891	100.0%	$2,498,767

INTERMEDIATE CALCULATIONS

Process In Use	1.00 [1=Y 0=N]	PRO7
Cumulative Yield	95.0%	CYLD7
Effective Production Volume	1,053 /yr	ENUM7
Process Cycle Time	0.25 hrs	CTIME7
Runtime for One Station	10%	RTIME7
Number of Parallel Stations	0.10	NSTAT7
Energy Requirement	0 kWh/pc	ENERGY7
Building Space/Station	50 sq ft	SPACE7
Installed Equipment Cost	$67,500 /sta	IEQUIP7
Auxiliary Equipment Cost	$7,500 /sta	AEQUIP7
Equipment Annuity	$1,936 /yr	EINT7
Tooling Annuity	$0 /yr	TINT7
Building Annuity	$59 /yr	BINT7
Working Annuity	$10,877 /yr	WINT7

SUMMARY INFORMATION

Part Name	6 in. substrate
Total Direct Laborers	6.30 /shift
Total Floor Space	5,150 sqft
Total Capital Investment	$2.5 MM
Area Cost	$10.90 /sqcm
Cost Per Carat	$6.21 /ct

Operation	Equipment	Material	Labor	Other
Surface Preparation	$1	$64	$2	$2
Deposition	$224	$160	$145	$263
Etching	$0	$6	$9	$1
Laser Trimming	$0	$0	$1	$0
Lapping	$14	$725	$194	$155
Inspect - Microscopy	$2	$0	$10	$1
Inspect - Thermal Cond'vity	$2	$0	$10	$1
Total	$241	$955	$370	$423
Total =	$1,989			

Appendix B - The Microwave Model

MICROWAVE CVD DIAMOND TECHNICAL COST MODEL
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

Revision Date: 9/94

PRODUCT SPECIFICATIONS

Part Name	16 in. substrate		NAME	
Finished Wafer Thickness	1,000	um	THIK	
Thermal Conductivity	1,000	W/mK	THERMCON	
Annual Production Volume	1	(000/yr)	NUM	
Length of Production Run	5	yrs	PLIFE	

PROCESS RELATED FACTORS - SURFACE PREPARATION

Process In Use?	1.00	[1=Y 0=N]	USE1	
Dedicated Investment	0.00	[1=Y 0=N]	DED1	
Process Yield	95.0%		YLD1	
Average Equipment Downtime	20.0%		DOWN1	
Direct Laborers Per Station	0.50		NLAB1	
Substrate Material	2	[menu #]	MATL1	
Pieces Per Batch	20.00	pcs/batch	PCS1	
Process Time	60.00	min/batch	PTIME1	
Building Space Requirement	250	sqft/sta	FLR1	

PROCESS RELATED FACTORS - DEPOSITION

Process In Use?	1.00	[1=Y 0=N]	USE2	
Dedicated Investment	0.00	[1=Y 0=N]	DED2	
Process Yield	90.0%		YLD2	
Average Equipment Downtime	15.0%		DOWN2	
Direct Laborers	0.10	/sta	NLAB2	
Rated Microwave Power	250	kW	POW2	>5 kW
Reactor Pressure	127.9	torr	PRES2	
Recombine Coef. (gammaH)	0.10		HRECOMB2	
Plasma Ball Skew Factor (f)	3.00	(2=sym.)	SKEW2	
Diamond Density	3.51	g/cc	DENS	
Ideal Gas Constant (R)	62,358	cc torr/K mol	IDLGAS2A	
Ideal Gas Constant 2 (R)	8.31	J / mol K	IDLGAS2B	

NASA Enthalpy Constants	H2	H		
a1	2.99E+00	2.50E+00	H2EN2A	HEN2A
a2	7.00E-04	0.00E+00	H2EN2B	HEN2B
a3	-5.63E-08	0.00E+00	H2EN2C	HEN2C
a4	-9.23E-12	0.00E+00	H2EN2D	HEN2D
a5	1.58E-15	0.00E+00	H2EN2E	HEN2E
a6	-8.35E+02	2.55E+04	H2EN2F	HEN2F
a7	-1.36	-0.46	H2EN2G	HEN2G
MW	2.02	1.01	H2MW	HMW

	Menu #	vol%	
Hydrogen	9	88.7%	GASAVOLA

MICROWAVE CVD DIAMOND TECHNICAL COST MODEL
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

GAS DATABASE

#	Gas	Source	Purity	Price $/SCM	No. of Carbons	Liq Gas	Tank gal	Price Update
0	None			$0.00	0.00	0.00		
1	Liq Hydrogen	Airco	99.998%	$0.34	0.00	1.00	6000	1/93
2	Liq Hydrogen	Airco	99.998%	$0.32	0.00	1.00	11000	1/93
3	Liq Hydrogen	Airco	99.998%	$0.30	0.00	1.00	20000	1/93
4	Liq Argon	Airco	99.998%	$1.41	0.00	1.00	3000	1/93
5	Liq Argon	Airco	99.998%	$1.32	0.00	1.00	6000	1/93
6	Liq Argon	Airco	99.998%	$1.29	0.00	1.00	11000	1/93
7	Hydrogen	MG Ind.	99.9999%	$29.86	0.00	0.00		1/93
8	Hydrogen	MG Ind.	99.9996%	$40.61	0.00	0.00		1/93
9	Hydrogen	MG Ind.	99.999%	$10.28	0.00	0.00		1/93
10	Hydrogen	Air Prod.	99.95%	$1.59	0.00	0.00		1/93
11	Argon	MG Ind.	99.9999%	$33.09	0.00	0.00		1/93
12	Argon	Air Prod.	99.9997%	$37.33	0.00	0.00		1/93
13	Argon	Air Prod.	99.999%	$11.74	0.00	0.00		1/93
14	Argon	Air Prod.	99.997%	$2.03	0.00	0.00		1/93
15	Methane	Air Prod.	99.99%	$21.99	1.00	0.00		1/93
16	Methane	Air Prod.	99%	$13.76	1.00	0.00		1/93
17	Methane	Air Prod.	93%	$4.93	1.00	0.00		1/93
18	Acetylene	Air Prod.	99.6%	$6.80	2.00	0.00		1/93
19	Acetylene	Air Prod.	98%	$5.85	2.00	0.00		1/93
20	Helium	Air Prod.	99.9995%	$15.90	0.00	0.00		1/93
21	Helium	Air Prod.	99.995%	$4.77	0.00	0.00		1/93
22	Nitrogen	Air Prod.	99.9996%	$45.50	0.00	0.00		1/93
23	Nitrogen	MG Ind.	99.999%	$9.23	0.00	0.00		1/93
24	Nitrogen	Air Prod.	99.998%	$1.24	0.00	0.00		1/93
25	Oxygen	Air Prod.	99.998%	$2.00	0.00	0.00		1/93
26								

SUBSTRATE DATABASE

#	Substrate	Source	Price Exp.	Price Coef.	Price Const.	Etch um/min	Life use#	Price Update
0	None		0.000	0.00	0	1.00	1.00	
1	Silicon	Si-Tech	4.335	0.00	2.81	20.00	1	1/93
2	Molybdenum	Schwarzkopf Te	2.000	0.34	11.17	10.00	46.00	1/93
3	Tungston	Schwarzkopf Te	1.366	12.97	-80.44	10.00	46.00	1/93
4								

TARGET DATABASE

#	Metal	Vendor	Price $/g A/kWm	Dep.Rt.	Density g/cc	Price Update
0	None		$0	**********	1.00	
1	Titanium	Tosoh	$1.90	80.00	4.51	1/93

Carbon Containing Gas	16	10.0%	GASBVOLB
Carrier Gas	0	0.0%	GASCVOLC
Other Gas	25	1.3%	GASDVOLD
		100.0%	

Hydrogen Recycle Rate	0.0%		RECYC
Carrier Gas Recycle Rate	0.0%		RECYC2
Gas Recycle Equipment Cost	$250,000	total	MCH2A
Microwave Coupling Eff.	98%		P2GEFF2
Total Power Multiplier	120%		TPM2
Carbon Capture Factor	10.0%		CCF2
Machine Load/Unload Time	30.00	min/batch	PTIME2
Available Deposition Time	8,640	hrs/yr	DAYHR2
Microwave Tube Life	10000	hrs	LIFE2
Coolant Temp. Rise	7.00	C	TEMP2
Heat Capacity of Coolant	1.0	cal/g/C	CP2
Building Space Requirement	400	sqft/sta	FLR2

PROCESS RELATED FACTORS - ETCHING

Process In Use?	1.00	[1=Y 0=N]	USE3
Dedicated Investment	0.00	[1=Y 0=N]	DED3
Process Yield	99.0%		YLD3
Average Equipment Downtime	10.0%		DOWN3
Direct Laborers Per Station	1.00		NLAB3
Load/Unload and Rinse Time	30.00	min/batch	PTIME3
Pieces Per Batch	20.00		PCS3
Machine Cost	$6,000	/sta	MCH3
Etchant Cost	$70	/liter	ETCH3A
Etchant Disposal Cost	$30	/liter	ETCH3B
Machine Etchant Capacity	1.00	l/batch	CAP3
Machine Power	0.00	kW	POW3
Building Space Requirement	100	sqft/sta	FLR3

PROCESS RELATED FACTORS - LASER TRIMMING

Process In Use?	1.00	[1=Y 0=N]	USE4
Dedicated Investment	0.00	[1=Y 0=N]	DED4
Process Yield	99.0%		YLD4
Average Equipment Downtime	10.0%		DOWN4
Direct Laborers Per Station	1.00		NLAB4
Machine Cost	$6,000	/sta	MCH4
Trimming Rate	1.00	cm/s	RATE4
Machine Power	5.00	kW	POW4
Building Space Requirement	100	sqft/sta	FLR4

PROCESS RELATED FACTORS - LAPPING

Process In Use?	1.00	[1=Y 0=N]	USE5
Dedicated Investment	0.00	[1=Y 0=N]	DED5
Process Yield	90.0%		YLD5

2	Platinum	Tosoh	$19.00	125.00	21.45	1/93
3	Gold	Tosoh	$17.00	230.00	19.32	1/93
4	Silver	Tosoh	$2.45	215.00	10.50	1/93
5	Copper	Tosoh	$1.15	210.00	8.96	1/93
6	Nickel	Tosoh	$0.95	30.00	8.91	1/93
7	Palladium	Tosoh	$8.45	210.00	12.02	1/93
8	Silicon	Tosoh	$0.80	15.00	2.33	1/93

EVAPORATION DATABASE

#	Metal	Vendor	Price $/g	Dep.Rt. A/kWm	Density g/cc	Price Update
0	None		$0	**********	1.00	
1	Titanium	Pure Tech Inc	$4.40	9,520.00	4.51	1/93
2	Platinum	Pure Tech Inc	$18.59	6,428.57	21.45	1/93
3	Gold	Pure Tech Inc	$14.58	6,428.57	19.32	1/93
4	Silver	Pure Tech Inc	$3.12	215.00	10.50	1/93
5	Copper	Pure Tech Inc	$1.08	210.00	8.96	1/93
6	Nickel	Pure Tech Inc	$1.49	30.00	8.91	1/93
7	Palladium	Pure Tech Inc	$7.03	210.00	12.02	1/93
8	Silicon	Pure Tech Inc	$7.51	15.00	2.33	1/93

##########

Average Equipment Downtime	15.0%		DOWN5
Direct Laborers Per Station	0.25		NLAB5
Lapped Material Removal	10.0%	by wgt	TLAP5
No of Lapping Steps	2.00		LAPS5
Pieces Per Batch	5.00		PCS5
Load/Unload and Clean Wafers	40.00	min/batch	PTIME5
Average Lapping Rate	1.0	um/hr	RATE5
Lapping Slurry Cost	$53	/liter	LAPSL5
Lapping Slurry Usage Rate	0.50	liter/hr	LAPR5
Lapping Plate Life	320.00	hrs	PLAL5
Available Lapping Time	8,640	hrs/yr	DAYHR5
Building Space Requirement	400	sqft/sta	FLR5

PROCESS RELATED FACTORS - INSPECTION - MICROSCOPY

Process In Use?	1.00	[1=Y 0=N]	USE6
Dedicated Investment	0.00	[1=Y 0=N]	DED6
Process Yield	95.0%		YLD6
Average Equipment Downtime	5.0%		DOWN6
Direct Laborers Per Station	1.00		NLAB6
Average Inspection Time	15.00	min/batch	PTIME6
Percent Inspection	100%		INSP6
Machine Cost	$50,000	/sta	MCH6
Machine Power	0.10	kW	POW6
Building Space Requirement	50	sqft/sta	FLR6

PROCESS RELATED FACTORS - INSPECTION - THERMAL CONDUCTIVITY

Process In Use?	1.00	[1=Y 0=N]	USE7
Dedicated Investment	0.00	[1=Y 0=N]	DED7
Process Yield	95.0%		YLD7
Average Equipment Downtime	5.0%		DOWN7
Direct Laborers Per Station	1.00		NLAB7
Average Inspection Time	15.00	min/batch	PTIME7
Percent Inspection	100%		INSP7
Machine Cost	$50,000	/sta	MCH7
Machine Power	0.10	kW	POW7
Building Space Requirement	50	sqft/sta	FLR7

OPTIONAL INPUTS

	override	estimate		
Surface Preparation				
Machine Cost	$0	$65,774	/sta	OMCH1
Machine Power	0.0	19.2	kW	OPOW1
Deposition				
Plasma Ball Area	0.00	1297.32	sq cm	OBAREA2
Deposition Diameter	0.00	40.64	cm	ODDIAM2
Deposition Rate	0.00	3.70	g/hr	ODRATE2
Deposition Equipment Cost	$0	$1,387	k$/sta	OMCH2
New Microwave Tube Cost	$0	$25,000	/sta	OTUBE2

Refurb Microwave Tube Cost	$0	$12,500 /sta	ORTUBE2
Etching			
Process Cycle Time	0.00	0.03 hrs	OCTIME3
Chemical Requirement	$0	$5.00 /pc	OCHEM3
Laser Trimming			
Process Cycle Time	0.00	0.04 hrs	OCTIME4
Lapping			
Lapping Time	0.00	111.11 hrs	OCTIME5
Lapping Plate Cost	$0	$869 /ea	OWHEEL5
Lapping Machine Cost	$0	$11,939 /sta	OMCH5
Lapping Machine Power	0.00	4.2 kW	OPWR5

EXOGENOUS COST FACTORS

Direct Wages	$13.33	/hr	WAGE
Indirect Salary	$50,000	/yr	SALARY * exc. dep. & lap
Indirect:Direct Labor Ratio	1.00		ILAB
Benefits on Wage and Salary	35.0%		BENI
Working Days per Year	360.00		DAYS
Working Hours per Day (*)	8.00	hr	HRS
Capital Recovery Rate	10%		CRR
Capital Recovery Period	5.00	yrs	ELIFE
Building Recovery Life	20.00	yrs	BLIFE
Working Capital Period	3.00	months	WCP
Price of Electricity	$0.050	/kWh	ELEC
Price of Natural Gas	$6.50	/MBTU	GAS
Price of Building Space	$100	/sqft	PBLD
Price of Cooling Water	$0.03	/100 gal	WATER
Auxiliary Equipment Cost	15.0%		AUX
Equipment Installation Cost	35.0%		INST
Maintenance Cost	8.0%		MNT

PHYSICAL CONSTANTS, REGRESSION CONSTANTS, COEFFICIENTS, AND EXPONENTS

-Surface Preparation-			
Machine Cost Constant	1,334	MCH1A	
Machine Cost Capacity Coef	3,222	MCH1B	
Machine Power Constant	-0.75	PWR1A	
Machine Power Capacity Coef	1.00	PWR1B	
-Deposition-			
Gas Temperature (>1000K)	3,000	K	GTEMP2
Substrate Temperature	1,200	K	STEMP2
Plasma Ball Diam Power Exponent	1.08	BDIAM2X	
Plasma Ball Diam Pres Exponent	-1.68	BDIAM2Y	
Plasma Ball Diam Coefficient	11332.00	BDIAM2Z	
Machine Cost Power Coef	135,000	MCH2Y	
Machine Cost Power Exponent	0.50	MCH2Z	
Machine Cost Power Constant	0	MCH2X	
Mach Cost Volume Asymptote	0.65	MCH2V	
Machine Cost Volume Exp	-0.14	MCH2W	
New Tube:Refurbished Cost	2.00	TUBE2X	
Tube Cost Constant	0	TUBE2Y	

Tube Cost Coef	100.00	TUBE2Z
H/CH3 Therm. Cond. Coeff.	0.00	TC2A
H/CH3 Therm. Cond. Exp.	4.07	TC2B
Growth Rate Coeff. 1	1.80E+11	GRC2A
Growth Rate Coeff. 2	5.00E-09	GRC2B
Tank 1 $ Capacity Constant	1,175	TANK2A
Tank 1 $ Capacity Coef	0.165	TANK2B
Tank 2 $ Capacity Constant	370.00	TANK2X
Tank 2 $ Capacity Coef	0.03	TANK2Y
-Etching-		
-Lapping-		
Machine Cost Constant	2,719	MCH5A
Machine Cost Capacity Coef	1,844	MCH5B
Machine Power Constant	-0.75	PWR5A
Machine Power Capacity Coef	1.00	PWR5B
Tool Cost Constant	771.00	TOOL5A
Tool Cost Capacity Coef	0.92	TOOL5B
Tool Cost Capacity Exponent	2.90	TOOL5C

##########

IBIS ASSOCIATES, INC.
TECHNICAL COST MODEL (C) 1993
RESTRICTED RIGHTS LEGEND

Use, duplication, or disclosure by the Government is subject to restrictions as set forth in subparagraph (c)(1)(ii) of the Rights in Technical Data and Computer Software clause at DFARS 252.227-7013

##########

MICROWAVE CVD TCM: SURFACE PREPARATION
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$17.90	$17,899	84.8%	
Direct Labor Cost	$0.82	$818	3.9%	
Utility Cost	$0.07	$70	0.3%	
FIXED COST ELEMENTS				
Equipment Cost	$0.62	$623	3.0%	$98,661
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.04	$39	0.2%	$25,000
Maintenance Cost	$0.31	$312	1.5%	
Overhead Labor Cost	$0.79	$789	3.7%	
Cost of Capital	$0.56	$555	2.6%	
TOTAL FABRICATION COST	$21.11	$21,106	100.0%	$123,661

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO1
Cumulative Yield	68.8%		CYLD1
Effective Production Volume	1,454	/yr	ENUM1
Substrate Area	1297.3	sq cm	AREA1
New Substrate Cost	$566.09	/pc	SUB1
Substrate Useful Life	46.00	cycle	LIFE1
Process Cycle Time	3	min/pc	CTIME1
Runtime for One Station	3%		RTIME1
Number of Parallel Stations	0.03		NSTAT1
Energy Requirement	0.959	kWh/pc	ENERGY1
Building Space/Station	250	sqft	SPACE1
Machine Cost	$65,774	/sta	MCH1
Machine Power	19.2	kW	POW1
Installed Equipment Cost	$88,795	/sta	IEQUIP1
Auxiliary Equipment Cost	$9,866	/sta	AEQUIP1
Equipment Annuity	$794	/yr	EINT1
Tooling Annuity	$0	/yr	TINT1
Building Annuity	$91	/yr	BINT1
Working Annuity	$20,221	/yr	WINT1

MICROWAVE CVD TCM: DEPOSITION
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$1,498.63	$1,498,635	6.3%	
Direct Labor Cost	$401.80	$401,803	1.7%	
Utility Cost	$3,239.02	$3,239,024	13.6%	
FIXED COST ELEMENTS				
Equipment Cost	$10,753.88	$10,753,882	45.0%	$54,110,524
Tooling Cost	$195.00	$195,000	0.8%	$975,000
Building Cost	$51.67	$51,672	0.2%	$1,040,000
Maintenance Cost	$4,384.23	$4,384,228	18.4%	
Overhead Labor Cost	$129.18	$129,180	0.5%	
Cost of Capital	$3,238.33	$3,238,331	13.6%	
TOTAL FABRICATION COST	$23,891.76	$23,891,756	100.0%	$56,125,524
	$18.42 /sqcm			

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO2
Cumulative Yield	72.4%		CYLD2
Effective Production Volume	1,382	/yr	ENUM2
Delivered Power	245.0	kW	EPOW2

HYDROGEN DIFFUSION CALCULATIONS

	H2	H·	
Enthalpy Per Unit Mass	385	271,987	J/g
Molar Enthalpy	776	274,136	J/mol
Molar Entropy	202.79	162.59	J/K mol
Molar Heat Capacity (Cp)	37.11	20.79	J/K mol

Heat of Reaction (H2==>2H·)	547,496	J/mol	HTRXN2
Plasma Ball Diameter	40.64	cm	BDIAM2
Plasma Ball Area	1297.32	sq cm	BAREA2
Deposition Diameter	40.64	cm	DDIAM2
0.19	0.19		
Mean H· Thermal Speed	502,063	cm/s	HSPEED2
H· Generation Rate	1.15E-04	mol/s/cc	HGEN2
H· Conc. at Substrate	1.83E-09	mol/cc	HCONC2
H/CH3 Ratio	10.89		HCH3R
CH3 Concentration	1.68E-10	mol/cc	CH3CON2

DEPOSITION RATE CALCULATIONS

Mass of Diamond Deposited	505.96	g	MASS2
Linear Deposition Rate	8.1	um/hr	LINDEP2
Mass Deposition Rate	3.7	g/hr	MASDEP2
Deposition Time	136.82	hrs	CTIMEB2
Machine Setup Time	0.50	hrs	CTIMEA2

Runtime for One Station	2584%		RTIME2
Number of Parallel Stations	25.84		NSTAT2
Total Carbon Gas Volume	10.31	SCM	CARGAS2
Total Gas Volume	103	SCM	TVOL2
Total Gas Flow Rate	12,559	sccm	FLOWR2

	Consumption (SCM/pc)	Cost ($/pc)		
Hydrogen Consumption	91.44	$1,298.92	GASA2	COSTA2
Carbon Gas Consumption	10.31	$196.01	GASB2	COSTB2
Carrier Gas Consumption	0.00	$0.00	GASC2	COSTC2
Other Gas Consumption	1.34	$3.70	GASD2	COSTD2

Energy Requirement	40,224	kWh/pc	ENERGY2
Physical Tube Life	1.36	years	TLIFE2
Number of Tubes per Station	4	incl. orig.	NTUBE2
Number of New Tubes /Sta	0	/sta	NTUBE2A
Number of Refurb /Sta	3	/sta	NTUBE2B
New Microwave Tube Cost	$25,000	/tube	TUBE2A
Reworked Microwave Tube Cost	$12,500	/tube	TUBE2B
Cooling Water Flow Rate	135.2	gal/min	WATER2
Cooling Water Requirement	1,109,690	gal/pc	COOL2
Building Space/Station	400	sqft	SPACE2
Recycle Equipment Cost	$0	/sta	REC2
Liquid Hydrogen Tank Rental	$0	/mo/tank	HYD2
Liq Carrier Gas Tank Rental	$0	/mo/tank	CAR2
Gas Storage Equipment Rent	$0	/year	GTANK2
Machine Cost	$1,387,449	/sta	MCH2B
Installed Equipment Cost	$1,873,057	/sta	IEQUIP2
Auxiliary Equipment Cost	$208,117	/sta	AEQUIP2
Equipment Annuity	$13,709,293	/yr	EINT2
Tooling Annuity	$248,590	/yr	TINT2
Building Annuity	$119,675	/yr	BINT2
Working Annuity	$9,814,197	/yr	WINT2

##########

MICROWAVE CVD TCM: ETCHING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	ERR	
Direct Labor Cost	$0.00	$0	ERR	
Utility Cost	$0.00	$0	ERR	
FIXED COST ELEMENTS				
Equipment Cost	$0.00	$0	ERR	$0
Tooling Cost	$0.00	$0	ERR	$0
Building Cost	$0.00	$0	ERR	$0
Maintenance Cost	$0.00	$0	ERR	
Overhead Labor Cost	$0.00	$0	ERR	
Cost of Capital	$0.00	$0	ERR	
TOTAL FABRICATION COST	$0.00	$0	ERR	$0

INTERMEDIATE CALCULATIONS

Process In Use	0.00	[1=Y 0=N]	PRO3
Cumulative Yield	80.4%		CYLD3
Effective Production Volume	1,244	/yr	ENUM3
Total Etched Thickness	0	um	ETHIK3
Average Etchant Rate	10.00	um/min	ERATE3
Process Cycle Time	0.03	hrs/pc	CTIME3
Runtime for One Station	1%		RTIME3
Number of Parallel Stations	0.01		NSTAT3
Chemical Requirement	$5.00	/pc	CHEM3
Energy Requirement	0	kWh/pc	ENERGY3
Building Space/Station	100	sq ft	SPACE3
Installed Equipment Cost	$8,100	/sta	IEQUIP3
Auxiliary Equipment Cost	$900	/sta	AEQUIP3
Equipment Annuity	$0	/yr	EINT3
Tooling Annuity	$0	/yr	TINT3
Building Annuity	$0	/yr	BINT3
Working Annuity	$0	/yr	WINT3

##########

MICROWAVE CVD TCM: LASER TRIMMING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$0.88	$882	47.5%	
Utility Cost	$0.01	$11	0.6%	
FIXED COST ELEMENTS				
Equipment Cost	$0.03	$31	1.6%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.01	$9	0.5%	$10,000
Maintenance Cost	$0.03	$26	1.4%	
Overhead Labor Cost	$0.85	$851	45.8%	
Cost of Capital	$0.05	$49	2.6%	
TOTAL FABRICATION COST	$1.86	$1,858	100.0%	$19,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO4
Cumulative Yield	80.4%		CYLD4
Effective Production Volume	1,244	/yr	ENUM4
Process Cycle Time	0.04	hrs/pc	CTIME4
Runtime for One Station	2%		RTIME4
Number of Parallel Stations	0.02		NSTAT4
Energy Requirement	0	kWh/pc	ENERGY4
Building Space/Station	100	sq ft	SPACE4
Installed Equipment Cost	$8,100	/sta	IEQUIP4
Auxiliary Equipment Cost	$900	/sta	AEQUIP4
Equipment Annuity	$39	/yr	EINT4
Tooling Annuity	$0	/yr	TINT4
Building Annuity	$20	/yr	BINT4
Working Annuity	$1,799	/yr	WINT4

##########

MICROWAVE CVD TCM: LAPPING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$725.01	$725,009	66.7%	
Direct Labor Cost	$146.58	$146,579	13.5%	
Utility Cost	$5.79	$5,786	0.5%	
FIXED COST ELEMENTS				
Equipment Cost	$13.50	$13,503	1.2%	$71,634
Tooling Cost	$74.41	$74,415	6.8%	$372,073
Building Cost	$7.54	$7,540	0.7%	$160,000
Maintenance Cost	$17.47	$17,465	1.6%	
Overhead Labor Cost	$47.13	$47,125	4.3%	
Cost of Capital	$49.83	$49,828	4.6%	
TOTAL FABRICATION COST	$1,087.25	$1,087,251	100.0%	$603,707

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO5
Cumulative Yield	81.2%		CYLD5
Effective Production Volume	1,231	/yr	ENUM5
Thickness of Material Lapped	111.11	um	HLAP5
Setup Time	1.33	hrs/batch	CTIME5A
Lapping Time	111.11	hrs/batch	CTIME5B
Runtime for One Station	377%		RTIME5
Number of Parallel Stations	3.77		NSTAT5
Lapping Plate Cost	$869	/ea	PLA5
Lapping Plate Life	14	pcs	WHEEL5
Number of Plates Required	428.00		PLAT5
Lapping Slurry Consumption	11.11	l/pc	GRIT5
Machine Power	4.2	kW	PWR5
Energy Requirement	94	kWh/pc	ENERGY5
Machine Cost	$11,939	/sta	MCH5
Building Space/Station	400	sq ft	SPACE5
Installed Equipment Cost	$16,118	/sta	IEQUIP5
Auxiliary Equipment Cost	$1,791	/sta	AEQUIP5
Equipment Annuity	$17,214	/yr	EINT5
Tooling Annuity	$94,865	/yr	TINT5
Building Annuity	$17,463	/yr	BINT5
Working Annuity	$957,709	/yr	WINT5

##########

MICROWAVE CVD TCM: INSPECTION - MICROSCOPY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$5.25	$5,249	39.9%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.52	$1,519	11.6%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.03	$25	0.2%	$5,000
Maintenance Cost	$0.65	$648	4.9%	
Overhead Labor Cost	$5.06	$5,062	38.5%	
Cost of Capital	$0.63	$634	4.8%	
TOTAL FABRICATION COST	$13.14	$13,138	100.0%	$80,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO6
Cumulative Yield	90.3%		CYLD6
Effective Production Volume	1,108	/yr	ENUM6
Process Cycle Time	0.25	hrs	CTIME6
Runtime for One Station	10%		RTIME6
Number of Parallel Stations	0.10		NSTAT6
Energy Requirement	0	kWh/pc	ENERGY6
Building Space/Station	50	sq ft	SPACE6
Installed Equipment Cost	$67,500	/sta	IEQUIP6
Auxiliary Equipment Cost	$7,500	/sta	AEQUIP6
Equipment Annuity	$1,936	/yr	EINT6
Tooling Annuity	$0	/yr	TINT6
Building Annuity	$59	/yr	BINT6
Working Annuity	$11,143	/yr	WINT6

##########

MICROWAVE CVD TCM: INSPECTION - THERMAL CONDUCTIVITY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$4.99	$4,986	38.7%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.52	$1,519	11.8%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.03	$25	0.2%	$5,000
Maintenance Cost	$0.65	$648	5.0%	
Overhead Labor Cost	$5.06	$5,062	39.3%	
Cost of Capital	$0.63	$629	4.9%	
TOTAL FABRICATION COST	$12.87	$12,871	100.0%	$80,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO7
Cumulative Yield	95.0%		CYLD7
Effective Production Volume	1,053	/yr	ENUM7
Process Cycle Time	0.25	hrs	CTIME7
Runtime for One Station	10%		RTIME7
Number of Parallel Stations	0.10		NSTAT7
Energy Requirement	0	kWh/pc	ENERGY7
Building Space/Station	50	sq ft	SPACE7
Installed Equipment Cost	$67,500	/sta	IEQUIP7
Auxiliary Equipment Cost	$7,500	/sta	AEQUIP7
Equipment Annuity	$1,936	/yr	EINT7
Tooling Annuity	$0	/yr	TINT7
Building Annuity	$59	/yr	BINT7
Working Annuity	$10,877	/yr	WINT7

##########

MICROWAVE CVD TCM: COST SUMMARY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

	per piece	per year	percent	investment
VARIABLE COST ELEMENTS				
Material Cost	$2,241.54	$2,241,543	9.0%	
Direct Labor Cost	$560.32	$560,317	2.2%	
Utility Cost	$3,244.89	$3,244,894	13.0%	
FIXED COST ELEMENTS				
Equipment Cost	$10,771.08	$10,771,076	43.0%	$54,439,819
Tooling Cost	$269.41	$269,415	1.1%	$1,347,073
Building Cost	$59.31	$59,311	0.2%	$1,245,000
Maintenance Cost	$4,403.33	$4,403,328	17.6%	
Overhead Labor Cost	$188.07	$188,070	0.8%	
Cost of Capital	$3,290.03	$3,290,027	13.1%	
TOTAL FABRICATION COST	$25,027.98	$25,027,981	100.0%	$57,031,892

SUMMARY INFORMATION

Part Name	16 in. substrate		
Total Direct Laborers	8.10	/shift	
Total Floor Space	12,550	sqft	
Total Capital Investment	$57.0	MM	
Area Cost	$19.29	/sqcm	$18.42
Cost Per Carat	$10.99	/ct	$10.49

Operation	Equipment	Material	Labor	Other
Surface Preparation	$1	$18	$2	$1
Deposition	$10,754	$1,499	$531	$11,108
Etching	$0	$0	$0	$0
Laser Trimming	$0	$0	$2	$0
Lapping	$14	$725	$194	$155
Inspect - Microscopy	$2	$0	$10	$1
Inspect - Thermal Cond'vity	$2	$0	$10	$1
Total	$10,771	$2,242	$748	$11,267
Total =	$25,028			

##########

Appendix C - The Combustion Flame Model

COMBUSTION FLAME CVD DIAMOND TECHNICAL COST MODEL - LONG TERM
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

Revision Date: 9/94

PRODUCT SPECIFICATIONS

Torch Type	Single Nozzle		
Part Name	4 in. substrate		NAME
Wafer Diameter	10.40	cm	DIAM
Finished Wafer Thickness	1,000	um	THIK
Thermal Conductivity	1,000	W/mK	THERMCON
Annual Production Volume	1.0	(000/yr)	NUM
Length of Production Run	5	yrs	PLIFE

PROCESS RELATED FACTORS - SURFACE PREPARATION

Process In Use?	1	[1=Y 0=N]	USE1
Dedicated Investment	0	[1=Y 0=N]	DED1
Process Yield	95.0%		YLD1
Average Equipment Downtime	20.0%		DOWN1
Direct Laborers Per Station	0.50		NLAB1
Substrate Material	11	[menu #]	MATL1
Pieces Per Batch	20	pcs/batch	PCS1
Process Time	60	min/batch	PTIME1
Building Space Requirement	250	sqft/sta	FLR1

PROCESS RELATED FACTORS - DEPOSITION

Process In Use?	1	[1=Y 0=N]	USE2
Dedicated Investment	0	[1=Y 0=N]	DED2
Process Yield	90.0%		YLD2
Average Equipment Downtime	15.0%		DOWN2
Direct Laborers	0.40	/sta	NLAB2
Machine Power	2	kW	POW2
Machine Load/Unload Time	120	min/batch	PTIME2
Available Deposition Time	8,640	hrs/yr	DAYHR2
Heat Removal via Substrate	50.0%	of total	HTRMV2
Coolant Temp. Rise	50	C	TEMP2
Heat Capacity of Coolant	1.0	cal/g/C	CP2
Building Space Requirement	1,500	sqft/sta	FLR2
Acetylene:Oxygen Ratio (R)	1.02	[1.02<x<1.1]	GRATIO2
Oxygen	26	[menu #]	GASA2
Acetylene	20	[menu #]	GASB2
Oxygen Recycle Rate	0.0%		RECYC2A
Carrier Gas Recycle Rate	0.0%		RECYC2B
Gas Recycle Equipment Cost	NA	total	MCH2A
Substrate:Duct Area Ratio	3.00	[1<x<=4]	SUBDUC2
Substrate Distance:Duct Diam	1.00	[0<x<=10]	L:D2

PROCESS RELATED FACTORS - ETCHING

Process In Use?	1	[1=Y 0=N]	USE3

GAS DATABASE

#	Gas	Source	Purity	Price $/SCM	No. of Carbons	Req Amt SCM	Mo.Tank Rental	Price Update
0	None			$0.00	0.00	0E+00		
1	Liq Hydrogen	Airco	99.998%	$0.34	0.00	3E+04	$2,070	1/93
2	Liq Hydrogen	Airco	99.998%	$0.32	0.00	4E+04	$2,970	1/93
3	Liq Hydrogen	Airco	99.998%	$0.30	0.00	1E+05	$4,500	1/93
4	Liq Argon	Airco	99.998%	$1.41	0.00	8E+03	$590	1/93
5	Liq Argon	Airco	99.998%	$1.32	0.00	2E+04	$820	1/93
6	Liq Argon	Airco	99.998%	$1.29	0.00	3E+04	$1,300	1/93
7	Hydrogen	MG Ind.	99.9999%	$29.86	0.00	0E+00		1/93
8	Hydrogen	MG Ind.	99.9996%	$40.61	0.00	0E+00		1/93
9	Hydrogen	MG Ind.	99.999%	$10.28	0.00	0E+00		1/93
10	Hydrogen	Air Prod.	99.95%	$1.59	0.00	0E+00		1/93
11	Argon	MG Ind.	99.9999%	$33.09	0.00	0E+00		1/93
12	Argon	Air Prod.	99.9997%	$37.33	0.00	0E+00		1/93
13	Argon	Air Prod.	99.999%	$11.74	0.00	0E+00		1/93
14	Argon	Air Prod.	99.997%	$2.03	0.00	0E+00		1/93
15	Methane	Air Prod.	99.99%	$21.99	1.00	0E+00		1/93
16	Methane	Air Prod.	99%	$13.76	1.00	0E+00		1/93
17	Methane	Air Prod.	93%	$4.93	1.00	0E+00		1/93
18	Acetylene	Air Prod.	99.6%	$9.70	2.00	0E+00		1/93
19	Acetylene	Air Prod.	98.5%	$5.30	2.00	0E+00		1/93
20	Acetylene	Pipeline	98.5%	$2.00	2.00	0E+00		1/93
21	Helium	Air Prod.	99.9995%	$15.90	0.00	0E+00		1/93
22	Helium	Air Prod.	99.995%	$4.77	0.00	0E+00		1/93
23	Nitrogen	Air Prod.	99.9996%	$45.50	0.00	0E+00		1/93
24	Nitrogen	MG Ind.	99.999%	$9.23	0.00	0E+00		1/93
25	Nitrogen	Air Prod.	99.998%	$1.24	0.00	0E+00		1/93
26	Liq Oxygen	Air Prod.	99.5%	$0.21	0.00	1E+00	$350	1/93
27	Oxygen	Air Prod.	99.5%	$0.58	0.00	0E+00		1/93

SUBSTRATE DATABASE

#	Substrate	Source	Price $/ea	Thick um	Diam cm	Etch um/min	Life use#	Price Update
0	None		$0.00	1	1.00	1.00	1.00	
1	Silicon	Si-Tech	$2.65	1270.00	5.08	20.00	1	1/93
2	Silicon	Si-Tech	$3.50	1270.00	7.62	20.00	1	1/93
3	Silicon	Si-Tech	$6.25	1270.00	10.16	20.00	1	1/93
4	Silicon	Si-Tech	$9.70	1270.00	12.70	20.00	1	1/93
5	Silicon	Si-Tech	$18.60	1270.00	15.24	20.00	1	1/93
6	Silicon	Si-Tech	$57.95	1270.00	20.32	20.00	1	1/93
7	Silicon	Si-Tech	$4.35	3810.00	5.08	20.00	1	1/93
8	Silicon	Si-Tech	$8.15	3810.00	7.62	20.00	1	1/93
9	Silicon	Si-Tech	$14.50	3810.00	10.16	20.00	1	1/93
10	Silicon	Si-Tech	$22.65	3810.00	12.70	20.00	1	1/93

Dedicated Investment	0	[1=Y 0=N]	DED3
Process Yield	99.0%		YLD3
Average Equipment Downtime	10.0%		DOWN3
Direct Laborers Per Station	1.00		NLAB3
Load/Unload and Rinse Time	30.00	min/batch	PTIME3
Pieces Per Batch	20		PCS3
Machine Cost	$6,000	/sta	MCH3
Etchant Cost	$70	/liter	ETCH3A
Etchant Disposal Cost	$30	/liter	ETCH3B
Machine Etchant Capacity	1.00	l/batch	CAP3
Machine Power	0.00	kW	POW3
Building Space Requirement	100	sqft/sta	FLR3

PROCESS RELATED FACTORS - LASER TRIMMING

Process In Use?	1	[1=Y 0=N]	USE4
Dedicated Investment	0	[1=Y 0=N]	DED4
Process Yield	99.0%		YLD4
Average Equipment Downtime	10.0%		DOWN4
Direct Laborers Per Station	1.00		NLAB4
Machine Cost	$6,000	/sta	MCH4
Trimming Rate	1.00	cm/s	RATE4
Machine Power	5.00	kW	POW4
Building Space Requirement	100	sqft/sta	FLR4

PROCESS RELATED FACTORS - LAPPING

Process In Use?	1	[1=Y 0=N]	USE5
Dedicated Investment	0	[1=Y 0=N]	DED5
Process Yield	90.0%		YLD5
Average Equipment Downtime	15.0%		DOWN5
Direct Laborers Per Station	0.25		NLAB5
Lapped Material Removal	10.0%	by wgt	TLAP5
No of Lapping Steps	2		LAPS5
Pieces Per Batch	5		PCS5
Load/Unload and Clean Wafers	40.00	min/batch	PTIME5
Average Lapping Rate	1.0	um/hr	RATE5
Lapping Slurry Cost	$53	/liter	LAPSL5
Lapping Slurry Usage Rate	0.50	liter/hr	LAPR5
Lapping Plate Life	320	hrs	PLAL5
Available Lapping Time	8,640	hrs/yr	DAYHR5
Building Space Requirement	400	sqft/sta	FLR5
			/rnd

PROCESS RELATED FACTORS - INSPECTION - MICROSCOPY

Process In Use?	1	[1=Y 0=N]	USE6
Dedicated Investment	0	[1=Y 0=N]	DED6
Process Yield	95.0%		YLD6
Average Equipment Downtime	5.0%		DOWN6
Direct Laborers Per Station	1.00		NLAB6

11	Silicon	Si-Tech	$43.45	3810.00	15.24	20.00	1	1/93
12	Silicon	Si-Tech	$135.20	3810.00	20.32	20.00	1	1/93
13	Silicon	Si-Tech	$6.85	6350.00	5.08	20.00	1	1/93
14	Silicon	Si-Tech	$12.80	6350.00	7.62	20.00	1	1/93
15	Silicon	Si-Tech	$22.75	6350.00	10.16	20.00	1	1/93
16	Silicon	Si-Tech	$35.55	6350.00	12.70	20.00	1	1/93
17	Silicon	Si-Tech	$68.30	6350.00	15.24	20.00	1	1/93
18	Silicon	Si-Tech	$212.45	6350.00	20.32	20.00	1	1/93
19	Molybdenum	Phil. Elmet	$3.90	254	5.08	10.00	1	1/93
20	Molybdenum	Phil. Elmet	$8.20	254	10.16	10.00	1.00	1/93
21	Molybdenum	Phil. Elmet	$14.50	254	15.24	10.00	1.00	1/93
22	Molybdenum	Schwarzkopf Te	$25.35	254	20.32	10.00	1.00	1/93
23	Molybdenum	Schwarzkopf Te	$4.80	508.00	5.08	10.00	4	1/93
24	Molybdenum	Schwarzkopf Te	$14.75	508.00	10.16	10.00	4	1/93
25	Molybdenum	Schwarzkopf Te	$24.30	508.00	15.24	10.00	4	1/93
26	Molybdenum	Schwarzkopf Te	$37.10	508.00	20.32	10.00	4	1/93
27	Molybdenum	Phil. Elmet	$9.15	1524.00	5.08	10.00	20	1/93
28	Molybdenum	Schwarzkopf Te	$27.60	1524.00	10.16	10.00	20	1/93
29	Molybdenum	Schwarzkopf Te	$52.25	1524.00	15.24	10.00	20	1/93
30	Molybdenum	Schwarzkopf Te	$85.25	1524.00	20.32	10.00	20	1/93
31	Molybdenum	Schwarzkopf Te	$14.75	2286.00	5.08	10.00	32.00	1/93
32	[illegible]	ybdenumSchwarzkopf Te	$36.00	2286.00	10.16	10.00	32.00	1/93
33	[illegible]	olybdenumSchwarzkopf Te	$69.00	2286.00	15.24	10.00	32.00	1/93
34	[illegible]	ybdenumSchwarzkopf Te	$113.50	2286.00	20.32	10.00	32.00	1/93
35	[illegible]	olybdenumSchwarzkopf Te	$18.50	3175.00	5.08	10.00	46.00	1/93
36	Molybdenum	Schwarzkopf Te	$46.75	3175.00	10.16	10.00	46.00	1/93
37	Molybdenum	Schwarzkopf Te	$90.50	3175.00	15.24	10.00	46.00	1/93
38	Molybdenum	Schwarzkopf Te	$149.00	3175.00	20.32	10.00	46.00	1/93
39	Tungsten	Schwarzkopf Te	$7.75	254	5.08	10.00	1	1/93
40	Tungsten	Schwarzkopf Te	$24.50	254	10.16	10.00	1.00	1/93
41	Tungsten	Schwarzkopf Te	$50.00	254	15.24	10.00	1.00	1/93
42	Tungsten	Schwarzkopf Te	$79.25	254	20.32	10.00	1.00	1/93
43	Tungsten	Schwarzkopf Te	$10.00	508.00	5.08	10.00	4.00	1/93
44	Tungsten	Schwarzkopf Te	$35.10	508.00	10.16	10.00	4.00	1/93
45	Tungsten	Schwarzkopf Te	$67.00	508.00	15.24	10.00	4.00	1/93
46	Tungsten	Schwarzkopf Te	$109.20	508.00	20.32	10.00	4.00	1/93
47	Tungsten	Schwarzkopf Te	$50.00	1524.00	5.08	10.00	20.00	1/93
48	Tungsten	Schwarzkopf Te	$112.00	1524.00	10.16	10.00	20.00	1/93
49	Tungsten	Schwarzkopf Te	$317.00	1524.00	15.24	10.00	20.00	1/93
50	Tungsten	Schwarzkopf Te	$422.00	1524.00	20.32	10.00	20.00	1/93
51	Tungsten	Schwarzkopf Te	$60.00	3175.00	5.08	10.00	46.00	1/93
52	Tungsten	Schwarzkopf Te	$161.25	3175.00	10.16	10.00	46.00	1/93
53	Tungsten	Schwarzkopf Te	$521.30	3175.00	15.24	10.00	46.00	1/93
54	Tungsten	Schwarzkopf Te	$687.00	3175.00	20.32	10.00	46.00	1/93
55								

##########

Average Inspection Time	15.00	min/batch	PTIME6
Percent Inspection	100%		INSP6
Machine Cost	$50,000	/sta	MCH6
Machine Power	0.10	kW	POW6
Building Space Requirement	50	sqft/sta	FLR6

PROCESS RELATED FACTORS - INSPECTION - THERMAL CONDUCTIVITY

Process In Use?	1	[1=Y 0=N]	USE7
Dedicated Investment	0	[1=Y 0=N]	DED7
Process Yield	95.0%		YLD7
Average Equipment Downtime	5.0%		DOWN7
Direct Laborers Per Station	1.00		NLAB7
Average Inspection Time	15.00	min/batch	PTIME7
Percent Inspection	100%		INSP7
Machine Cost	$50,000	/sta	MCH7
Machine Power	0.10	kW	POW7
Building Space Requirement	50	sqft/sta	FLR7

OPTIONAL INPUTS

	override	estimate		
Surface Preparation				
Machine Cost	$0	$65,774	/sta	OMCH1
Machine Power	0.0	19.2	kW	OPOW1
Deposition				
Duct Area	0.00	28.32	sqcm	ODAREA2
Total Gas Flow Rate	0	564	slm	OTFLOW2
Deposition Rate	0.00	0.50	g/hr	ODRATE2
Deposition Equipment Cost	$0	$55	k$/sta	OMCH2
Etching				
Process Cycle Time	0.00	0.18	hrs	OCTIME3
Chemical Requirement	$0	$5.00	/pc	OCHEM3
Laser Trimming				
Process Cycle Time	0.00	0.01	hrs	OCTIME4
Lapping				
Lapping Time	0.00	111.11	hrs	OCTIME5
Lapping Plate Cost	$0	$869	/ea	OWHEEL5
Lapping Machine Cost	$0	$11,939	/sta	OMCH5
Lapping Machine Power	0.00	4.2	kW	OPWR5

EXOGENOUS COST FACTORS

Direct Wages	$13.33	/hr	WAGE	
Indirect Salary	$50,000	/yr	SALARY	
Indirect:Direct Labor Ratio	1.00		ILAB	
Benefits on Wage and Salary	35.0%		BENI	
Working Days per Year	360.00		DAYS	
Working Hours per Day (*)	8.00	hr	HRS	* exc. dep. & lap
Capital Recovery Rate	10%		CRR	
Capital Recovery Period	5.00	yrs	ELIFE	
Building Recovery Life	20.00	yrs	BLIFE	
Working Capital Period	3.00	months	WCP	
Price of Electricity	$0.050	/kWh	ELEC	

Price of Natural Gas	$6.50 /MBTU	GAS
Price of Building Space	$100 /sqft	PBLD
Price of Cooling Water	$0.03 /100 gal	WATER
Auxiliary Equipment Cost	15.0%	AUX
Equipment Installation Cost	35.0%	INST
Maintenance Cost	8.0%	MNT

REGRESSION CONSTANTS, COEFFICIENTS, AND EXPONENTS

-Surface Preparation-		
Machine Cost Constant	1,334	MCH1A
Machine Cost Capacity Coef	3,222	MCH1B
Machine Power Constant	-0.75	PWR1A
Machine Power Capacity Coef	1.00	PWR1B
-Deposition-		
Diamond Density (g/cc)	3.51	DENS
[H]/[CH3] Quality Constant	133	QUAL3
[H]/[CH3] Quality Coefficient	164	QUAL3A
[H]/[CH3] Qual. GRatio Exp.	20	QUAL3B
[H]/[CH3] Qual. QMult. Exp.	1.77	QUAL3C
Diameter Therm.Cond. Coefficient	8253.58	DIAM2A
Diameter Therm. Cond. Exponent	-1.02	DIAM2B
QMult. Coefficient	0.00	QM2A
QMult. Tc Exponent	4.07	QM2B
[H]/[CH3] Qual. Baseline	10.15	QUAL3D
Vol. Expansion Factor Const.	4.76	VEFA2
Vol. Expansion Factor Coeff.1	4.46	VEFB2
Vol. Expansion Factor Coeff.2	-1.83	VEFC2
Atomic Hydrogen Coeff.	0.00	HCA2
Atomic Hydr. Strain Rate Exp.	0.79	HCB2
Atomic Hydr. Gas Ratio Exp.	-5.14	HCC2
H/CH3 Ratio Thermcon Coeff.	0.00	HRA2
H/CH3 Ratio Thermcon Exp.	4.07	HRB2
Growth Rate Coefficient 1	1.80E+11	GRA2
Growth Rate Coefficient 2	5.00E-09	GRB2
Enthalpy (kcal/mol) - C2H2	54.19	HF2A
Enthalpy (kcal/mol) - CO	-26.42	HF2B
Machine Cost Wafer Area Coef	161.46	MCH2Y
Machine Cost Area Exponent	1.00	MCH2Z
Machine Cost Area Constant	41,667	MCH2X
-Etching-		

-Lapping-		
Machine Cost Constant	2,719	MCH5A
Machine Cost Capacity Coef	1,844	MCH5B
Machine Power Constant	-0.75	PWR5A
Machine Power Capacity Coef	1.00	PWR5B
Tool Cost Constant	771.00	TOOL5A
Tool Cost Capacity Coef	0.92	TOOL5B
Tool Cost Capacity Exponent	2.90	TOOL5C

##########

IBIS ASSOCIATES, INC.
TECHNICAL COST MODEL (C) 1993
RESTRICTED RIGHTS LEGEND

Use, duplication, or disclosure by the Government is subject to
restrictions as set forth in subparagraph (c)(1)(ii) of the Rights in
Technical Data and Computer Software clause at DFARS 252.227-7013

##########

COMBUSTION CVD TCM: SURFACE PREPARATION
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$63.84	$63,836	94.1%	
Direct Labor Cost	$0.83	$826	1.2%	
Utility Cost	$0.07	$70	0.1%	
FIXED COST ELEMENTS				
Equipment Cost	$0.63	$629	0.9%	$98,661
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.04	$40	0.1%	$25,000
Maintenance Cost	$0.32	$315	0.5%	
Overhead Labor Cost	$0.80	$797	1.2%	
Cost of Capital	$1.33	$1,326	2.0%	
TOTAL FABRICATION COST	$67.84	$67,840	100.0%	$123,661

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO1
Cumulative Yield	68.1%		CYLD1
Effective Production Volume	1,469	/yr	ENUM1
Substrate Area	84.9	sq cm	AREA1
New Substrate Cost	$43.45	/pc	SUB1
Substrate Useful Life	1.00	cycle	LIFE1
Process Cycle Time	3	min/pc	CTIME1
Runtime for One Station	3%		RTIME1
Number of Parallel Stations	0.03		NSTAT1
Energy Requirement	0.959	kWh/pc	ENERGY1
Building Space/Station	250	sqft	SPACE1
Machine Cost	$65,774	/sta	MCH1
Machine Power	19.2	kW	POW1
Installed Equipment Cost	$88,795	/sta	IEQUIP1
Auxiliary Equipment Cost	$9,866	/sta	AEQUIP1
Equipment Annuity	$802	/yr	EINT1
Tooling Annuity	$0	/yr	TINT1
Building Annuity	$92	/yr	BINT1
Working Annuity	$66,945	/yr	WINT1

##########

COMBUSTION CVD TCM: DEPOSITION
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$3,474.93	$3,474,927	64.7%	
Direct Labor Cost	$803.12	$803,124	14.9%	
Utility Cost	$19.99	$19,992	0.4%	
FIXED COST ELEMENTS				
Equipment Cost	$214.50	$214,503	4.0%	$1,079,965
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$96.83	$96,827	1.8%	$1,950,000
Maintenance Cost	$240.72	$240,725	4.5%	
Overhead Labor Cost	$258.21	$258,206	4.8%	
Cost of Capital	$266.55	$266,551	5.0%	
TOTAL FABRICATION COST	$5,374.85	$5,374,854	100.0%	$3,029,965
	$63.27 /sqcm			

INTERMEDIATE CALCULATIONS

Process In Use	1	[1=Y 0=N]	PRO2
Cumulative Yield	71.6%		CYLD2
Effective Production Volume	1,396	/yr	ENUM2
Machine Power	2	kW	DAPOW2
Duct Area (A inf.)	28.32	sqcm	DAREA2
Duct Diameter	6.00	cm	DDIAM2
Quality Multiplier	1.07	[0.4<x<5]	QMULT2
Strain Rate (a)	412	1/sec	STRN2A
Atomic Hydrogen Concentr.	2.82E-09	mol/cc	HCONC2
H/CH3 Ratio at Substrate	10.89		HRATIO2
Methyl (CH3) Concentr.	2.59E-10	mol/cc	MCONC2
Volume Expansion Factor	7.40		VOLEF2A
Gas Velocity	2,458	cm/s	SPEED2A
Total Gas Flow Rate	564	slm	TFLOW2A
Acetylene Flow Rate	285	slm	CFLOW2A
Oxygen Gas Flow Rate	279	slm	XFLOW2A
Mass of Diamond Deposited	33.13	g	MASS2
Linear Deposition Rate	16.9	um/hr	LINDEP2
Mass Deposition Rate	0.5	g/hr	MASDEP2
Deposition Time	65.93	hrs	CTIMEB2
Machine Setup Time	2.00	hrs	CTIMEA2
Runtime for One Station	1291%		RTIME2
Number of Parallel Stations	12.91		NSTAT2
Total Oxygen Gas Volume	1,105	SCM/pc	XGAS2
Total Carbon Gas Volume	1,127	SCM/pc	CARGAS2
Oxygen Gas Cost	$232	/pc	COSTA2
Acetylene Gas Cost	$2,255	/pc	COSTB2
Carbon Capture Factor	0.0030%		CCF2

Combustion Enthalpy Change	-447	kJ/mol	ENTH2
Mass Flow of C2H2 and O2	0.38	mol/sec	MFLOW2
Combustion Eff. Power	172	kW	CPOW2
Cooling Water Flow Rate	6.5	gal/min	WATER2
Cooling Water Requirement	25,768	gal/pc	COOL2
Energy Requirement	132	kWh/pc	ENERGY2
Building Space/Station	1,500	sqft	SPACE2
Recycle Equipment Cost	$0	/sta	REC2
Liquid Oxygen Tank Rental	$350	/mo/tank	XRENT2
Gas Storage Equipment Rent	$4,200	/year	GTANK2
Machine Cost	$55,383	/sta	MCH2B
Installed Equipment Cost	$74,767	/sta	IEQUIP2
Auxiliary Equipment Cost	$8,307	/sta	AEQUIP2
Equipment Annuity	$273,453	/yr	EINT2
Tooling Annuity	$0	/yr	TINT2
Building Annuity	$224,257	/yr	BINT2
Working Annuity	$4,877,144	/yr	WINT2

##########

COMBUSTION CVD TCM: ETCHING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$3.98	$3,980	29.0%	
Direct Labor Cost	$4.62	$4,616	33.7%	
Utility Cost	$0.00	$0	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$0.16	$160	1.2%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.04	$45	0.3%	$10,000
Maintenance Cost	$0.14	$135	1.0%	
Overhead Labor Cost	$4.45	$4,452	32.5%	
Cost of Capital	$0.32	$323	2.4%	
TOTAL FABRICATION COST	$13.71	$13,712	100.0%	$19,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO3
Cumulative Yield	79.6%		CYLD3
Effective Production Volume	1,256	/yr	ENUM3
Total Etched Thickness	3,810	um	ETHIK3
Average Etchant Rate	20.00	um/min	ERATE3
Process Cycle Time	0.18	hrs/pc	CTIME3
Runtime for One Station	9%		RTIME3
Number of Parallel Stations	0.09		NSTAT3
Chemical Requirement	$5.00	/pc	CHEM3
Energy Requirement	0	kWh/pc	ENERGY3
Building Space/Station	100	sq ft	SPACE3
Installed Equipment Cost	$8,100	/sta	IEQUIP3
Auxiliary Equipment Cost	$900	/sta	AEQUIP3
Equipment Annuity	$204	/yr	EINT3
Tooling Annuity	$0	/yr	TINT3
Building Annuity	$103	/yr	BINT3
Working Annuity	$13,405	/yr	WINT3

##########

COMBUSTION CVD TCM: LASER TRIMMING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$0.23	$226	47.5%	
Utility Cost	$0.00	$3	0.6%	
FIXED COST ELEMENTS				
Equipment Cost	$0.01	$8	1.6%	$9,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.00	$2	0.5%	$10,000
Maintenance Cost	$0.01	$7	1.4%	
Overhead Labor Cost	$0.22	$218	45.8%	
Cost of Capital	$0.01	$13	2.6%	
TOTAL FABRICATION COST	$0.48	$475	100.0%	$19,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO4
Cumulative Yield	80.4%		CYLD4
Effective Production Volume	1,244	/yr	ENUM4
Process Cycle Time	0.01	hrs/pc	CTIME4
Runtime for One Station	0%		RTIME4
Number of Parallel Stations	0.00		NSTAT4
Energy Requirement	0	kWh/pc	ENERGY4
Building Space/Station	100	sq ft	SPACE4
Installed Equipment Cost	$8,100	/sta	IEQUIP4
Auxiliary Equipment Cost	$900	/sta	AEQUIP4
Equipment Annuity	$10	/yr	EINT4
Tooling Annuity	$0	/yr	TINT4
Building Annuity	$5	/yr	BINT4
Working Annuity	$460	/yr	WINT4

##########

COMBUSTION CVD TCM: LAPPING
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$725.01	$725,009	66.7%	
Direct Labor Cost	$146.58	$146,579	13.5%	
Utility Cost	$5.79	$5,786	0.5%	
FIXED COST ELEMENTS				
Equipment Cost	$13.50	$13,503	1.2%	$71,634
Tooling Cost	$74.41	$74,415	6.8%	$372,073
Building Cost	$7.54	$7,540	0.7%	$160,000
Maintenance Cost	$17.47	$17,465	1.6%	
Overhead Labor Cost	$47.13	$47,125	4.3%	
Cost of Capital	$49.83	$49,828	4.6%	
TOTAL FABRICATION COST	$1,087.25	$1,087,251	100.0%	$603,707

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO5
Cumulative Yield	81.2%		CYLD5
Effective Production Volume	1,231	/yr	ENUM5
Thickness of Material Lapped	111.11	um	HLAP5
Setup Time	1.33	hrs/batch	CTIME5A
Lapping Time	111.11	hrs/batch	CTIME5B
Runtime for One Station	377%		RTIME5
Number of Parallel Stations	3.77		NSTAT5
Lapping Plate Cost	$869	/ea	PLA5
Lapping Plate Life	14	pcs	WHEEL5
Number of Plates Required	428.00		PLAT5
Lapping Slurry Consumption	11.11	l/pc	GRIT5
Machine Power	4.2	kW	PWR5
Energy Requirement	94	kWh/pc	ENERGY5
Machine Cost	$11,939	/sta	MCH5
Building Space/Station	400	sq ft	SPACE5
Installed Equipment Cost	$16,118	/sta	IEQUIP5
Auxiliary Equipment Cost	$1,791	/sta	AEQUIP5
Equipment Annuity	$17,214	/yr	EINT5
Tooling Annuity	$94,865	/yr	TINT5
Building Annuity	$17,463	/yr	BINT5
Working Annuity	$957,709	/yr	WINT5

##########

COMBUSTION CVD TCM: INSPECTION - MICROSCOPY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$5.25	$5,249	39.9%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.52	$1,519	11.6%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.03	$25	0.2%	$5,000
Maintenance Cost	$0.65	$648	4.9%	
Overhead Labor Cost	$5.06	$5,062	38.5%	
Cost of Capital	$0.63	$634	4.8%	
TOTAL FABRICATION COST	$13.14	$13,138	100.0%	$80,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO6
Cumulative Yield	90.3%		CYLD6
Effective Production Volume	1,108	/yr	ENUM6
Process Cycle Time	0.25	hrs	CTIME6
Runtime for One Station	10%		RTIME6
Number of Parallel Stations	0.10		NSTAT6
Energy Requirement	0	kWh/pc	ENERGY6
Building Space/Station	50	sq ft	SPACE6
Installed Equipment Cost	$67,500	/sta	IEQUIP6
Auxiliary Equipment Cost	$7,500	/sta	AEQUIP6
Equipment Annuity	$1,936	/yr	EINT6
Tooling Annuity	$0	/yr	TINT6
Building Annuity	$59	/yr	BINT6
Working Annuity	$11,143	/yr	WINT6

##########

COMBUSTION CVD TCM: INSPECTION - THERMAL CONDUCTIVITY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$0.00	$0	0.0%	
Direct Labor Cost	$4.99	$4,986	38.7%	
Utility Cost	$0.00	$1	0.0%	
FIXED COST ELEMENTS				
Equipment Cost	$1.52	$1,519	11.8%	$75,000
Tooling Cost	$0.00	$0	0.0%	$0
Building Cost	$0.03	$25	0.2%	$5,000
Maintenance Cost	$0.65	$648	5.0%	
Overhead Labor Cost	$5.06	$5,062	39.3%	
Cost of Capital	$0.63	$629	4.9%	
TOTAL FABRICATION COST	$12.87	$12,871	100.0%	$80,000

INTERMEDIATE CALCULATIONS

Process In Use	1.00	[1=Y 0=N]	PRO7
Cumulative Yield	95.0%		CYLD7
Effective Production Volume	1,053	/yr	ENUM7
Process Cycle Time	0.25	hrs	CTIME7
Runtime for One Station	10%		RTIME7
Number of Parallel Stations	0.10		NSTAT7
Energy Requirement	0	kWh/pc	ENERGY7
Building Space/Station	50	sq ft	SPACE7
Installed Equipment Cost	$67,500	/sta	IEQUIP7
Auxiliary Equipment Cost	$7,500	/sta	AEQUIP7
Equipment Annuity	$1,936	/yr	EINT7
Tooling Annuity	$0	/yr	TINT7
Building Annuity	$59	/yr	BINT7
Working Annuity	$10,877	/yr	WINT7

##########

COMBUSTION CVD TCM: COST SUMMARY
IBIS ASSOCIATES, INC. Copyright (c) 1991 v4.0

VARIABLE COST ELEMENTS	per piece	per year	percent	investment
Material Cost	$4,267.75	$4,267,752	65.0%	
Direct Labor Cost	$965.61	$965,606	14.7%	
Utility Cost	$25.85	$25,854	0.4%	
FIXED COST ELEMENTS				
Equipment Cost	$231.84	$231,840	3.5%	$1,418,260
Tooling Cost	$74.41	$74,415	1.1%	$372,073
Building Cost	$104.50	$104,505	1.6%	$2,165,000
Maintenance Cost	$259.94	$259,943	4.0%	
Overhead Labor Cost	$320.92	$320,923	4.9%	
Cost of Capital	$319.30	$319,303	4.9%	
TOTAL FABRICATION COST	$6,570.14	$6,570,142	100.0%	$3,955,333
	$77.34 /sqcm			

SUMMARY INFORMATION

Part Name	4 in. substrate
Total Direct Laborers	10.70 /shift
Total Floor Space	21,650 sqft
Total Capital Investment	$4.0 MM
Area Cost	$77.34 /sqcm
Cost Per Carat	*$44.07 /ct*

Operation	Equipment	Material	Labor	Other
Surface Preparation	$1	$64	$2	$2
Deposition	$215	$3,475	$1,061	$624
Etching	$0	$4	$9	$1
Laser Trimming	$0	$0	$0	$0
Lapping	$14	$725	$194	$155
Inspect - Microscopy	$2	$0	$10	$1
Inspect - Thermal Cond'vity	$2	$0	$10	$1
Total	$232	$4,268	$1,287	$784
Total =	$6,570			

##########