Study of the Feasibility of Introducing Automation into Critical Manufacturing Processes for Producing Mercury Cadmium Telluride Detector Arrays

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Final Report

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Prepared for
U.S. Army
Director--Night Vision and Electro Optics Laboratory
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
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Abstract

The task was divided into two phases.

Phase I was a systems study of the existing process and recommendation of a plan for automation. Since this process is complex, with over 100 steps, three options were proposed for implementation:

- Option 1 Automation of eight critical subprocesses at a Laboratory level.
- Option 2 Automation of five critical subprocesses in an existing production line.
- Option 3 Automation of the complete process in a new facility.

Approximate costs were prepared for each of these options as required by the contract.

Phase II was to implement a near term demonstration of automation in infrared fabrication. This was directed to the development of a more efficient way for the measurement of the crystal axis orientation of cadmium telluride substrates. A breadboard model of a toroidal laser scanner with pattern recognition was developed. This instrument will reduce the mapping time for a substrate from 4 hours to 4 minutes. The scanner can identify three different crystal orientations and characterize four others in a fraction of a second. This can improve the yield by 300 %. A goniometric mount controlled by a dedicated computer is planned for fully automating this inspection process.

Key Words: Automation; Clean Room Applications; Crystal Axis Measurement; Fabrication Processes; Infrared Sensor Arrays; Laser Scanner, Mercury Cadmium Telluride Detectors; Robotics.

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FINAL REPORT ON STUDY OF
AUTOMATION OF HgCdTe ARRAY
FABRICATION PROCESS

Phase I--Automation Study of the Process

I. Overview of this Study

This study was initiated to explore the feasibility of introducing automation into the manufacture of mercury cadmium telluride (HgCdTe) arrays for detecting infrared radiation. The present fabrication technology is changing very rapidly, driven by the need for larger arrays, smaller detectors and lower costs. Due to the critical nature of the present fabrication process and its similarity to semiconductor processing, much of this work is conducted in a clean room environment. The continuing problems of reduced yields in this processing have been attributed in part to particle contamination.

Recent advances in the use of robotics and other automation in the clean room have resulted in notable reductions in particle counts. This study was intended to explore and define the manufacturing processes which would be most suitable for automation and provide the greatest return in improved yield and reduced time and labor.

The goal of this program was to study the feasibility of introducing automated concepts into the material growth and fabrication processes necessary to produce I.R. detector arrays. In addition the program was to develop the following:

A. A conceptual block diagram of the major elements of an automated infrared material and array fabrication line.

B. A listing of non-contact, automated inspection procedures which detect visual material flaws and evaluate electrical parameters.

C. A recommendation of available robotic technology which can be incorporated into infrared processing, and recommendation of specific technology which requires further development.

D. An estimate of the cost and time schedule for implementation of an automated infrared fabrication process.

E. An implementation of a near term demonstration of automation in infrared detector fabrication.

The program was initiated January 13, 1985 to run until September 30, 1985. An extension to December 31, 1985 was granted for the final report.

II. General Discussion.

The first step in implementing this study was to acquire a thorough background in the process for manufacturing HgCdTe infrared detectors. This includes the technology for bulk grown HgCdTe (first generation) as well as the epitaxial layer detectors grown on cadmium telluride substrates (second generation). Since some of these techniques are still under development, and the technology is rapidly changing, it was necessary to acquire this background as quickly as possible. This was done by visits to the Night Vision Laboratory at Fort Belvoir Va., to vendors presently engaged in the development and production of these detectors, and to technical conferences with scientists working in this field at NBS. New techniques for non-destructive testing and evaluation were explored and instrumentation for spectral measurements was reviewed.

The processes for Liquid Phase Epitaxy (LPE), Vapor Phase Epitaxy (VPE) and Molecular Beam Epitaxy (MBE) were discussed and the equipment for performing these processes was examined for suitability to automation.

The nature of the defects which reduce yields was examined and reviewed. Discussions were held with scientists at NBS on the feasiblity of relating defects to the performance of these detectors using the following types of measurements:

XPS - X-ray Photo Emission Spectroscopy

UPS - Ultra Violet Photo Emission Spectroscopy

SIMS - Secondary Ion Mass Spectroscopy

TPD - Temperature Programmed Desorption

LEED - Low Energy Electron Diffraction

ISS - Low Energy Ion Spectroscopy

AES - Auger Electron Spectroscopy

FTIR - Spectrophotometry

Automated Spectroscopic Ellipsometry

Ultrasonic Non-Destructive Testing

Ultrasonic Surface Imaging of Elastic Moduli and Near Surface Defects.

Utrasonic Tomographic Imaging of Internal Crystal Structure.

While some of these scientific techniques are already being investigated at the Night Vision Laboratory, the conferences, exposure to this equipment, and expertise of the NBS scientific staff have been very valuable in identifying new testing techniques which may be applicable to this project.

III. Technical Approach.

A. Feasibility Study Report

This phase was implemented by reviewing of R and D reports in this field furnished by the Night Vision Laboratory, References 1, 2, 3, 9, 10, 11, and 12. These reports supplemented by visits and field trips from January 1985 to November 1985 (Appendix 2) provided basic familiarization with infrared detector fabrication technology and the applicable clean room robotics technology.

B. Analysis of the HgCdTe Fabrication Process

1. History of HgCdTe Sensor Technology

Early infrared detector technology used large HgCdTe detectors cooled in liquid nitrogen to get usable D* values (signal to noise ratio). The detectors were usually used to sense radiation levels in spectrophotometric instrumentaion. With the need for infrared sensors for imaging, a technology for spatial scanning was developed to get two-dimensional information. These systems were implemented by using two-dimensional mechanical scanning techniques with relatively large I.R. detectors.

For this reason, early I.R. scanners were bulky and limited in resolution capability. With the need for higher resolution it became necessary to reduce the size of the HgCdTe detectors.

As the size was reduced the area was reduced. This resulted in a reduction in the signal level. Fortunately the noise is also proportional to the area so that the signal to noise ratio is maintained in the smaller I.R. detectors.

A further reduction in the size of these scanners is now feasible using detector arrays with a single opto-mechanical system to provide the second coordinate. With this history it is easy to understand why a size reduction of approximately 250 times in individual sensor dimensions presents such a challenge to technology.

a) First Generation I.R. Detectors

The original detectors were generally fabricated from bulk grown HgCdTe crystals. This type of detector is generally considered as first generation technology. More advanced configurations for these I.R. detectors have been in development for several years. In general they have consisted of an epitaxial layer of HgCdTe grown on a CdTe single crystal substrate. The new technology has generally been referred to as second generation technology.

Since it is still early in development, the present epitaxial layer I.R. detectors are sometimes referred to as early second generation (1 1/2 generation) detectors. These new infrared detectors have many features which make them very suitable for arrays. This study addressed improvements in processing which can be applied to 1-1/2 generation detectors. Application to future technology is self evident.

b. Typical Early Second Generation Fabrication Process

Techniques for fabrication of HgCdTe infrared detectors are in the process of very rapid development. Techniques which are appropriate in the laboratory are being carried over into limited production. In some cases the equipment used is identical, confirming the need to improve portions of the process. The epitaxial layer is presently grown by liquid phase epitaxy in the laboratory. Experimental work is concurrently being done in vapor phase epitaxy, molecular beam epitaxy, and metal organic chemical vapor deposition. This study considered liquid phase epitaxy and molecular beam epitaxy since the automation and material handling elements for these two technologies are similar.

A sequential (simplified) description of the process has been prepared to identify areas for potential automation. Automating all parts of the process at once may be extremely difficult at this time, due to the limits in dexterity available in robotics and the state of the art of vision systems. Therefore an attempt was made to prioritize the selection of areas which have automation potential.

It is recognized that contamination of the material used in fabricating these detectors is a prime factor in reducing yield. This contamination may be due to the operators handling the components and assemblies, the atmosphere, or other production factors. It is also recognized that the materials used in these detectors have some toxic properties. In addition, many of the fabrication and assembly operations are already performed in clean rooms. The use of robotics to replace the human operator, where possible, within the clean room is now well recognized. A brief description of the process is given in the next section.

2. Generalized Processes

This is shown in six subprocesses in Figure 8. A brief summary of these is given below.

Subprocess 1) Prepare, grow single crystal material and slice CdTe wafer substrates.

Subprocess 2) Grow epitaxial layer on substrate and test.

Subprocess 3) Prepare arrays by photo etching, and metal deposition processes.

Subprocess 4) Saw arrays to size and optically inspect.

Subprocess 5) Bond leads

Subprocess 6) Final test.

In order to evaluate the potential for applying robotics and automation to these generalized processes, they must be expanded to include detailed fabrication and inspection steps. The following process chart has been prepared in greater detail for only Subprocess 1.

Subprocess 1) Prepare, Grow, and Slice CdTe Substrates

a. Material Growth

1. Refine Cd and Te materials

2. Divide into small pieces suitable for precision alloying

3. Alloy and grow single crystal in vertical Bridgman furnace or equivalent.

4. Zone, refine and anneal crystal boule.

b. Substrate Preparation

1. Sandblast boule

2. Determine 1,1,1 crystal axis plane

3. Orient and slice boule into wafers

4. Polish wafers mechanically and chemically and then clean.

5. Dice wafers into substrates 12 x 20 mm.

c. Substrate evaluation and testing

1. Flatness

2. Resistivity

3. Etch pit density

4. Te precipitates

5. Orientation

6. Dimensions

The above process is further expanded in Appendix 3 to include a more detailed description. This process may vary in industry from vendor to vendor. However, certain areas of the fabrication process are particularly suitable to automation. These are considered to have the highest priority.

d. Define areas of this fabrication technology which are suitable to automation.

In order to evaluate these areas a typical process chart is included in Appendix 3. Even this process chart is abbreviated since listing of all the detailed steps would be prohibitive; however, it is typical for the fabrication of an LPE epitaxial layer array. The steps which lend themselves to automation are indicated with an asterisk (*) in Appendix 3.

1) <u>Automation of the Fabrication Process</u>

The design of an automated system to perform this fabrication process is extremely difficult since the process is changing rapidly. It is presently highly dependent upon the human skills of manual dexterity and visual sensing. A glossary of terms for robotics is given in Reference 13. In order to initiate an automation effort it is necessary to establish a set of principles which can be followed. These are:

a) The elimination of operators from clean room areas to reduce particulate counts.

b) Operator assisted automation will be acceptable where it can afford a saving in production cost.

c) Partial automation will be an acceptable goal provided it can be accomplished at a reasonable cost.

d) The use of several smaller clean rooms in place of one large clean room will be acceptable since this allows the progressive introduction of automation with minimum disruption of production.

e) The use of robots in production will be acceptable where they can economically perform the work equivalent to a human operator. The operations may be tailored to the robot's capability, if required.

f) The use of fixtures or carriers to simplify material handling is an acceptable technique so long as the technical process, the costs and the production rate justify this approach.

Examination of the typical array fabrication process in Appendix 3 indicates the large number of detailed operations performed by human operators. In many of them the manual skill requirements are very high. In some of these operations visual sensing is required in addition to the manual skills. These operations are more difficult to automate.

Due to the complexity of this process and the fact that it is rapidly changing, it is necessary to define an approach which can be immediately applied but which has potential for future enhancement. This can be done by analyzing the fabrication processes and defining all the typical processes which exist. In that way when a process is successfully automated, it can be used in more than one production operation.

It is also desirable to classify the operations and the types of automation so that applications of technique where feasible can be applied across the entire fabrication process. This approach can be aided by considering the process with regard to the following parameters.

1) Type of Operation - Active (much manipulation) or Passive (little manipulation)

    a) Fabrication

b) Assembly

c) Testing or Calibration

2) Dexterity Required

a) High

b) Medium

c) Low

3. Part Handling

a) Single

b) Multiple

4) Speed of Process

a) Fast

b) Slow

5) Sensors Required

a) None - Open Loop

b) One - Closed Loop (vision)

c) More than one - closed loop (Vision and Test Instruments)

6) Human Interaction Required

a) Possible

b) Not Possible

In considering the type of automation, active pertains to an operator performing a task which modifies the product while passive pertains to measuring and recording a characteristic of the product. In the fabrication process, most of the operations are active. This also applies to the assembly operations. Testing may be passive while calibration may be either active or passive.

The dexterity requirement together with process speed really determines the type of automation required. Where the speed is low and dexterity is low it may be possible to use a programmed robot to perform the operation. This may be single part or multiple part handling dependent on the

production rate required. Multiple handling is more difficult unless the multiple parts are fastened together (not cut apart) or mounted in a magazine or on a holder.
Generally this type of automation is less flexible and more difficult to modify when the process is changed. An example of this is etching a number of subtrates on a single carrier. This is particularly suitable where the process requires appreciable time for completion.

Where the dexterity requirement is high, it may be difficult to use a robot without adding sensors for vision and touch. However, it may be possible to divide this operation to allow a robot to perform part and a human operator to perform the remainder of the operation.

At the present time robots cannot achieve the production rate of human operators in highly dextrous operations. A robot, however, can perform repetitive operations and reliably count occurrences with a lower error rate than human operators. Robots can also perform tasks which require greater strength than the human operator.

Therefore, in analyzing the typical HgCdTe fabrication process, the operations can be broken down as follows:

- Manual positioning - (loading, unloading, carrying)
  - Low dexterity - robot
  - Medium dexterity - robot or robot assisted operation
  - High dexterity - human operator
- Process control - computer
- Cleaning - low dexterity - robot
- Polishing - low dexterity - robot
- Etching - low dexterity - robot
- Sandblasting - medium dexterity - robot to turn part while in process
- Cutoff ends of boule - medium dexterity - robot with vision sensor and interactive feedback.

- o Slice wafers - low dexterity - robot
- o Dice wafers - medium dexterity - robot with vision sensor and interactive feedback
- o Furnace loading and unloading - high dexterity - robot or human operator depending upon analysis of specific operation
- o Contact formation - high dexterity - robot or human operator depending upon analysis of specific operation

The types of automation which can be applied to this technology will depend upon the specific process, the production rate required, the system flexibility needed and the capital cost. Since the HgCdTe fabrication process is presently in an evolutionary state, the automation selected should be capable of modification. This type of automation should utilize medium dexterity robots programmed by a computer and capable of being reprogrammed if required. Several of these robots could be programmed to perform multiple operations in a synchronized manner.

One of these robots is shown in Figure 1. This is a light duty robot. Generally this type of automation is more costly than fixed automation. Its advantage however is that it can be modified and reprogrammed to conform with process changes. A light duty robot with programming control can cost from $30,000 to $40,000 without any special tooling. Light duty robots of this type can move rapidly but cannot carry a heavy payload (one pound to three pound capacity). Vision systems to improve the robot capability are often carried on the robot arm. Light duty robots usually cannot carry the weight of a robot vision system which may weigh 2 to 3 pounds.

A robot vision system is an optical system which can acquire the work piece, and redirect the control system of the robot to locate the work piece position and orientation. The vision system then translates this information to the robot wrist to orient the grippers to reliably pick up the work piece. Without a vision system the work piece will have to be preoriented before it is picked up by a light duty robot unless a simplified lighter weight optical sensor can be adapted to this application.

A larger robot is shown in Figure 2 carrying a cassette of wafers through a series of etching solutions. This type of robot has been

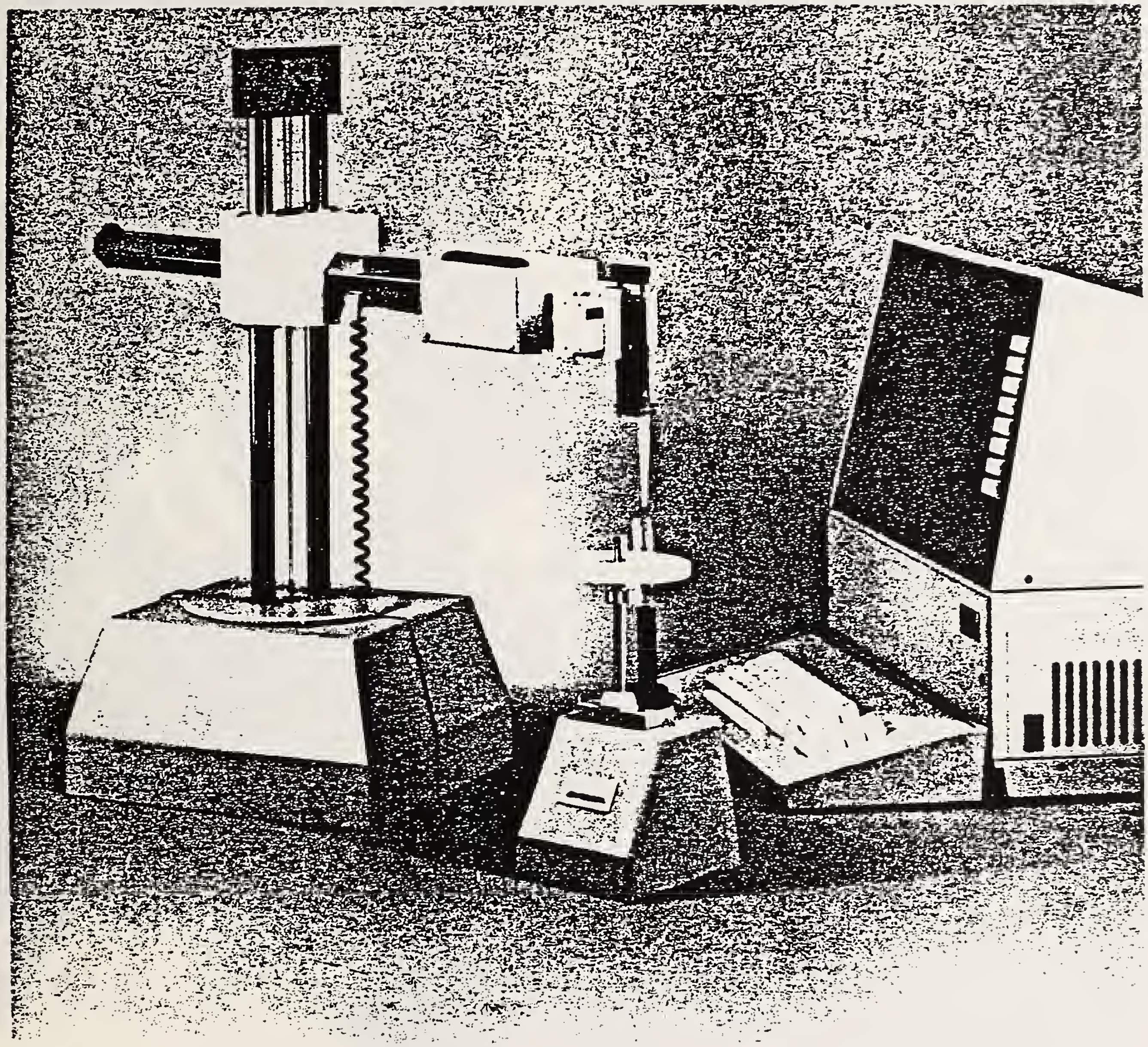


Figure 1 Light Duty Robot

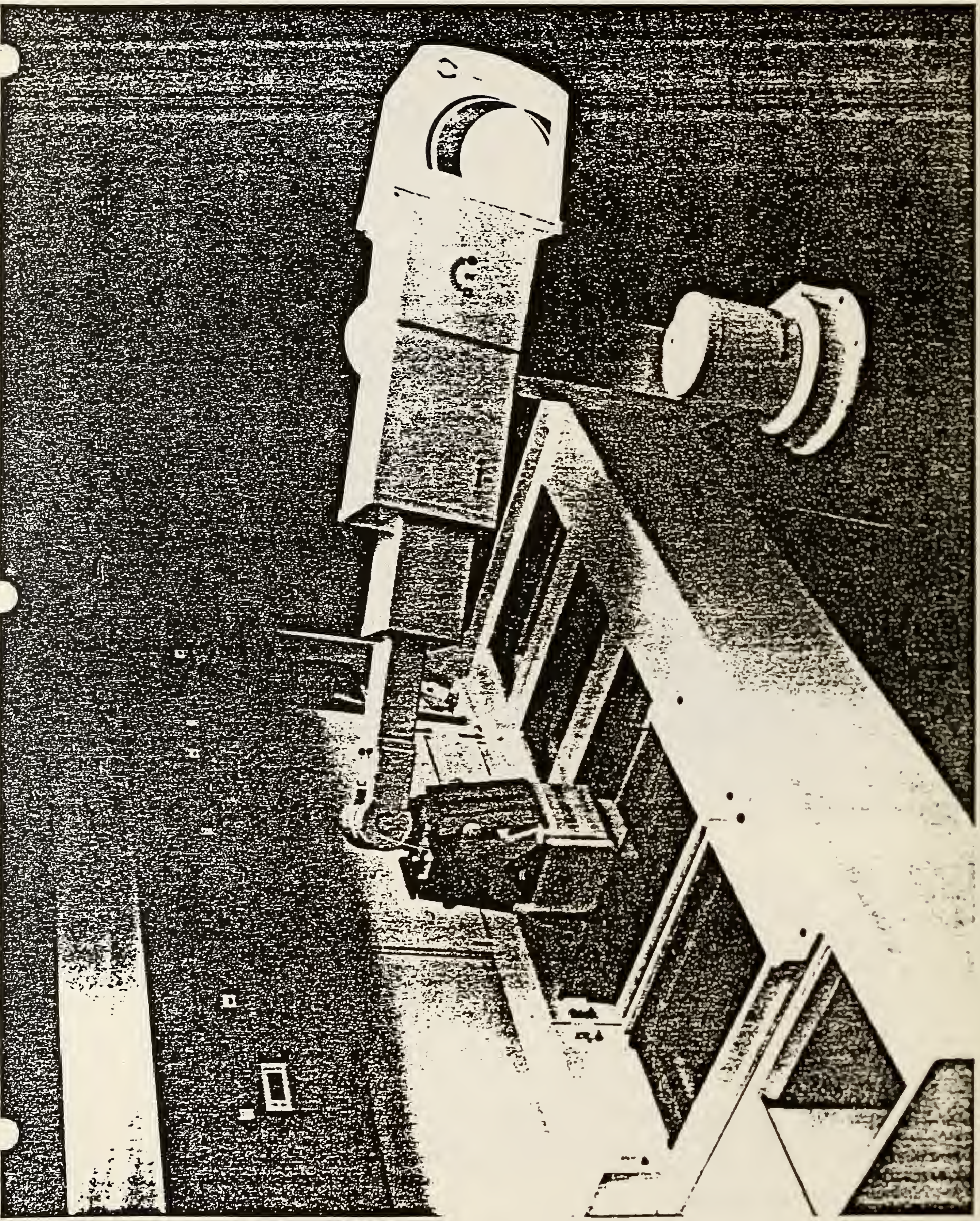


Figure 2 Robot for Etching Process

successfully used in clean room applications. The gripper on the end of the robot arm can be adapted to pick up and manipulate single wafers or cassettes holding a number of wafers. An example of the type of grippers used to pick up the cassette is shown in Figure 3. These robots may carry payloads as heavy as 5 pounds.

Where the etching and cleaning process is set up in a linear configuration, which is too long for the reach of a single robot, a series of robots can be operated from a single computer controller. An example of this is shown in Figure 4a. Each rotating arm is capable of transferring a cassette from one bath to the next.

Fixed automation such as pick and place systems of limited dexterity and flexibility are usually designed for a specific application and can cost from $10,000 to $20,000.

An alternate method for accomplishing this is to translate the robot on an additional longitudinal axis along the length of the process. This may affect the processing rate since a single arm must service several stations as shown in Figure 4b. This automation method requires accurate positioning of the robot in front of each station. It is not difficult to accomplish this positioning with a precision translation system and appropriate sensors.

Where the length of the etching process is much greater, it may be necessary to have a number of etching lines. Automating this type of process requires some type of transfer device to move the work piece or cassette from one line to another. This may be fixed automation at the end of a line, or a simple pick and place robot or it may be a more versatile robot dedicated to this operation.

Where the process is extensive as shown in Figure 5, a robotic vehicle may be used to transfer cassettes from one etching bath to the next. One robotic vehicle of this type is shown in Figure 6. This automation system has increased versatility since the robot vehicle may carry the work piece or pieces on to the next fabrication process. However, this system requires additional sensors and location devices for aligning the vehicle precisely with each work station. These vehicles are generally called mobile transfer units or MTU's. These units generally require an "on board" power source, such as storage batteries, to eliminate trailing umbilical cables. These mobile

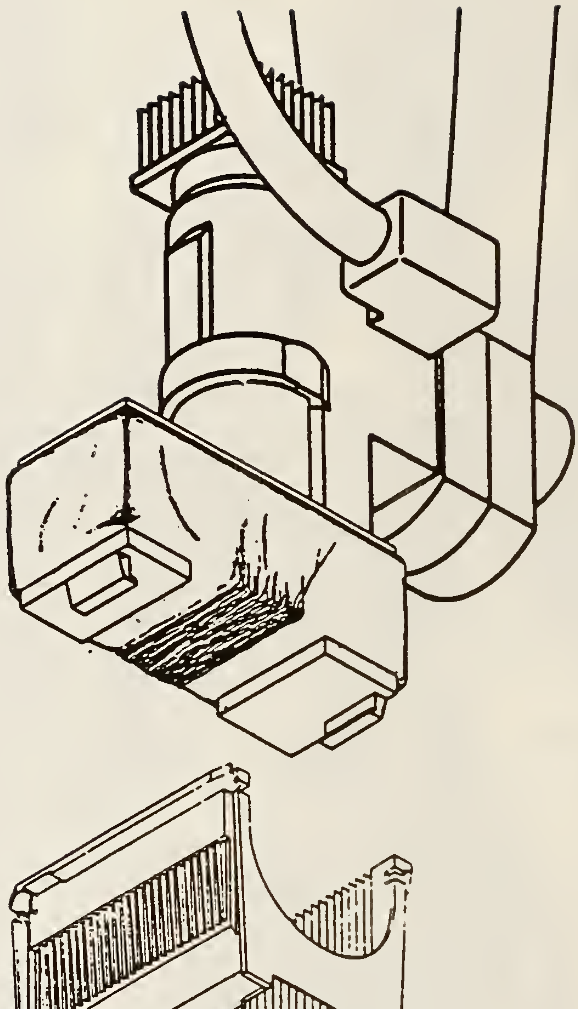


Figure 3

Robot Gripper for Cassette

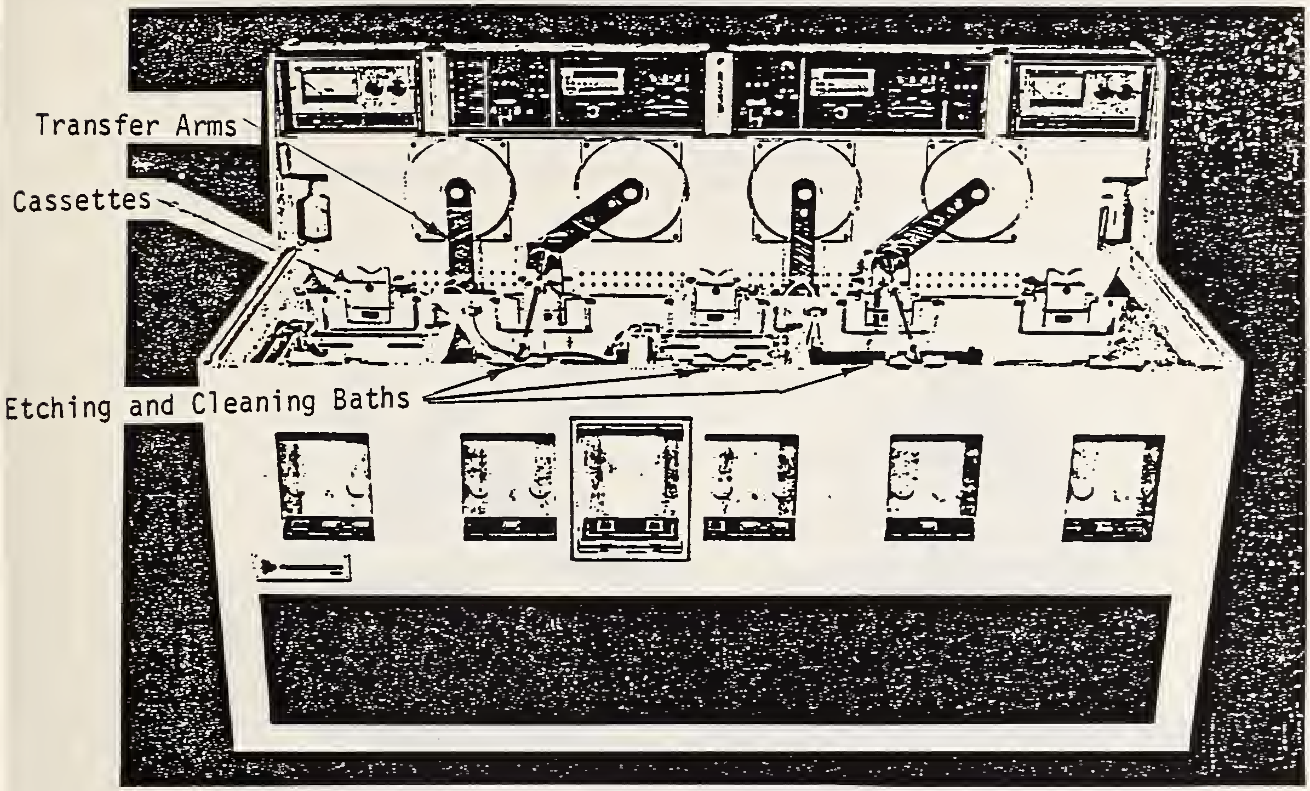


Figure 4a Etching Process with Multiple Robots

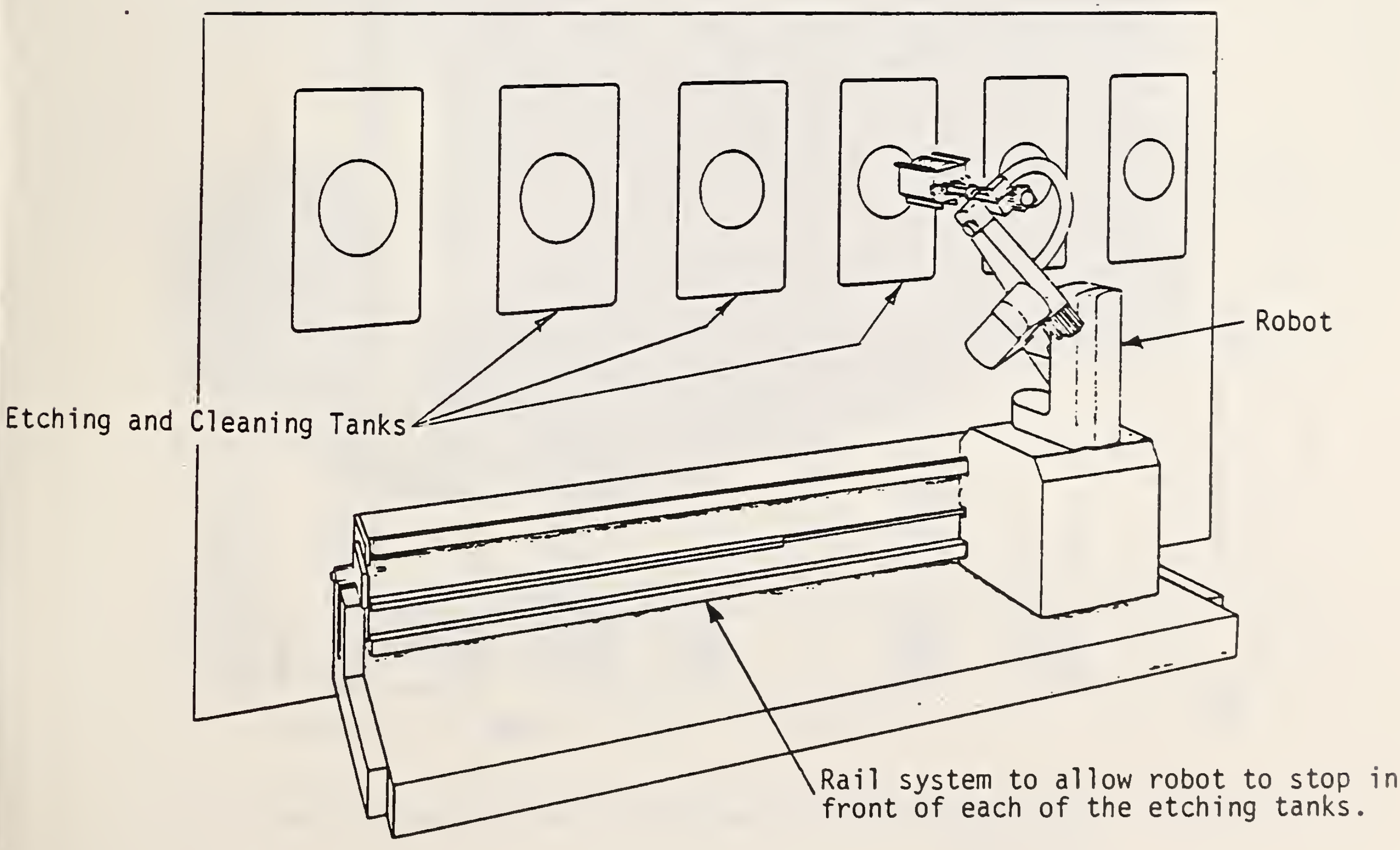


Figure 4b Etching Process with Single Robot on Rail

Basic CIM System

Service a Combined Total of Up to 10 Production Tools and WIP Stations

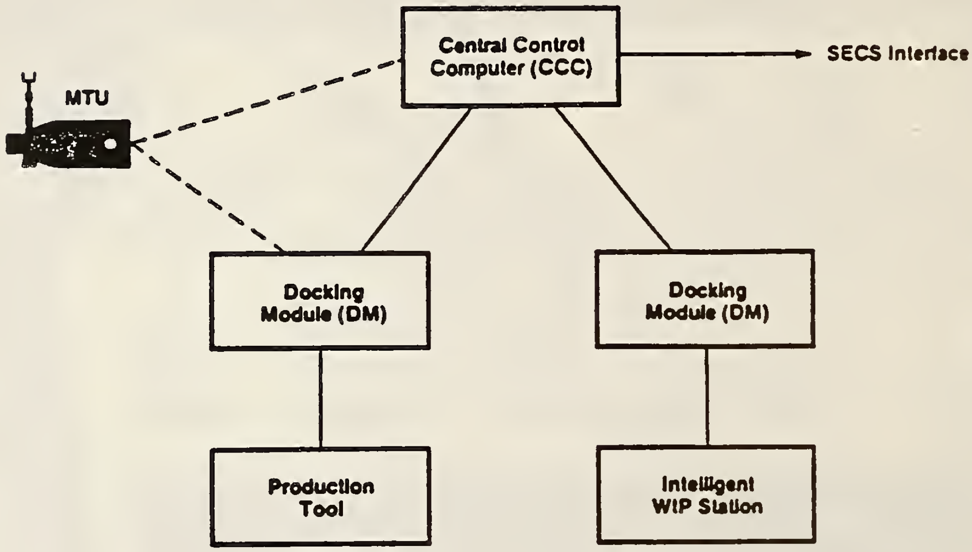


Figure 5a Basic CIM System and various module components.

Semiconductor Fab Area with MTU

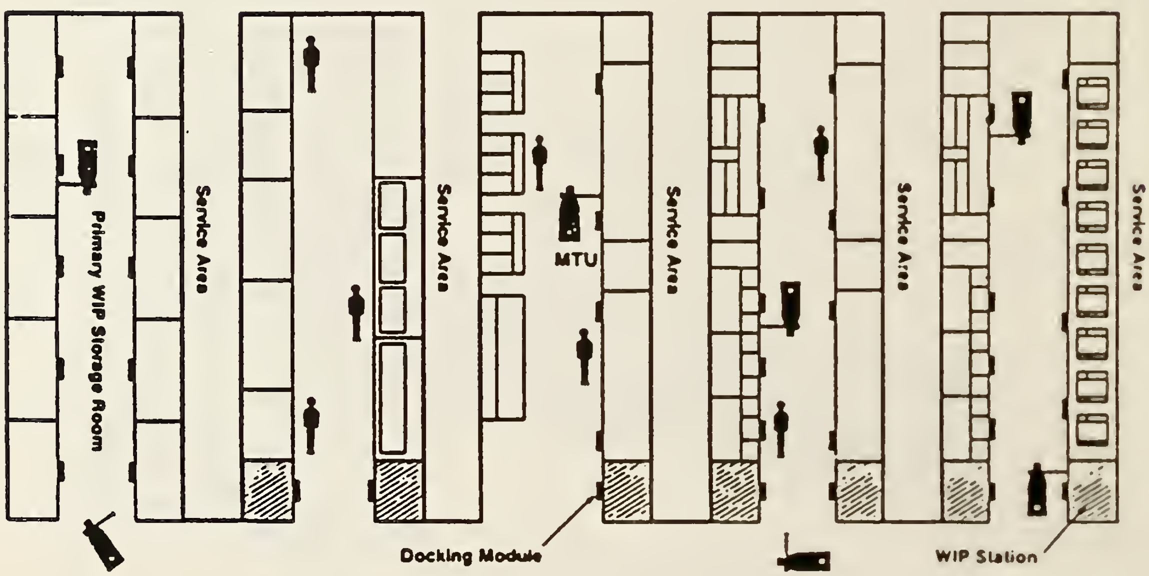


Figure 5b CIM System phased implementation into existing or new fab areas.

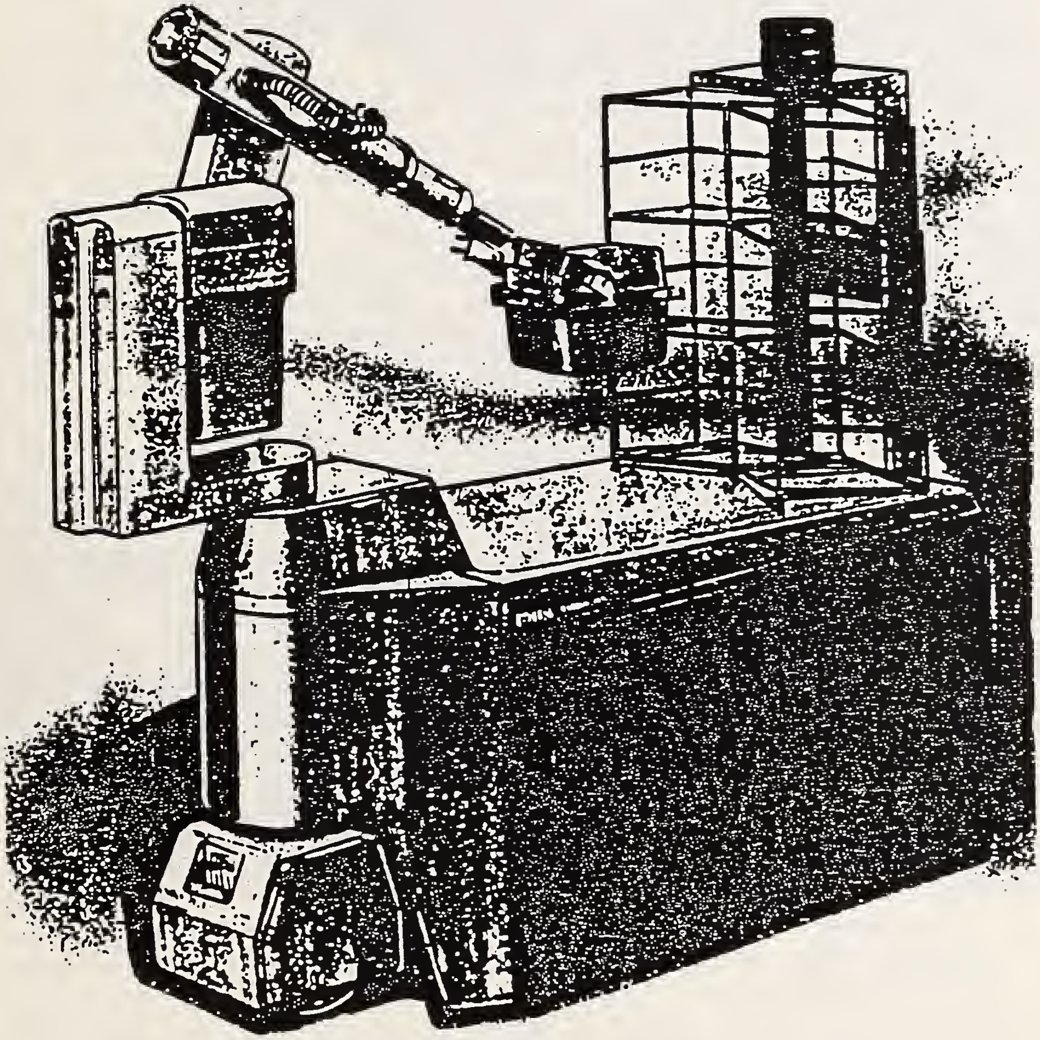


FIGURE 6 Illustration of robotic vehicle with robotic arm and on-board storage.

transfer units are usually used in Computer Integrated Manufacturing Systems (CIM) where more than one vehicle is required per system. Traffic control must be implemented to minimize the chance of collision. Figure 5 shows several robotic vehicles operating together with a number of human operators in the same clean room area. The safety problems must be carefully reviewed for this type of operation. Normally, these systems are designed to operate within the clean room area so that the low particulate count within the area can be maintained.

When the process requires a high level of dexterity the robot may require as many as six degrees of freedom. This may be improved by the addition of one or more sensors of various types to the end of the robot arm. However these sensors carried on the end of the arm reduce the actual payload which the robot can carry. A robot with five axes, having medium dexterity is shown in Figure 7. A high dexterity robot usually has six axes to allow it to manipulate a work piece almost as well as the human operator.

2) <u>Automation of the Inspection Process</u>

Inspection and testing can be very similiar to manual positioning, depending upon the dexterity needed to access and load the test equipment. This may be done by a robot or a human operator. However the success of this automation application may be dependent upon the ingenuity applied to selecting or developing the test equipment so that it requires low levels of dexterity to load and unload. If production quantities are high it may be feasible to not only develop the test equipment, but to develop a simplified pick and place robotic system for loading and unloading. This type of system can operate at higher cycle rates than general purpose robots. It may also be necessary to design the test instrumentation to do multiple product testing in order to increase the throughput.

One example of special test equipment designed to improve production is the substrate crystal axis mapping goniometer described in Phase II of this report. Other examples are the Hall Effect Test Equipment, and the FTIR interferometer spectrometer for mapping cutoff wavelength and expitaxial layer thickness.

Inspection instrumentation is generally similar to test instrumentation. However inspection

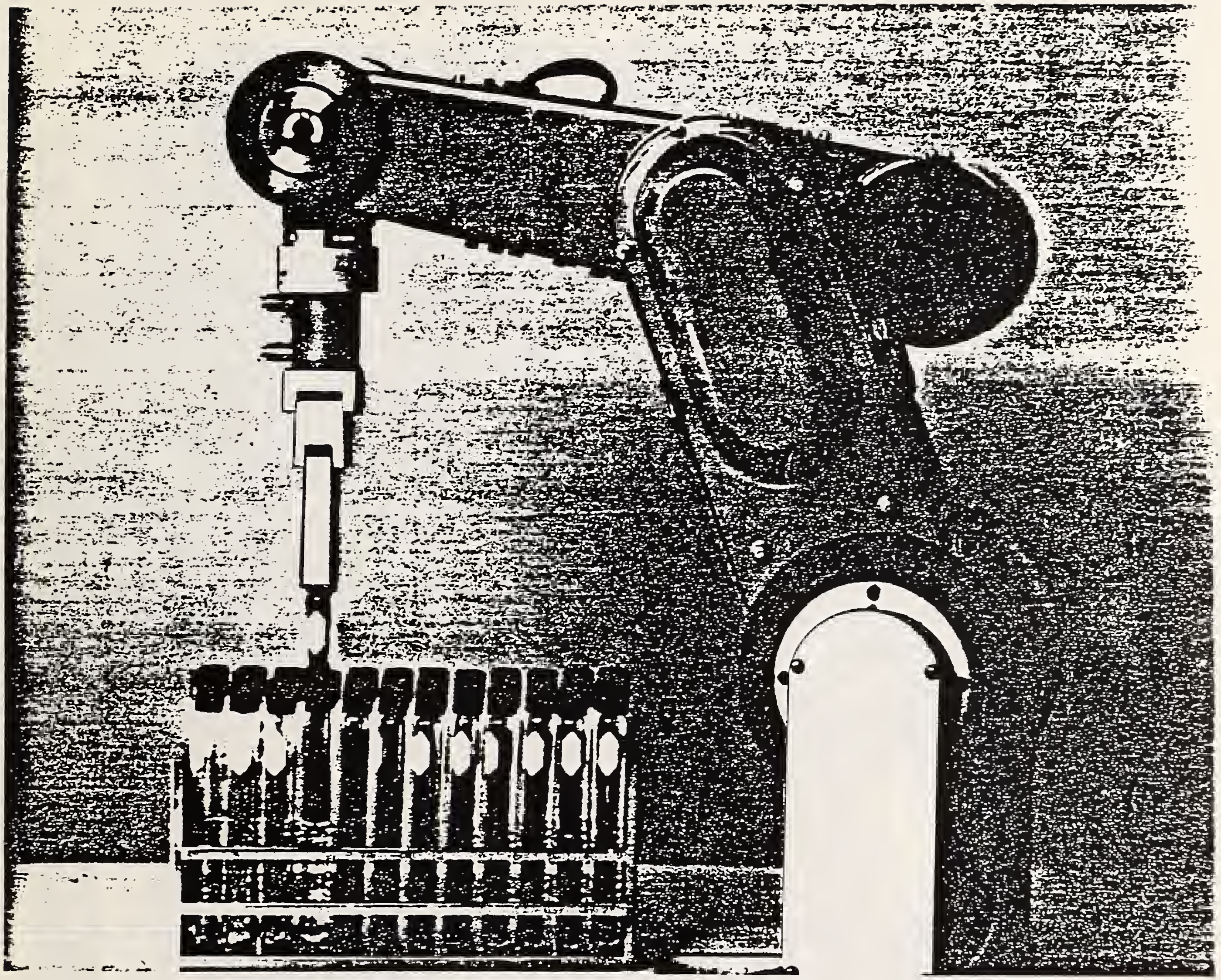


Figure 7 Five Axis Robot (Medium Dexterity)

instrumentation may depend more upon the visual sensing supplied by a human operator for judging the quality of the product. This type of instrumentation is much more difficult to automate since the measurement parameters are hard to quantify.

One example of this type of inspection instrument is the microscope station used to count etch pits on substrates. The automation of this type of station is dependent upon substituting a suitable optical scanner with a pattern recognition system for the human operator. Since the human operator is very knowledgeable in detecting subtle differences in small patterns, it is difficult to achieve the sensitivity from automated scanners. In addition it is difficult to program an automated scanner with a detection algorithm which is equal to the human data reduction capability. Consequently the inspection equipment and scanning algorithm may have to utilize techniques for increasing the contrast of artifacts to insure the quality of the inspection process. One of these techniques is to use level slicing or thresholding of the gray scale in the image. This is a commonly utilized technique in video image manipulation. The automated scanner, however, is far superior to the human operator for counting defects and reliably recording this data.

Examples of this type of inspection instrument are given in References 7 and 8. This system was developed at NBS for testing micro circuitry in the semi-conductor field. The principles used in this system are pertinent to inspection operations in the HgCdTe detector fabrication process. The basic laser scanner and computer programming system is adaptable to many microscope inspection systems which have a vertical camera port. An example of a microscope inspection station of this type is shown in Figure 7A. The vertical camera port in this figure contains an eye-piece to protect the optics. The basic laser scanner can fit over this microscope as shown in Figure 7B to project the scanning laser beam through the optical system. The advantage of this system is that the work is illuminated by coherent light which increases the contrast of the artifacts in the field. The modification to complete this laser flying spot scanner is to replace the vertical illuminator lamp with an optical sensor. This approach is well documented in References 7 and 8.

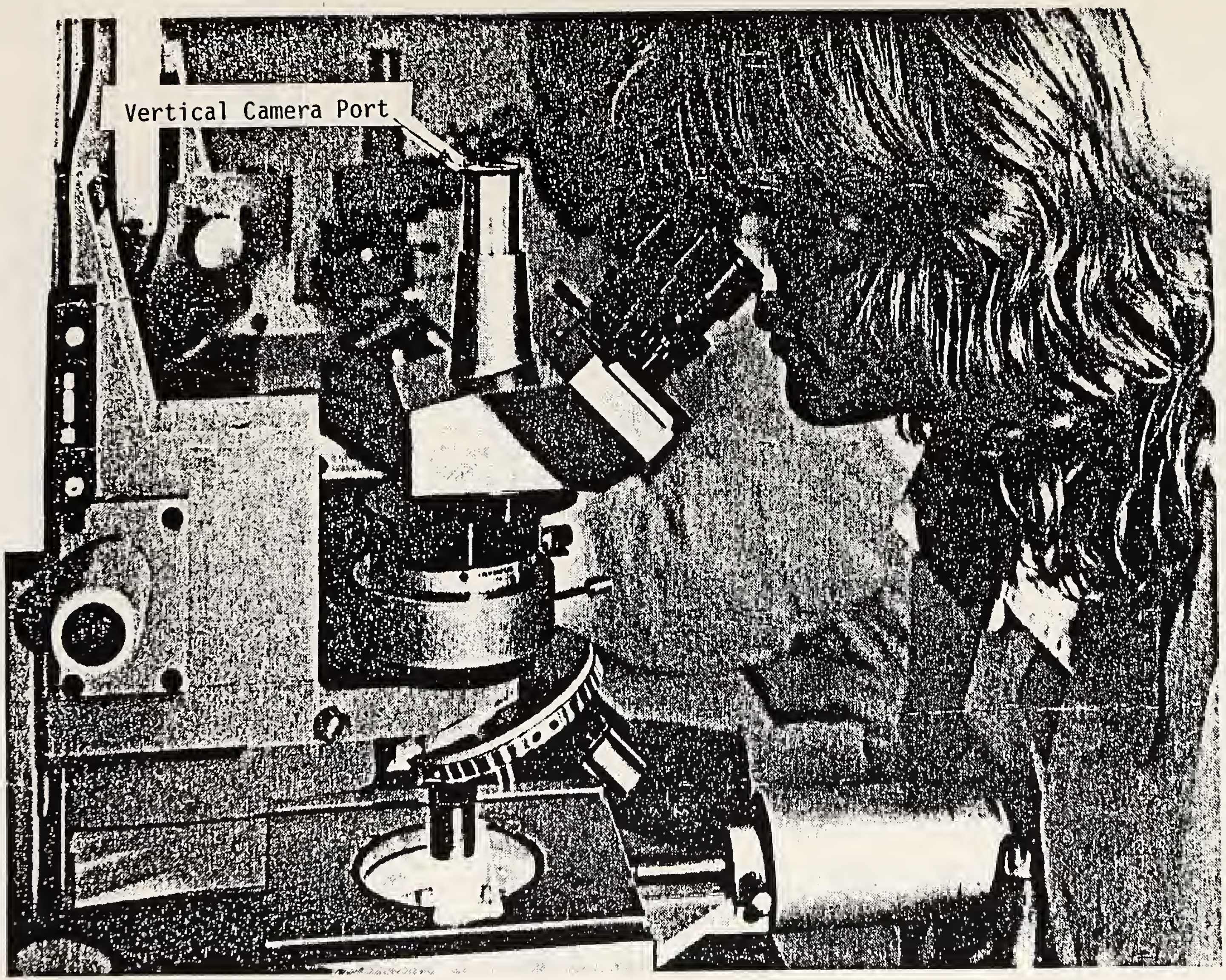


Figure 7a Array Measurements Being Made With A High-Power Microscope

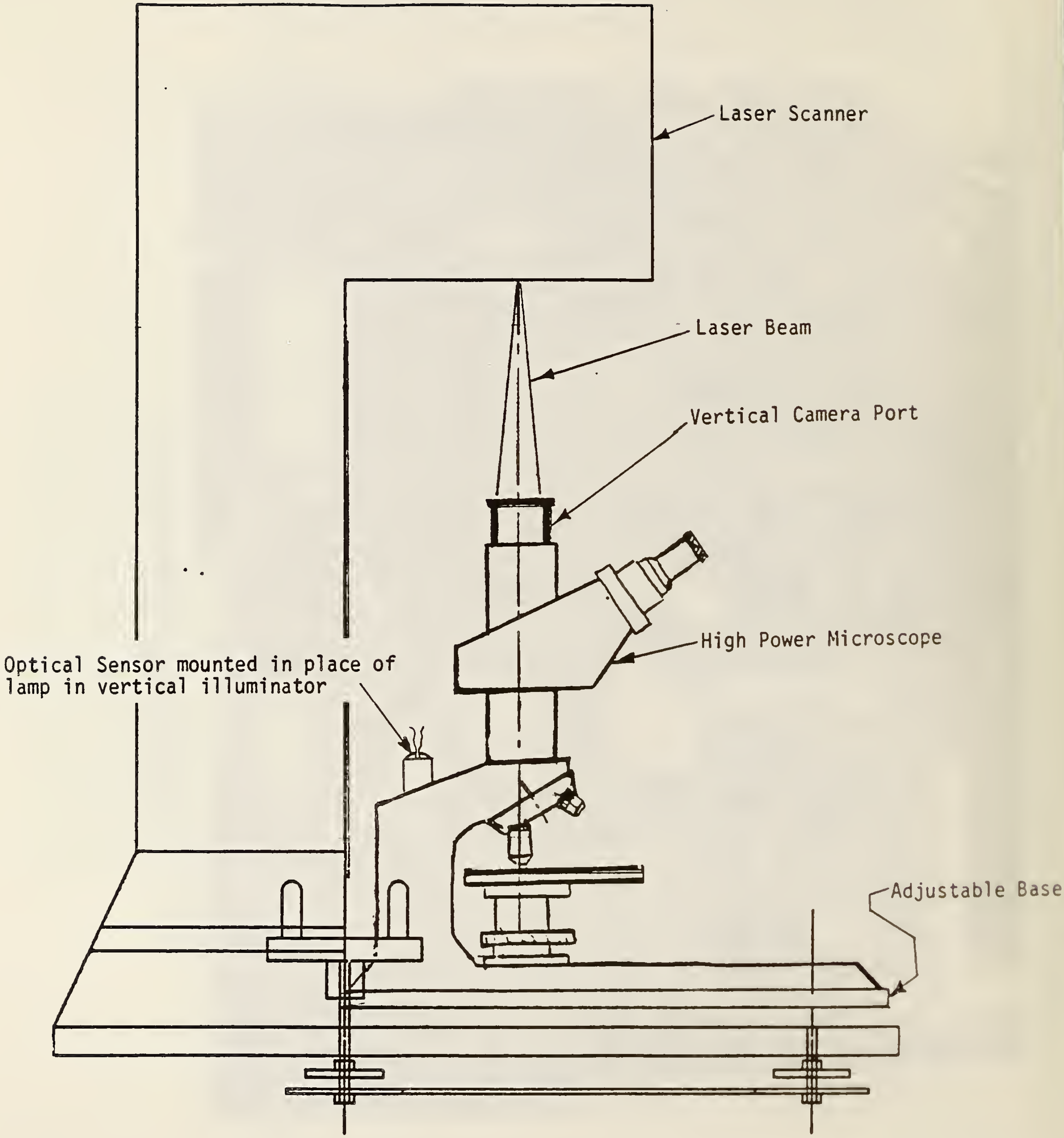


Figure 7b High Power Microscope with vertical camera port mounted under laser scanner

The coherent illumination can be varied in wavelength by using a tuneable dye laser. The references describe a raster scanning system for the laser. The same laser has been used with a polar scan in Phase II of this project. It is readily apparent that a diametral scan can also be easily introduced. This would enable the computer to initiate a suitable inspection algorithm to count and record defects using existing microscopic equipment already in place in the production process. A typical algorithm for recognizing random defects in the infrared detector array is to align the array perpendicular to the raster scan and to look for detectors which are not periodic. The repetition rate can then be programmed in microseconds and synchronized with the pattern, to count detectors. Any artifacts which do not appear at the repetition rate are defects. This is a very elementary algorithm for this type of detection. More elaborate algorithms are used in video processing of biological materials. By adapting the algorithm to the particular inspection process, this automated system can be utilized in several applications.

For these reasons this fabrication process must be carefully analyzed for access, feasibility, production rate, traffic patterns, potential changes and costs before it is implemented. A comparison of costs is usually made between partial and full automation to obtain the best return on capital investment. Where overiding factors such as contamination or particle count are present, it may be necessay to select a system which is not the most cost effective. The cost of robots with six degrees of freedom is much greater than those with three or four degrees of freedom. Sensors and robot vision systems also add to the cost. For complex computer controlled systems the one time programming costs may also be relatively high. It is also necessary to tool the end of the robot arm for holding and storing work pieces. These costs must also be considered part of the capital cost in automating a process. In some cases the process equipment must be altered to make it compatible with the robotic systems. This may reduce the reliability of the process equipment unless the changes are carefully planned and engineered.

C. Recommendations

The purpose of this study was to explore the feasibility of introducing automation into the manufacturing of HgCdTe detectors. The broader goals were to increase yields and reduce costs. The addition of robots to the clean room operations should also reduce the particulate count (Reference 9 and 10). This alone should result in an additional improvement in yield.

In considering this process for automation, it is very important to establish an order of priority which will optimize the benefits. Therefore the following criteria should be used to determine the order of priority.

- o Potential for cost reduction
- o Simplicity of the application
- o Probability of success
- o Potential for multiple applications

There are approximately 102 stations in the fabrication process described in Appendix 3 and each of these stations may have more than one step. Of these 102 stations approximately 69 are suitable for automation. These are marked with asterisks in Appendix 3. The projects selected for automation should be suitable for implementation at a laboratory level with provision for expansion to adapt to the production process.

A block diagram of the generic process for fabrication of HgCdTe detector arrays is shown in Figure 8. Many of the steps in this process are still under development to improve yields and reduce labor. Therefore some processes are being carried on at both the laboratory and the production levels simultaneously. For this reason there are a number of options available in planning the automation of this fabrication process. These will be listed below and then described in some detail so that the magnitude of these options can be evaluated.

Option 1--Automate several key steps in the process at <u>laboratory level</u> where evaluation can be performed without interfering with existing production. The steps selected should be typical so that they may be applied at several positions in the process. They should also be suitable for transfer from the laboratory to the production process.

Option 2--Automate some of the subprocesses on an <u>existing production line</u> to reduce the number of assembly and fabrication operators located in the clean room environment. The purpose is to reduce particulate counts and improve the yield of the production process.

Option 3--Set up and implement a <u>new production line</u> for the purpose of fabricating HgCdTe detector arrays using the latest automated equipment commercially available and designing robotic stations where needed. This option includes site and building location, implementing the design and installation of the clean room facility and specifying processing equipment and automation to eliminate human operators. This option also requires that the process and the production rate be studied to determine the optimum throughput and that operation times be equalized by either duplication of process steps and equipment or by automated buffer storage systems. This option may also include the design of automation equipment and inspection instrumentation where not commercially available.

HgCdTe Fabrication Process

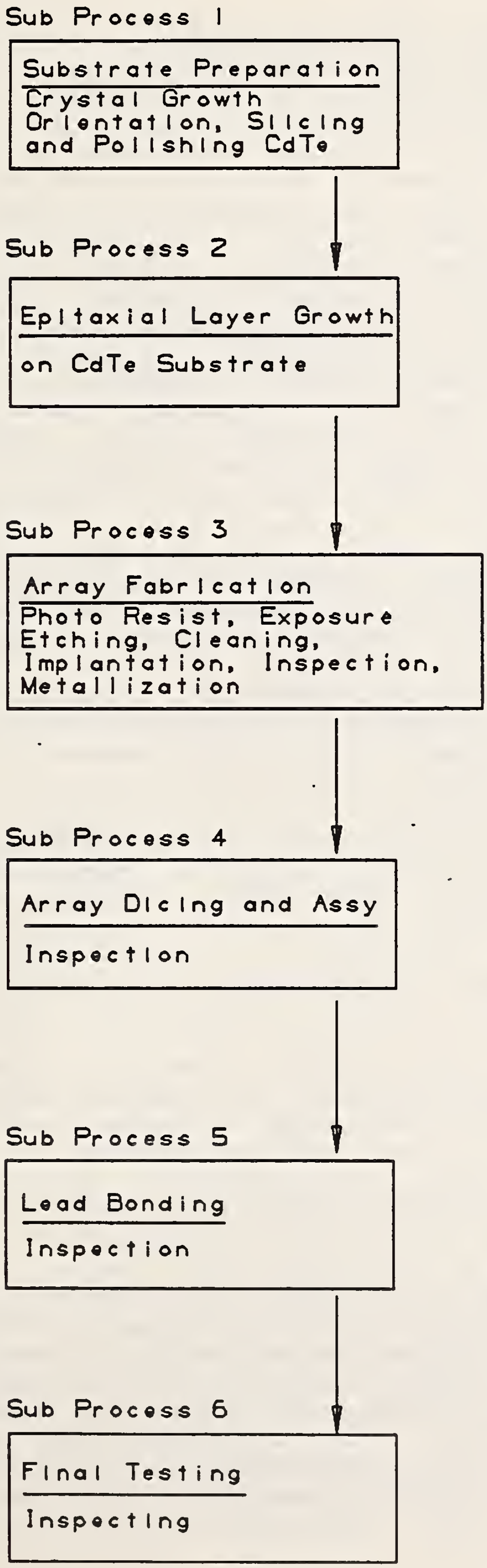


Figure 8 Block Diagram of Generic Process for Fabrication of HgCdTe Detector Arrays

General Discussion of Options

Automating a complex process is done to reduce labor, increase output, or improve safety or quality. Normally the process should be well defined so that there are no marginal steps which have high rejection rates. In addition the individual steps in the process should be matched to the output rate. Where necessary, multiple operations are used to maintain the output rate. The automation process therefore is based upon valid manufacturing, inspection and testing procedures which already provide a good quality product through the manual fabrication process. In order to satisfactorily resolve the production problems which arise from automation, it may be necessary to modify some step in the process. This must be done with great care since these modifications may affect performance or throughput. While these modifications are expected during automation, they should be kept to a minimum in order to insure the quality of the product and to keep within the time schedule.

In automating a process which is in the developmental stage it is necessary to carefully select the steps which are to be automated since it would be uneconomical to automate a process which will be changed. Therefore emphasis should be placed upon automating those processes for which there is a reasonable certainty of continued use. The processes which are subject to change should be scheduled last and reasonable alternatives should be planned for backup if technical problems are encountered.

It should be recognized that there is an element of risk which exists in automating a complex process. Some allowance in the time and cost is made for this risk in planning an automated process.

- Option 1. Automate several steps at a laboratory level.

  This plan has the least element of risk since automation can be carried out without affecting production. In addition measurements of quality, defects, and particulate count can be made to determine the benefits of automation and robotics in the clean room environment.

- Option 2. Automate several significant steps in an operating production environment.

  This plan will require the study of an existing fabrication process for the HgCdTe detector arrays to determine those process steps which can be automated. The fabrication process selected should be well defined technically and have a reasonable throughput so that improvement in performance resulting from automation can be measured. Implementing an existing fabrication process with even one automated step introduces intangibles which will probably affect production rate. Therefore allowance should be made to carry out the automation "off line" until performance can be assured. The automated process steps can then be incorporated into the production line one at a time with appropriate measurements to determine improvement. Allowance for these measurement costs must be made in the automation plan.

o Option 3. Set up a new automated production line.

Setting up of a new automated production line for fabricating HgCdTe detector arrays is both a challenge and a risk. Since the technology is not mature at this time, it would be necessary to select a suitable technical approach to the complex fabrication process with the understanding that some portions of the process may have to be changed. The portions of the process which can be performed using commercially available automated systems, will be integrated into the design. It would be logical to divide the facility into several clean room areas so that servicing of equipment or solving production problems will not shut down the entire process. This introduces the requirement for a suitable buffer storage area for both input and output ends of each clean room.

A typical clean room may be large enough to have more than one production line in order to conserve floor space and cost. However, the lines must be planned so that the flow of materials is not impeded and that access is available for trouble shooting production problems and for service and repair of equipment.

In designing a facility having several clean rooms, it is necessary to consider entrance and exit locks to preserve the dust free environment. In addition it is necessary to carry the work pieces in suitable dust tight containers or equivalent when transferring from one clean room to the next.

This option therefore requires an overall systems design in order to optimize its implementation.

D. Detailed Description of Recommended Options

Option I. The projects which are recommended for implementation under this option are at the laboratory process level. These are described in greater detail in this section. A plan for automating significant steps in this process is shown in Figure 9 adjacent to each of the six sub processes. The proposed automation is based upon the production labor required, yield or other pertinent factors which can reduce the cost of fabrication. The eight resulting candidates for automation projects under Option 1 are described as follows:

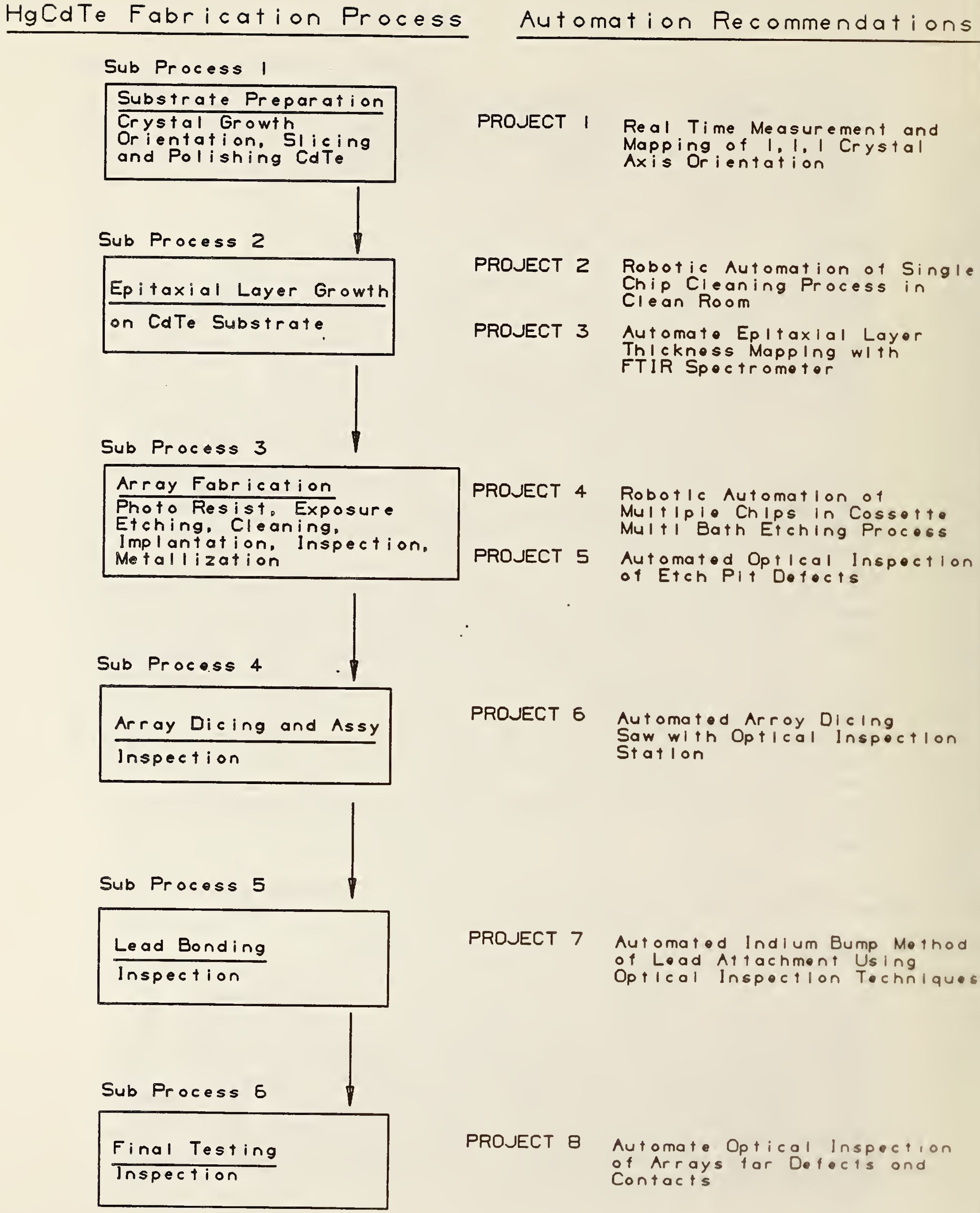


Figure 9 Block Diagram of HgCdTe Fabrication Process with Automation Recommendations for Option I

Project #1--Real-Time Measurement and Mapping 1, 1, 1, CdTe Crystal Axis Orientation.

This is part of subprocess (1) Figure 9. This measurement is now performed by an X-ray (Laue Pattern) technique on CdTe wafers which have already been sliced from a boule. This measurement technique requires exposure of film for 15 to 20 minutes per test location (1mm diameter) with an average testing time of 4 hours per wafer. The yield of 1,1,1 material per wafer using this method is indeterminate since it depends entirely upon the efficiency of the crystal growing process. There may be very little 1,1,1, oriented material on a wafer. The wafers are too thin to provide enough material to try to use crystals which occur in other axial orientations. If the wafers were sliced thicker, some of the other crystal orientations could be converted to the 1,1,1 axis. This however would be inefficient since more 1,1,1 oriented material would be wasted.

It therefore would be a great advantage to determine the crystallographic orientation of the material prior to slicing the boule. The boule could then be cut to optimize the yield of 1,1,1 material. In addition, identification of 1,0,0, and 1,1,0 crystal axes in the boule would provide additional useable material since these sections could then be reoriented to the 1,1,1 axis.

The development of a breadboard model of an instrument to rapidly identify crystal axes using laser technology has been done under Phase II of this project. Feasibility was demonstrated on October 24, 1985 to representatives of the Night Vision Laboratory. This instrument is being finished to a prototype level so that it can be delivered on this contract. This prototype has a hard wired pattern recognition system to identify seven different crystallographic orientations. Three of these orientations are the 1,1,1 the 1,0,0 and the 1,1,0 axes. The remaining four are patterns which appear frequently on one of the sample boules supplied by the Night Vision Laboratory. The hard wired pattern recognition system uses 960 shift registers which can be rewired, if required to identify other crystal orientations. However, this hard wired system does not have sufficient capability for recognizing more complex geometric patterns which may be encountered in further applications of this system.

Further work is needed under Project #1 to program this instrument to operate with a host computer, which will have enhanced software pattern recognition capability. This will allow much more sophisticated pattern recognition routines to be easily programmed to expand the capability of this instrument. Further research is suggested on "rocking curves" for the goniometric crystal mount to improve the accuracy of crystallographic orientation, and for mapping techniques. A more detailed description of this instrument is given in Phase II of this report.

<u>Project #2--Robotic Automation of Single Chip Cleaning Process in Clean Room.</u>

This is part of subprocess (2) Figure 9. This operation was selected since it is an example of a medium dexterity application which is typical of many steps in this process. The single chip handling capability will require the design of appropriate grippers to handle the substrates without chipping, stress damage or contamination. The manipulation of the unmounted chip will require the programming of intricate motions which are applicable to other processing steps as well as inspection and testing. The use of this robot in a clean room environment will require the solution of problems of material supply, finished part delivery, and robot particulate generation. Many clean room robots use shrouded members to contain any particles produced in the mechanism. In addition an evacuation system inside the robot is used to remove particles generated by the mechanism and carry them outside the clean room environment. This is done by keeping a negative pressure inside the robot mechanism. Experience has shown that particulate levels can be reduced from class 1000 to class 10 providing there are no operators inside the clean room. The robot should be able to perform a complex operation reliably and continuously to give consistent parts and an increased yield.

This project would employ a commercial robot such as shown in Figure 2 with modifications of the wrist mechanism and grippers to increase the dexterity. The grippers would probably use a vacuum system to hold the CdTe substrate. Special trays or magazines must be designed to facilitate the input and output of substrates. If the substrates are irregular in shape and size it will be necessary to use a sensor or vision system to help the robot locate each individual substrate. This vision system may be on the robot arm or it may be mounted above the station in a fixed position. If the cleaning process is a liquid dip or flush it may not be possible to use a vacuum pickup since the vacuum will aspirate the solutions. Therefore it may be necessary to have both vacuum and mechanical grippers built on the end of the robot arm so that the appropriate end effector can be selected. An example of this is shown in Figure 10. This single end effector has three modes of operation. It can pick up single pieces by vacuum, single pieces by mechanical jaws and it can pick up cassettes mechanically. If the substrate is cleaned by the plasma method it would be appropriate to use a vacuum gripper. However the plasma cleaning system will also have to be automated with racks for loading, doors for closing the vacuum chamber and controls for automatically cycling the time, the vacuum, the R. F.

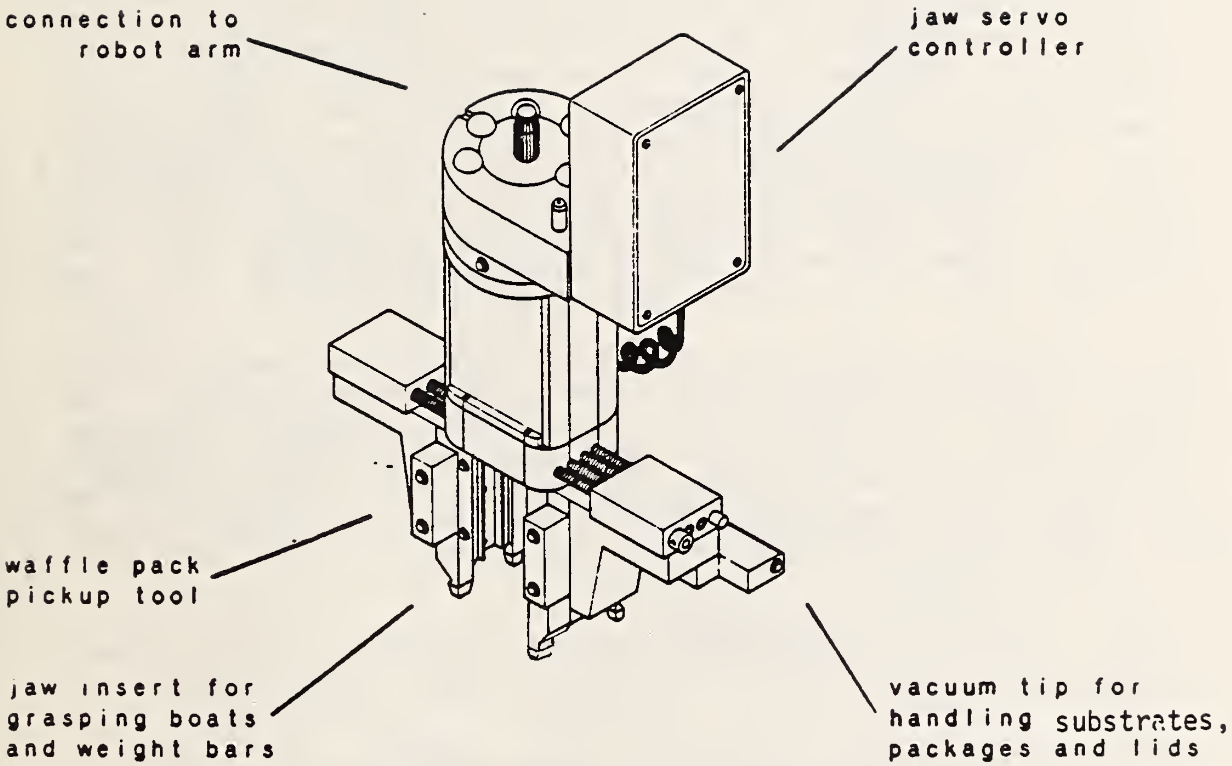


FIGURE 10
MULTI-FUNCTION ROBOT END-EFFECTOR

excitation, and the oxygen bleed. A typical configuration for the operation is shown in Figure 11.

For some materials, plasma cleaning may adversely affect the surface or the subsurface characteristics. With cadmium telluride substrates, surface anomalies can be cleaned with a bromine etch after plasma cleaning. The robot should therefore have appropriate grippers to enable it to carry the substrate through this process. If a vacuum pickup is used for a wet process, such as etching, the substrate may be delivered to a dry carrier which then feeds into an automated etching system. The substrate is then etched and dried and then delivered to an output station where the robot can again pick it up and take it to the next operation. Grippers which use vacuum to pick up parts must be made of materials which do not deteriorate, contaminate, or mechanically damage the substrates. Therefore, one or more elements of compliance must be built into the vacuum gripper. The gripper must be designed to pick up and to put down the substrate reliably, quickly and in a predetermined position. It is assumed that the finished item from one stage in the subprocess will be reliably fed to the next stage in the process.

An alternate method of cleaning the substrate would make use of semiautomated wafer cleaning stations such as the unit shown in Figure 12. This cleaning station uses a vacuum chuck to hold the substrate while solutions are sprayed and brushed across the surface to remove greases and particulate material. The robot shown in Figure 11 can be used to load and unload the vacuum chuck of this cleaning station.

Other steps in this process can be automated in the clean room by using a similar robot to load and unload the processing station.

<u>Project #3--Automate Epitaxial Layer Thickness Mapping with FTIR Spectrometer</u>

This instrument must measure the spectral transmittance of the chip in the infrared spectrum from 400 to 4000 wave numbers. The application of this instrument is to measure the thickness of the epitaxial layer to determine the potential sources of defects which reduce the yield. These defects may affect only one detector in the array. Therefore the exploring spot must be small enough to be able to measure the epitaxial film thickness of a single pixel having a size of 25 microns by 37 microns.

The spectral transmittance curve will also provide information on the cutoff wavelength. This instrument requires an automated "X", "Y" positioning system such that the substrate can be translated by small increments to map a selected area and record the data. The data storage

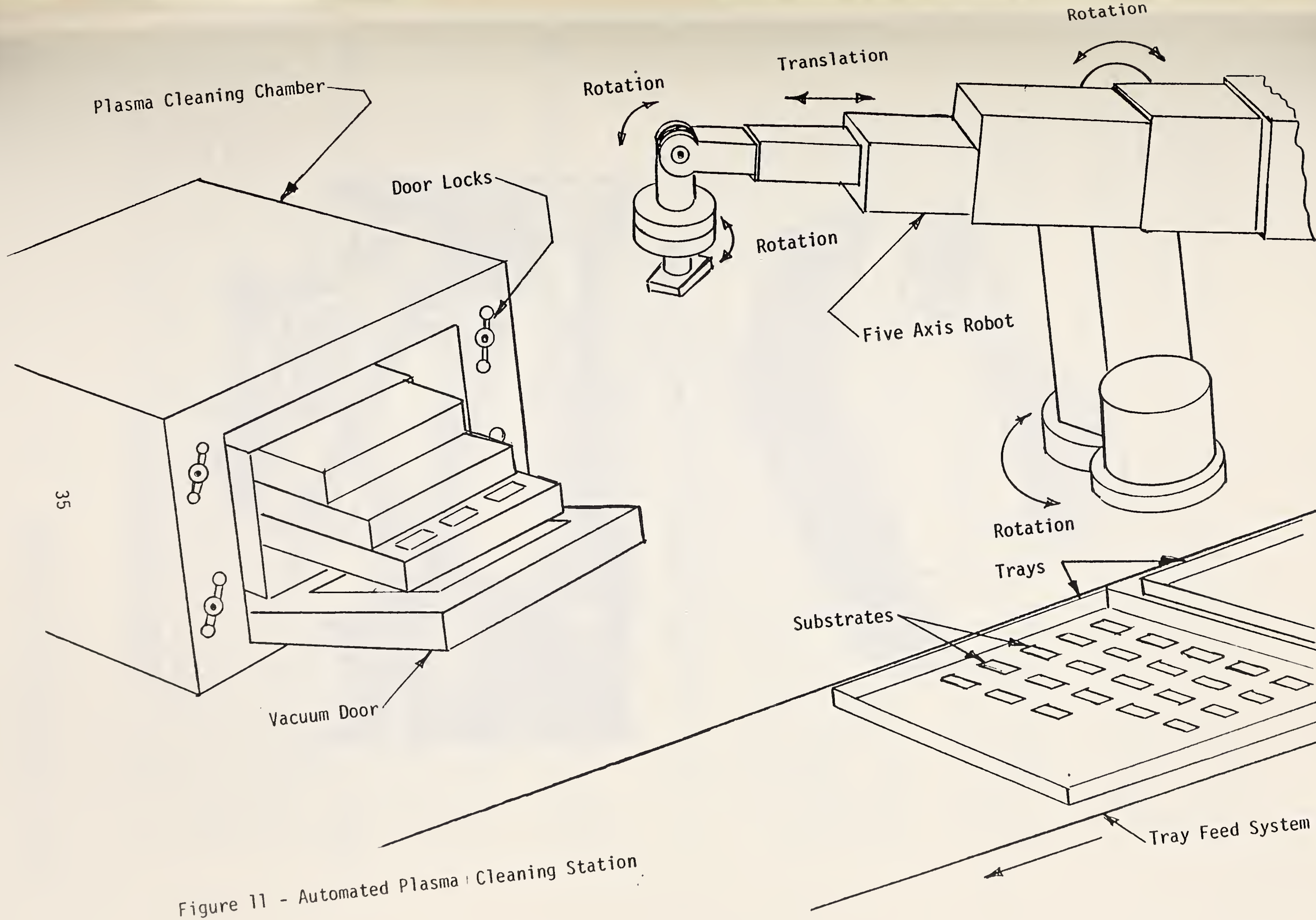
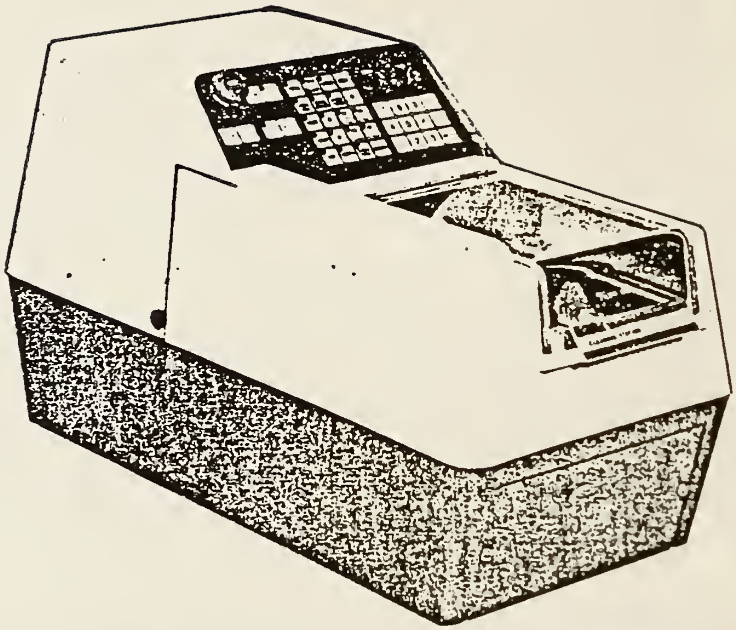
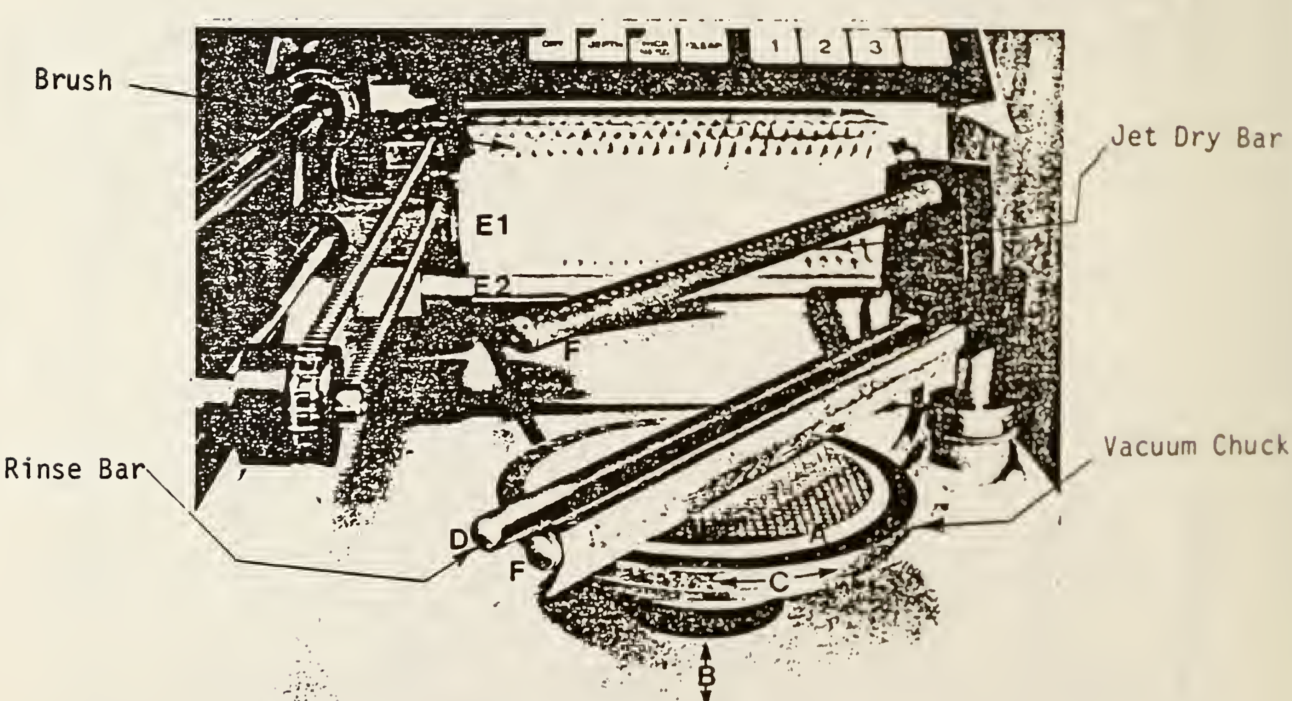


Figure 11 - Automated Plasma Cleaning Station



Overall View of Automated Washing Station



Inside of Washing Station

Figure 12 Automated Washing Station

requirement is very large in order to store a spectral transmission curve for each pixel on the 1/2" x 1" substrate. If this substrate is mapped in 25 micron steps this will require storing 500,000 transmission curves. In order to reduce the data storage, a set of data reduction algorithms can be used to calculate the cutoff wavelength and the epitaxial layer thickness for each point so that only this information is stored.

Specifications on this instrument were prepared by NBS and it was procured for this application. This instrument is presently being programmed with the data reduction algorithms for cutoff wavelength and expitaxial layer thickness. It is then scheduled for delivery to the U.S. Army Night Vision Laboratory (Figure 13).

Further research should be done on the mounting of sample substrates and the mapping techniques needed to locate and identify the surface morphology and the defects which affect the IR performance of these detector arrays. The identification of defect composition and substrate condition will require using one or more of the following nondestructive testing procedures for surface analysis. An instrument to perform theses tests is shown in Figure 14.

XPS--X-ray photo emission spectroscopy
UPS--Ultra violet photo emission spectroscopy
SIMS--Secondary ion mass spectroscopy (this may be destructive)
TPD--Temperature programmed desorption
LEED--Low energy electron diffraction
ISS--Low energy ion spectroscopy

<u>Project #4--Robotic Automation of Etching of Multiple Substrates in a Cassette.</u>

This project requires designing a special cassette for holding 1/2" X 1" substrates with minimum edges masking. The number of substrates in the cassette should be determined to give a throughput compatible with the overall process throughput. The robot may be similar to the unit shown in Figure 2. The etching process is usually associated with the photo resist, baking and mask transfer processes. Good automation systems incorporate the principle that once a part has been oriented it should not be released. It would therefore be advantageous to incorporate as much of the above processing as possible into the same automated line. Using this technical approach a number of suitable systems are commercially available. They may however have to be modified to fit the substrate size. One of these systems is shown in Figure 15. This system takes its input from a cassette and carries the substrates through the process on an air bearing transport device to minimize damage to the surface. It will however be necessary to investigate the affect of

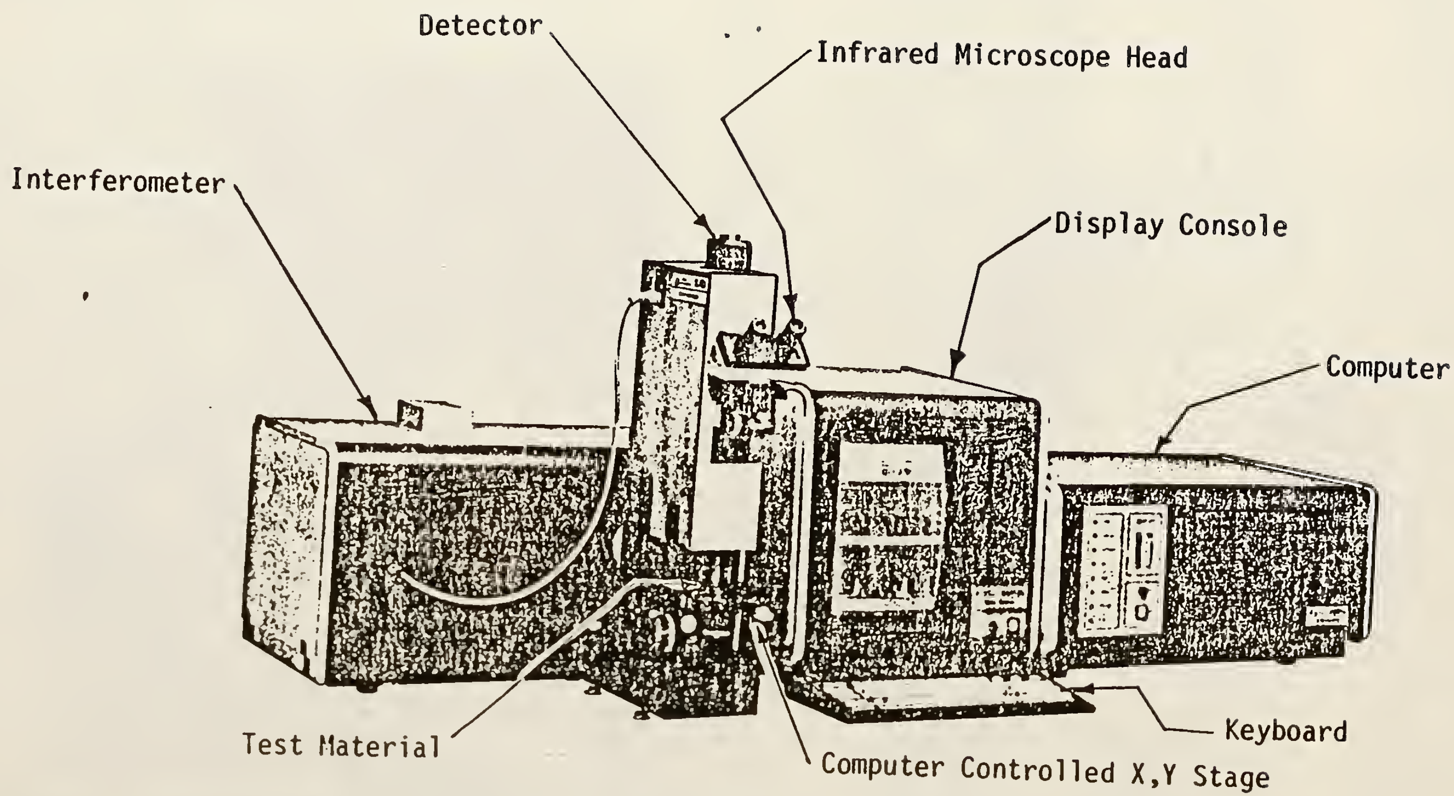


Figure 13 Fourier Transform Infrared Spectrometer for Transmission and Reflectance

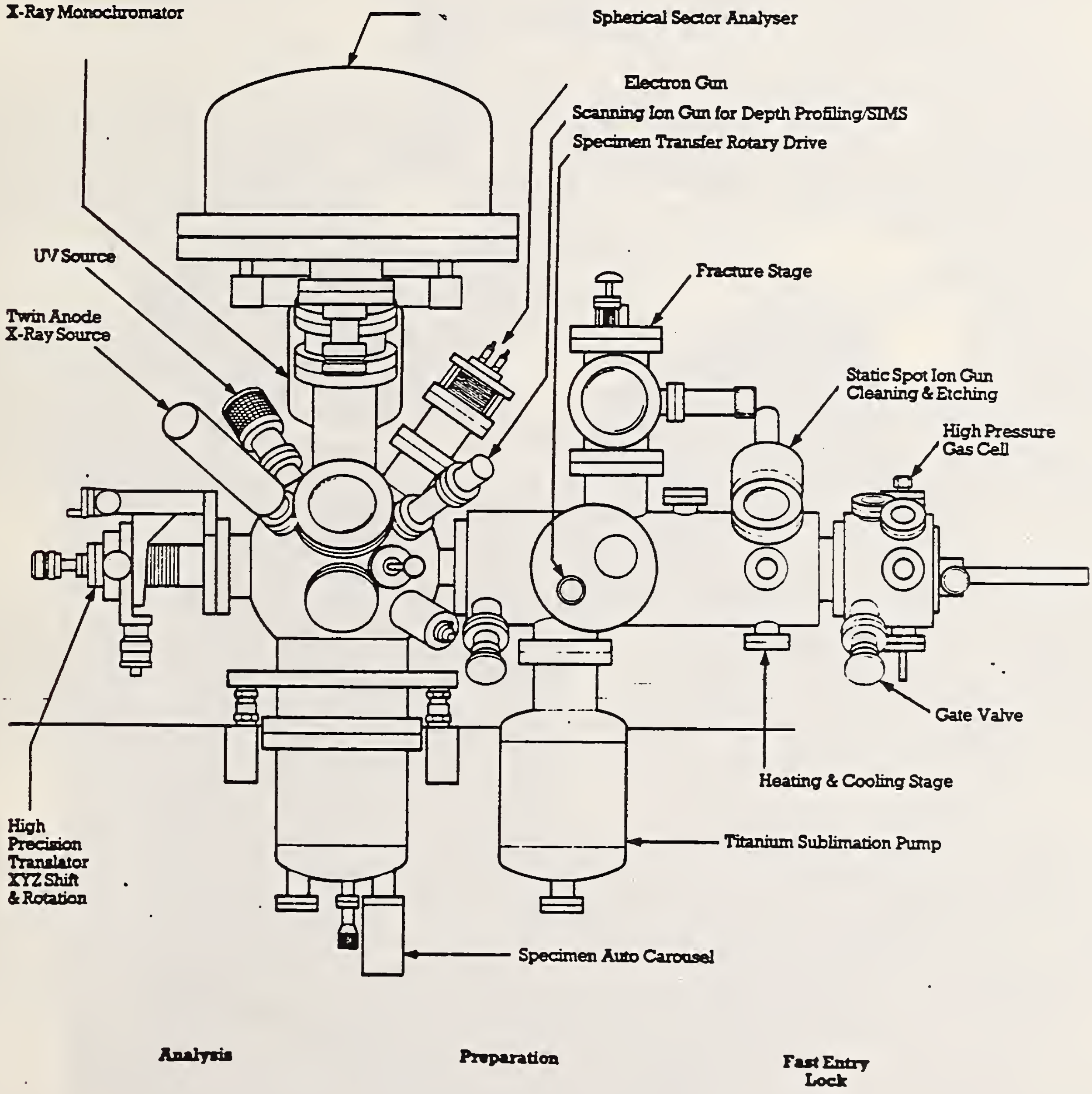
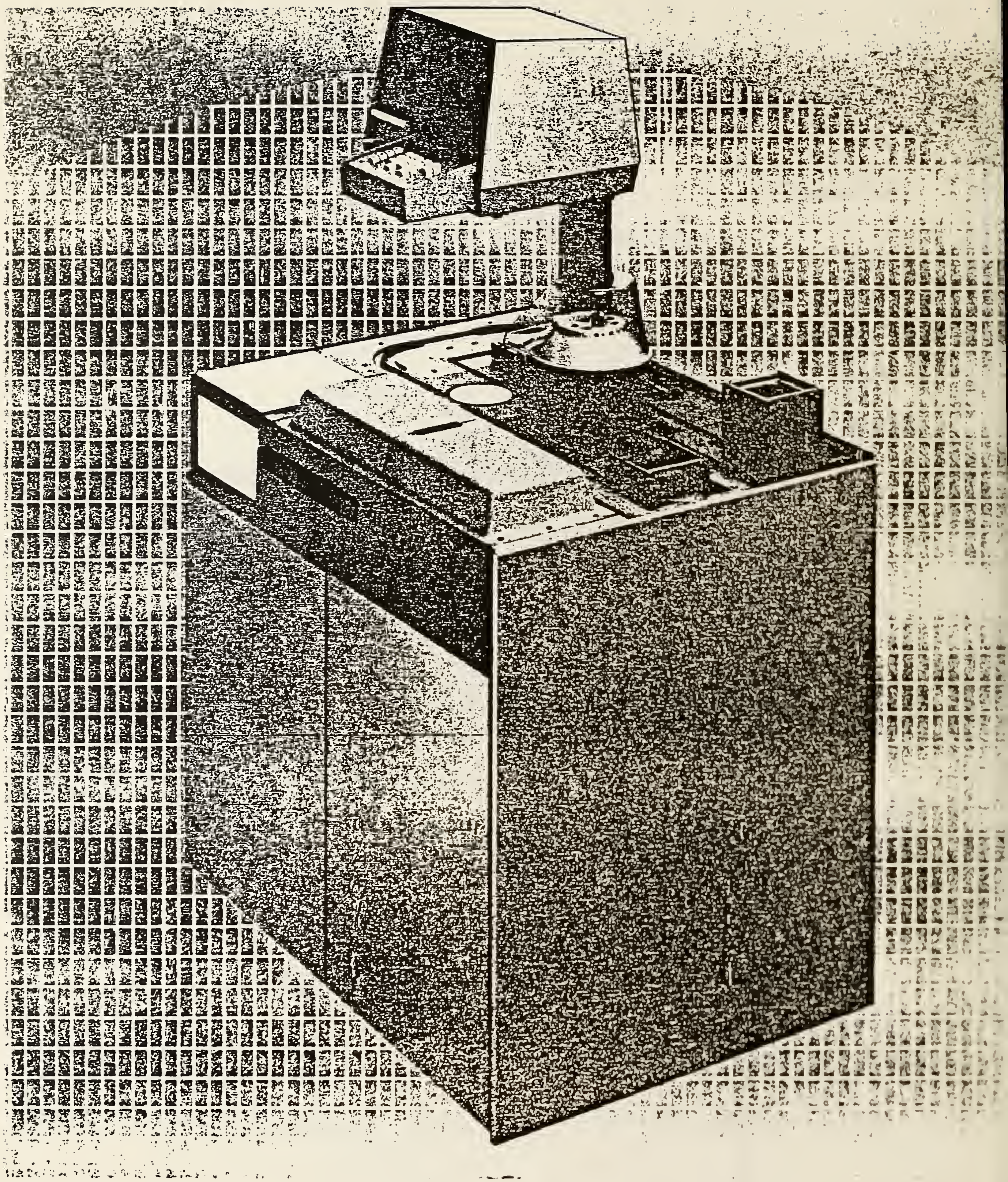


Figure 14 - Surface Analysis Instrument



re 15 - Automated Coater and | Baker

the air bearing transfer device on the distribution of the particulate count in the clean room. The substrates are taken from the feed cassette and delivered to a spinner where they are coated with the photo resist and then go to a hotplate for baking. The substrates are then returned to a second cassette where they are accumulated until the cassette is filled. The input and output cassettes are located adjacent to each other so that the robot can transfer the finished cassettes to the next stage of the process. This may be a mask printer to expose the photo resist. The throughput of this station is typically 80 wafers per hour allowing ample time for the robot to transfer the wafers. The mask printer may be cassette fed with the robot loading and unloading the printer. A more integrated layout of the clean room will be required to determine the optimum method for transferring the cassettes to the next stage in the process. This may be chemical etching or ion beam milling, dependent upon the specific process selected.

Project #5--Automate Optical Inspection of Etch Pit Defects

This project concerns the development of a general purpose scanning system which can be adapted not only to etch pit counting, but to other optical inspection operations. The use of coherent light to improve the resolution of a conventional inspection microscope is well recognized. In addition the inspection operation will need to be automated with signal enhancement, pattern recognition and special scan patterns. To perform this function, a laser flying spot scanner can be adapted to the inspection station.

The laser flying spot scanner can consist of the basic toroidal laser scanner from Phase II adapted to the microscope inspection station. This is shown in Figure 17. The inspection station is mounted on the adjustable height platform and aligned under the laser scanner so that the laser beam sweeps the full projection eyepiece. This configuration is illustrated in simplified form in Figure 16 with a conventional microscope. The laser beam is scanned in a circular pattern by exciting both the "X" and the "Y" galvanometers with a sinusoidal signal of the same amplitude having a 90 degree difference in phase between galvanometer signals. The resulting laser scan will then fill the eyepiece and be reimaged through the objective at a reduction ratio determined by the product of the powers of these optical elements. The excitation voltage to the galvanometers can be reduced during a discrete time interval so that the circle is gradually reduced to a point. This results in a spiral scan of the laser beam in the object plane of the microscope. Since this is also the substrate surface it will be scanned by a very small laser spot which will also describe a spiral. Any light which is reflected from the substrate surface will re-enter the objective and be reflected by the vertical illuminator beam

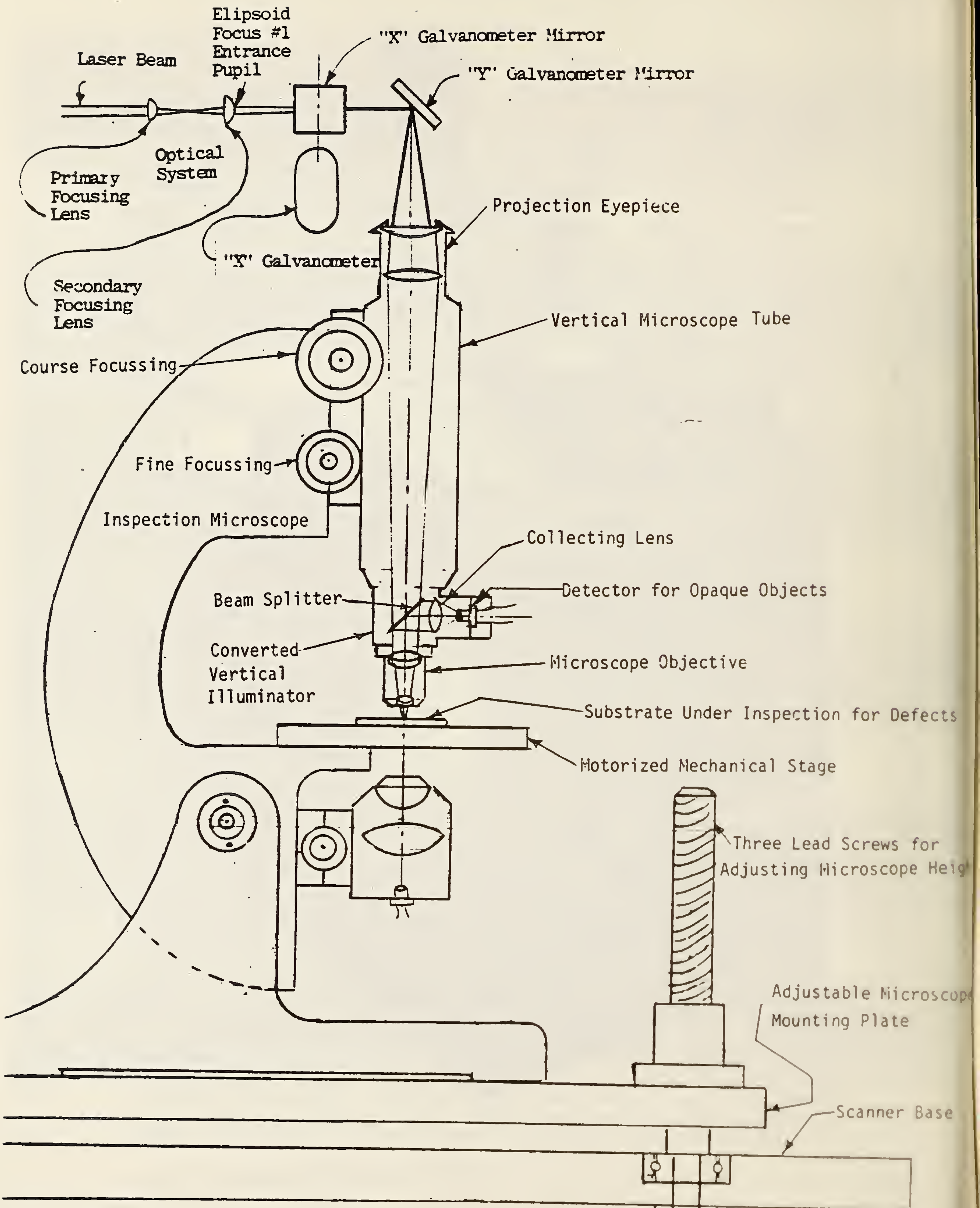


Figure 16 - Automated Optical Inspection Using Laser Scanner with Microscope

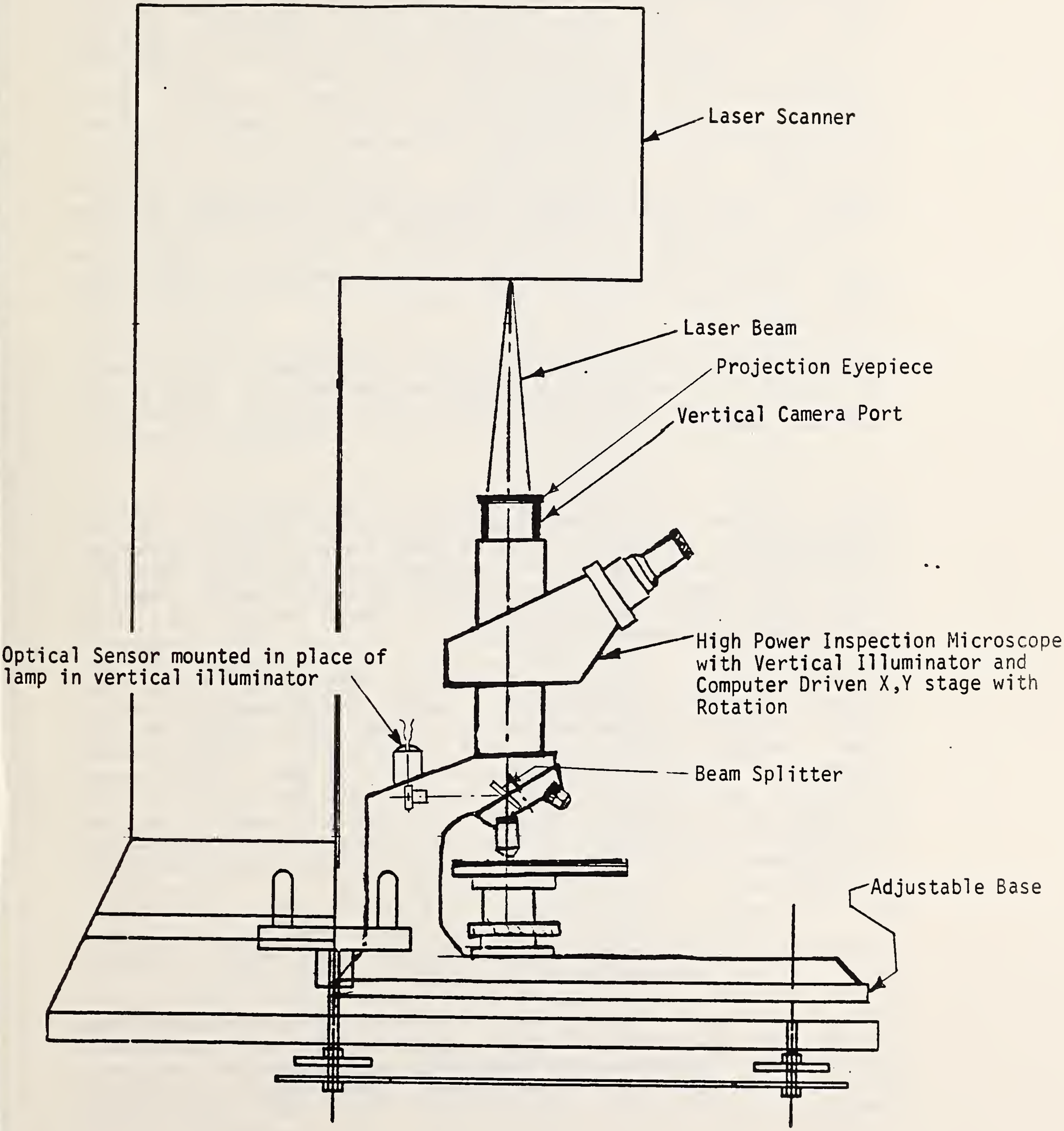


Figure 17 - A Typical Configuration for a Laser Flying Spot Scanner with Microscope

splitter to a detector mounted in place of a normal vertical illuminator light source. This signal will be synchronized with the galvanometer excitation signals to produce a polar coordinate scan. The detector signal will be used to intensity modulate the pattern displayed on a CRT. This will give an image of the substrate on the microscope stage. It can easily be seen that the scanning pattern can be changed to a two coordinate X, Y scan or a diametral scan of constant angle or variable angle. These techniques of scanning may be used interchangeably and can be programmed from the display console.

A pattern recognition system can be adapted to identify shape, size, and number of artifacts identified in the field. Reliable number counts can be obtained if programmed properly using a diametral scan with a motorized X, Y stage on the microscope. This system can eliminate the tedious counting operation now carried out by human operators.

The height of the microscope can be adjusted by changing the height of the mounting plate shown in Figure 16. Algorithms for image enhancement and pattern recognition can be added to this system to further enhance its uses in the inspection process.

This system can also be adapted to operate in the transmission mode and to allow lasers of different wavelengths to be used; see references 7 and 8 in Appendix 1. The laser flying spot scanner can also be adapted to the near infrared with appropriate reflecting type objectives and detectors.

This project includes the design and fabrication of a full defect counting system with a suitable microscope station and a computer driven mechanical stage, using a helium neon laser scanner (wavelength 6328 angstroms). The output image will be displayed on a monitor screen. Simplified controls for changing scan modes will be required. A tunable die laser, not included in this study, may be substituted for the helium neon laser to explore the improvement in detection which can be obtained by spectral filtering.

Project #6--Automated Array Slicing Saw with Optical Inspection Station

This project concerns inspecting the finished substrates after the epitaxial layer has been formed and the arrays have been processed through the photo resist spinner, baking, exposure and developing. This inspection is for determining the best yield of 60, 120, and 150 element detector arrays from the substrate. The inspection is for defects in the array as well as inclusions and other artifacts which limit array length. After the good arrays on the substrate have been located, an automated counting system will check length and determine how to cut for best yield of longest arrays or whatever other rationale is selected to meet the immediate production needs.

The substrate should be mounted on a carrier which will also be compatible with the " cutoff" saw. The substrate will be approximately 1/2" X 1" with a number of arrays located on its surface. The arrays will have sufficient space between them to allow for cutting and separating without damaging the detectors. A typical array is shown in Figure 18 after it has been cut from the substrate.

A number of carriers can be mounted in a cassette so that the operation may proceed with a minimum amount of human intervention. The input to this station will therefore be one or more cassettes. Since the substrate is mounted on a carrier, the output of this station can also be a cassette. The very small arrays which have been cut from the substrate will still be held in place on the carrier by a suitable cement.

The station can consist of an input buffer containing a number of magazines, a robot to unload and transfer the substrates to the laser scanner, a cutoff saw with magnetic or vacuum chuck for the carriers, a washing station and an output buffer for magazines. The robot must have enough reach to also transfer the carriers from the laser scanner to the "cutoff" saw. The data on the array lengths and defects will be fed to a computer which determines the cutting pattern and records it. This information is processed and used to determine the cutoff saw adjustments so that they can be made automatically. The finished carriers with cut substrates are processed through a washer before being transferred to the output cassette. A tentative floor plan for this station is shown in Figure 19. It is apparent that these operations must be carried out in a clean room area. Therefore the rearrangement of these operations within a clean room is shown in Figure 20. This station should be controlled by a computer which is programmed for this specific operation. The computer should be located outside of the clean room area to allow convenient access for programming. Ideally this clean room area should have glass partitions so that the work modules can be observed during operation. The clean room facilities for this station can have one of two configurations. Either a clean room can be built individually for this operation or this operation may be located in part of a larger clean room area. The particulate generating quality of a cutoff operation would

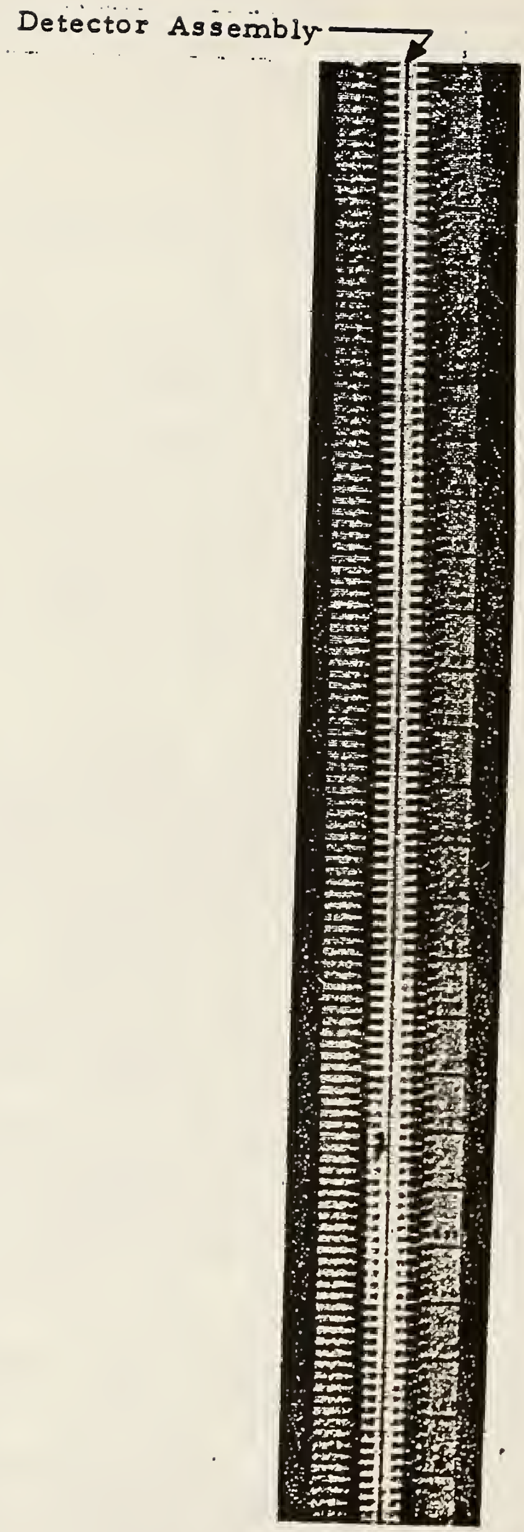


Figure 18 - One Detector Array (There will be several arrays on each substrate)

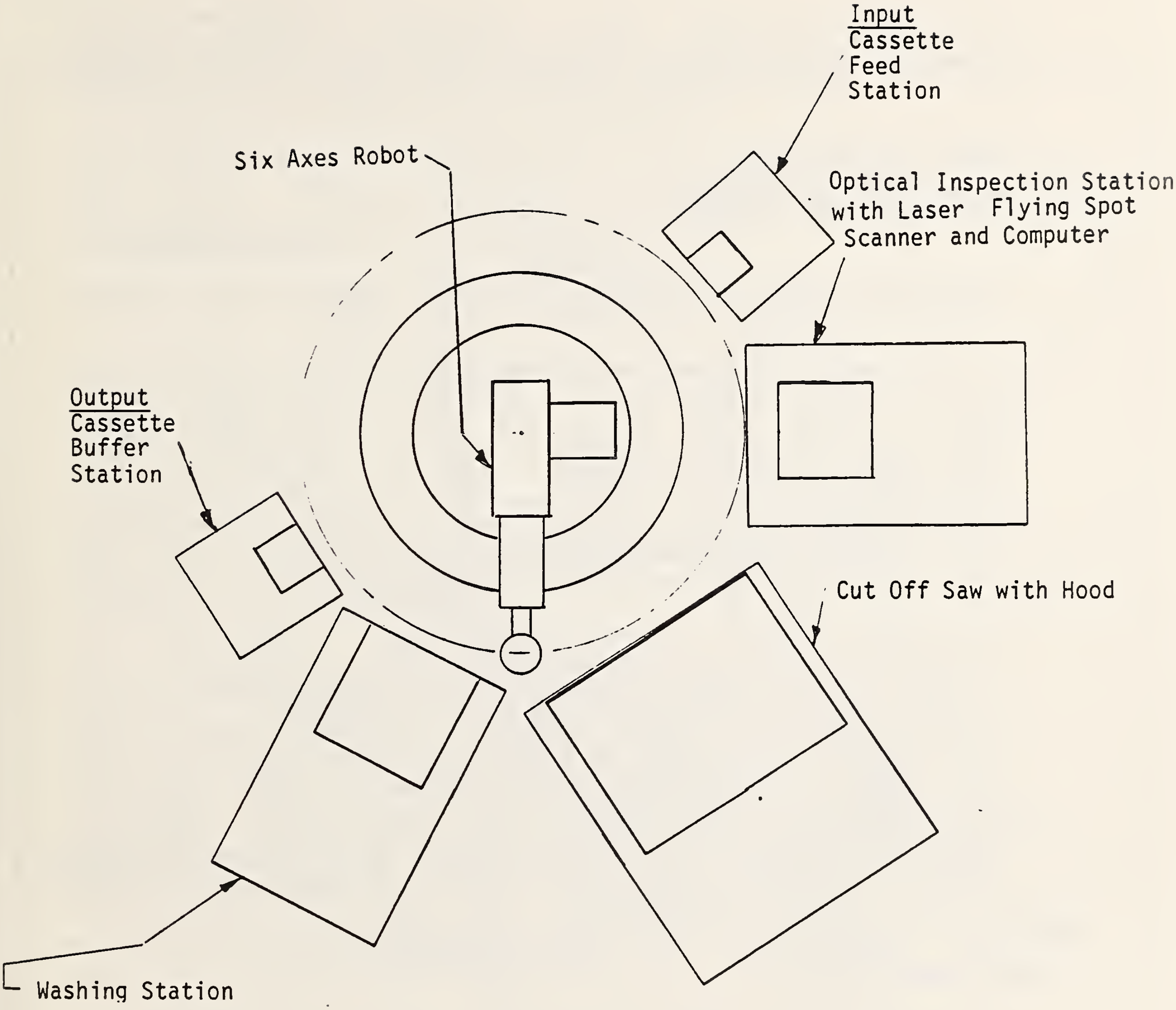


Figure 19 - Automated Array Slicing Saw with Optical Inspection Station

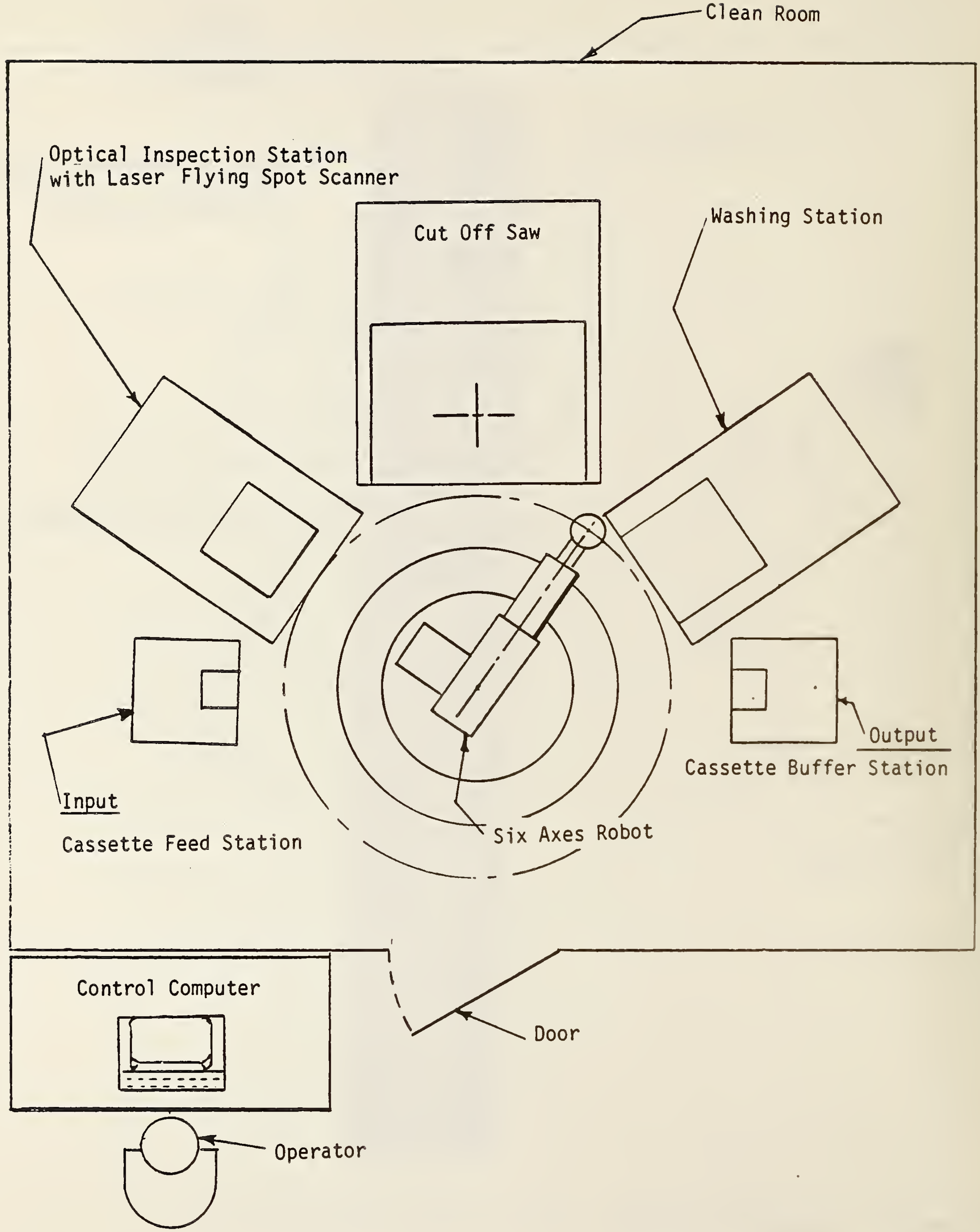


Figure 20 - Automated Array Slicing Station and Inspection Station Shown in a Clean Room

normally favor a separate room. The diffusion of particulate matter may be minimized by building a suitable shield around the cutoff saw and using a cutting liquid which does not contaminate the substrate.

The cost of installed clean rooms varies from $350 to $800 per square foot depending on particle count and accessories. Therefore, the clean room area assigned to each operation should be minimized.

Project #7--Automate Indium Bump Method of Lead Attachment Using Optical Inspection Techniques.

This project may consist of evaluating the features of already developed equipment for attaching leads to the HgCdTe detection array by the Indium Bump method. This equipment uses an infrared microscope to look through the detector array and the mask. These are displayed on a T.V. screen. The matching of fiducial marks is now accomplished by manual translation of the stage in X and Y coordinates. The stage should be converted to a motorized stage with stepping motors and suitable power supplies so that it can be driven by a computer.

This equipment should be examined to see whether there is an available optical port through which the laser scanner described in Project #6 can be used to find the fiducial marks. The dedicated computer can be programmed with a search algorithm to direct the laser scanner to locate the fiducial marks and measure their location with regard to a convenient datum point. This information can be matched with the fiducial marks from the infrared microscope and suitable difference signals can be generated. These signals can drive the X and Y translation motors to align the detector with the mask. The computer may also contain a program for automating the remaining steps in the lead attachment process.

The functions of loading the detector into this equipment and unloading the completed detector should be examined for suitability to automation. The detector arrays are very small and may have to be mounted on a subplate to be handled by a robot. This subplate must not interfere with the other steps in this operation, therefore it must transmit the infrared radiation used in the microscope system. This project should be a feasibility study with the implementation to be carried out on a best efforts basis.

Project #8--Automate the Optical Inspection of Arrays for Defects and the Examination of Contacts.

This project would utilize the laser scanning equipment described in Project #6 with a suitable high power microscope. The configuration for this equipment is shown in Figure 17. This project must explore the combination of raster polar and diametral scan techniques to determine the best combination to use in developing an algorithm for determining the quality of the overall detector array and contact structure. Pattern recognition techniques can be utilized with appropriate image enhancement to devise a method for automating this process. This inspection represents one of the highest skill levels which is performed by the operator. Therefore it is anticipated that the experimental nature of this project would make it appropriate to undertake it on a best efforts basis.

While it is difficult to estimate the cost of developmental projects in advance the following very rough estimates have been prepared for determining overall program magnitude.

Option 1	Budgetary Estimate
Project #1	$250,000
Project #2	300,000
Project #3	200,000
Project #4	350,000
Project #5	250,000
Project #6	450,000
Project #7	350,000
Project #8	250,000
	$2,400,000

This will be approximately a 2.4 million dollar effort over a period of two years. It is estimated that a team of 15 scientists and engineers would be required. The implementation of these projects could take place in the existing clean room facilities at the Night Vision Laboratory at Fort Belvoir, VA.

Option II. This option considers the automation of critical processes in an actual production line fabricating HgCdTe detector arrays (for profit). The difficulty, which can be immediately seen, is that any delay in production caused by this automation will cause scheduling problems and therefore losses. While there is no good way of avoiding some delays these can be minimized by developing the automated process "off line". The process can then be installed at the production facility with minimum downtime. Since this automation will be done in a clean room environment it will involve a duplication of facilities and efforts which add to the cost. A typical program for automating each operation is as follows:

- On site study of the selected process at the plant
- Design of the automated process at the laboratory
- Fabrication and purchase of equipment for the process
- Selection of a suitable laboratory "off line" clean room installation site

- o Installation at laboratory "off line" site
- o Trouble shooting process at laboratory site
- o Disassembly of equipment and shipment to production plant
- o Installation of equipment at production plant
- o Trouble shooting process at production plant

The duplication of effort involved in setting up the process twice has the advantage of showing up potential problem areas. The selection of the process to be automated at a production plant must be done with consideration of the probability of success since this type of task does not fit into a best efforts category. Consequently it is not logical to select the most difficult and intangible process for automation in a plant production line. The process must also be mature enough so that it is not changed during the period that the automation task is being carried out. These considerations point to the difficulty of automating a process which is already operating in a manufacturing plant. One additional consideration which past experience has disclosed is that the level of cooperation from the plant personnel is better when this automation is carried out by plant personnel. This often makes the difference between success and failure.

Considering these factors the cost of automating a process of mean complexity such as the "Automated Array Dicing Saw and Optical Inspection Station" similar to Option 1, Project 6, can be 8 to 10 times the cost of automating at a laboratory level. Nevertheless the following five subprocesses are listed for automation at a plant. They are identified with their estimated levels of complexity.

Subprocess	Level of Complexity
o Automated Optical Inspection of Etch Pit Defects	Medium to high
o Automated Loading and Unloading of CdTe in Horizontal Bridgman Furnace for Growing Single Crystals	Very high
o Automated Loading and Unloading of Liquid Phase Epitaxial Layer Growing Process	Very high
o Automated Array Dicing Saw with Optical Inspection Station	Mean
o Automated Indium Bump Method of Lead Attachment using Optical Inspection Technique	High

The approximate cost of automating a mean complexity process at plant level is between 2 and 3 million dollars. The cost of automating a high complexity process cannot be estimated in this report since a detailed estimate from a mature process must be used as a guide. However, it will be generally much higher than a process of mean complexity. A program to automate the five processes in Option II at production plant level is estimated to cost from 10 to 20 million dollars and success of the high complexity processes cannot be guaranteed.

Option III. Automate complete HgCdTe detector array process at a manufacturing plant level. Using the process in Appendix 3 as a guide, with direction from the Night Vision Laboratory project monitor, 69 of the 102 processes were to be considered for automation. However, if the manufacturing plant is to be considered operational it must have all processes performed at a reasonable throughput rate.

Since Option III is a considerable task, the site, building and clean room facilities should be adequate to perform the entire process. Using this principle as a guide it is possible to estimate the approximate area needed for the average sub-process steps and to allow for access areas. The parameters developed here are considered to be tentative since it will require a detailed engineering design to establish firm requirements.

The average floor space needed per operation with room for equipment, robots, and access area, excluding aisles can be estimated as 6 ft.X 10 ft. or 60 square feet. This should be doubled to allow for aisles and buffer storage. Therefore at 120 square feet per subprocess, 102 subprocesses will require 12,240 square feet of clean room facility. Using the cost of $800 per square foot gives a cost of $9,792,000 for the clean room area. The support facilities for this type of manufacturing will require approximately 8000 square feet so that a total building of 20,000 square feet would be required. This can probably be built at a cost of $100 per square foot or a total cost of $2,000,000.

The average cost of each automated operation can be estimated at $2.5 million while manual operations can be estimated at $600,000 each. Therfore if this plant contains 69 automated operations and 33 manual operations it is possible to get an overall estimate of installation costs.

20,000 square foot building at 100,000 per sq. ft.	2,000,000.00
12,240 square foot clean room installation at $800.00 per sq. ft.	9,792,000.00
69 automated operations at 2.5 million	172,500,000.00
33 manual operations at $600,000	19,800,000.00
Total	$194,092,000.00

This cost does not include the trouble shooting required by scientists, engineers, and technicians to get the facility operational. It is estimated that a team of 30 people will be required for a period of 4 years to carry out this work. With travel costs this can be estimated at approximately $5,000,000 per year for 4 years or $20,000,000. There will be many other factors not covered in these estimates including building site, partitions, power lines, office equipment, waste disposal and other facilities necessary to a manufacturing plant of this type.

It is therefore apparent that a more refined estimate is needed. It is also apparent that the clean room area should be minimized to accommodate the detailed operations. Some consideration has been given to developing a better operating clean room configuration to minimize cost. However, the principal costs are for the automated operations.

The total cost for this four year program is estimated at 215 million dollars. The estimates for Option I, II and III have been prepared from information gathered from industrial sources. The costs are based upon the process chart in Appendix 3. If changes in the process are introduced, it will be necessary to modify the cost estimates.

Phase II-- Implementation of a Near Term Demonstration of Automation. The Development of a Laser Scanner to Determine Crystal Axis Orientation

I. Statement of the Problem

The determination of the orientation of the crystal axis of the cadmium telluride substrate material has been one of the most time consuming operations in this process. This axis must be located within 0.5 degrees in order to optimize the performance of the detector. The subsequent processes of epitaxial layer growth and implantation are affected by errors in the alignment of the 1,1,1 crystal axis. The current method for determining the location of this axis is a Laue pattern using X-ray radiation. The X-ray beam is directed through a photographic film to a point on the cadmium telluride crystal. The X-rays are reflected back from the lattice planes of this crystal to give a pattern of dots. This requires an exposure of 15 to 20 minutes per print. The resulting pattern is then examined for threefold symmetry which indicates the 1,1,1 plane. The errors in angular position of the dots must be correlated with the error in the 1,1,1 axis. Therefore, this is not a real-time technique nor is it direct reading. Since the crystal growing process for cadmium telluride is not as mature as for silicon, the wafers may have several different crystal orientations over the surface. It is, therefore, necessary to take a number of Laue patterns over the surface of the wafer to locate the desired 1,1,1 crystal orientation. The areas which will have this orientation are unpredictable and with present crystal growing techniques it may take as long as 4 hours to completely explore a one inch wafer.

The objective of Phase II was to explore the techniques for the determination of the crystal axis orientation and seek a faster method which could be used for mapping the surface of the cadmium telluride wafer. A laser technique was demonstrated at the Night Vision Laboratory to illustrate an alternative method.

The goal was to develop, design and build a breadboard model of this instrumentation to demonstrate the feasibility of automating this process. The demonstration was to show that the measurement could be accomplished more rapidly and the yields of 1,1,1 material increased.

II. General Discussion

The cadmium telluride crystal must have a polished surface in order to get a good Laue pattern for crystal axis determination. The X-rays are diffracted from the atoms in the lattice planes of the crystal giving the characteristic pattern which can identify the crystal axis orientation. This technique is essentially a surface technique since the X-rays penetrate only 100 to 1000 lattice planes dependent upon the absorption constants of the crystal. The actual depth of penetration is very small.

Using an optical technique to measure the crystal orientation requires a different surface preparation from the X-ray technique. This technique requires a selectively etched surface where the etch pits follow the lattice plane boundaries and the etch pit density is high. Since selective etches for cadmium telluride have not had extensive development, it has been found that sandblasting the crystal with 15 micron silicon carbide abrasive gives a high population of etch pit related surfaces. These result from cleavage along lattice plane boundaries. Reflecting a coherent laser beam from a sandblasted surface of a crystal, therefore, can give a characteristic pattern. This is described in greater detail in the ASTM Standards, References 5 and 6. The laser technique is therefore also a surface technique but it uses much deeper surface morphology than the X-ray technique.

The pattern produced by a laser reflecting from a 1,1,1 oriented surface of a cadmium telluride single crystal has threefold symmetry. Therefore, if a real time system can be devised to detect this symmetry, the crystal axis determination can be automated.

The laser pattern from the 1,1,1 plane of cadmium telluride is reflected at a very wide angle and does not have good definition. This is due to the diffuse reflection which comes from surface features unrelated to the crystal lattice planes. The difficulty of this problem was recognized only after a number of crystal samples were tested with a laser beam in the laboratory. These samples were supplied in the form of wafers and boules of crystalline cadmium telluride. Since the crystal growing techniques for this material are not yet mature, these wafers and boules contained multiple crystals.

Methods for exploring the surface of the crystal with a laser beam were investigated. The problems of signal to noise ratio were reviewed with regard to improvement of this parameter. Laser scanning techniques were also analyzed for application to this problem. If the orientation of the crystals can be determined in the boule, then it may be possible to recover these crystals in addition to the 1,1,1 orientation.

From these inputs, the principles for the laser scanner were derived. The advantage of a laser scanner over a fixed laser beam is that it can generate much more information from the reflected patterns providing there is a means for correlating the laser beam position with the reflected energy. The proposed technical approach was developed from these principles.

III. Technical Approach

The 1,1,1 cadmium telluride crystal was explored with a laser beam normal to the surface as shown in Figure 21. A photo sensor was mounted on an angle sector so that it could be rotated 360 degrees through angle W around the laser axis. The angle of reflection, theta, was also adjustable. This allowed the photo sensor to measure the polar reflection from the crystal at a number of angular settings of theta. The angle theta was varied from 50 degrees to 70 degrees giving cone apex angles of 100 degrees to 140 degrees. Correlating this information in oscillographic patterns in Figures 22a, 22b, 23a and 23b it was found that the maximum signal reflected from 1,1,1 cadmium telluride occurred at an angle of reflection of 67.5 degrees. This is equivalent to a cone angle of 2 X 67.5 degrees or 135 degrees. The three lobed pattern was clearly detected. This signal was differentiated in Figure 24 and showed a signal to noise ratio which was good enough to be used in an automated system. It was inferred that other crystals would have different peak reflection angles. This was corroborated with a selectively etched 1,1,1 silicon crystal whose peak angle of reflectance was approximately 35 degrees giving a solid cone angle of 70 degrees.

A review of existing commercial laser scanners identified a bacteria colony counter having some features which were applicable to this requirement. This instrument is made by Exotech Inc. It uses a helium-neon laser beam in a circular scanning pattern to measure the transmission of light through a bacteria culture in a petri dish. This instrument is shown in Figure 24A. The laser beam deflection is accomplished by two galvonometer driven mirrors excited by two sine waves of the same frequency but 90 degrees out of phase. The radius of the circular scan is determined by the amplitude of the sine waves. This instrument was adapted to scan a point from all azimuth angles by using an ellipsoidal reflector to converge the circular scan. Using the exit pupil of the optical system at one focus of the ellipsoid, the second focus was then imaged directly on the crystal surface. This is shown in Figure 25a. In this manner the crystal was illuminated by a laser beam rotating 360 degrees about its axis at a rate of 125 revolutions per second. A detector in the center of the scanner, located close to the crystal, was used to detect the light reflected from the 1,1,1 crystal surfaces. The principle for enhancement in signal to noise ratio obtainable from this scanner is shown in Figure 25b. This enhancement is due to the fact that most of the light from the diffuse reflection surface does not reach the detector. The signal reflected from the facets of the crystal however is picked up by the detector. The diameter of the laser scan on the ellipsoidal mirror is changed to change the angle of incidence of the laser beam as shown in Figure 25c. This system, therefore, provided a rotating beam which is incident on a 1mm diameter spot on the crystal and whose apparent origin moves around in a toroidal conical path at the rate of 125 revolutions per second.

INTENSITY VS. ANGLE MEASUREMENTS

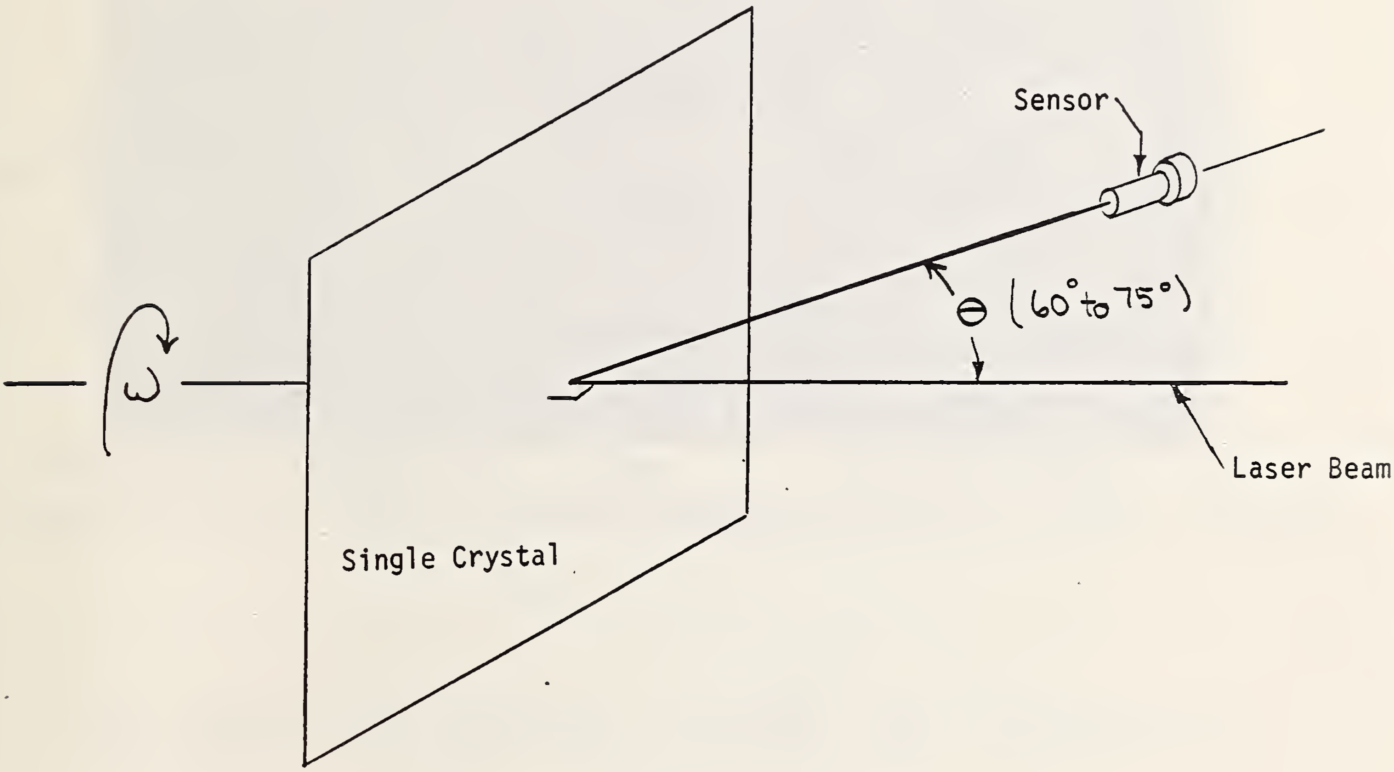
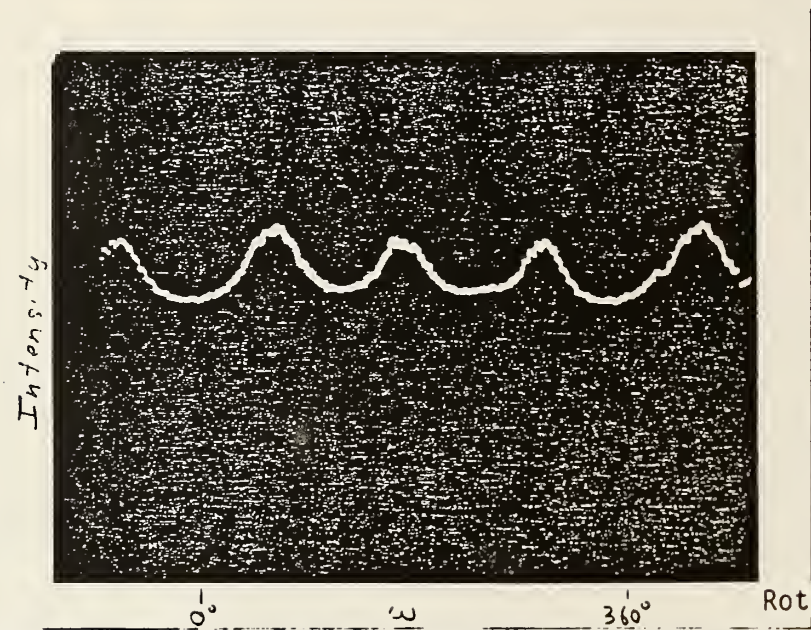


Figure 21 - Measurement of Reflection Pattern from Scanning a Single Crystal

INTENSITY VS. ANGLE ω FOR θ = 50°

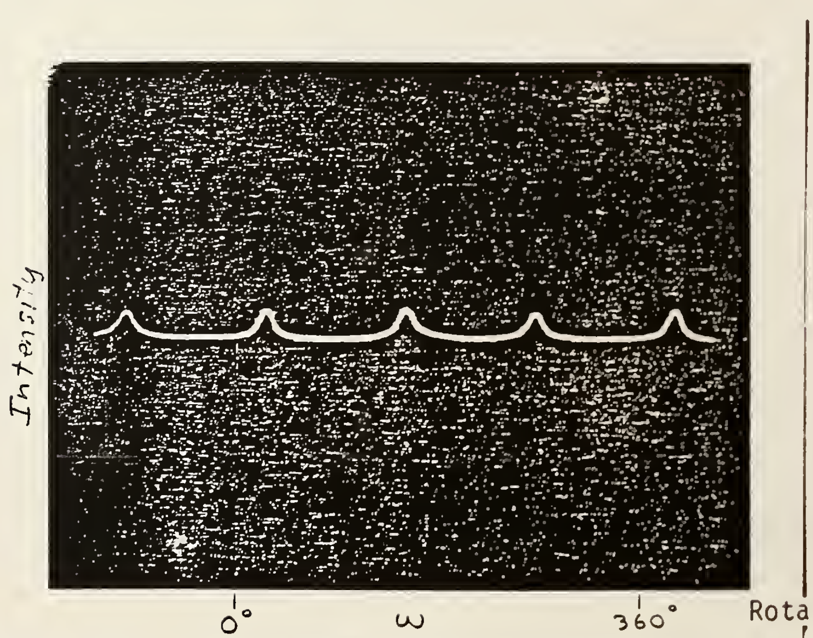


Y-AXIS = 1 VOLT/DIV

Rotation Angle is time base

Figure 22a - Oscilloscope Trace of Reflected Pattern at θ= 50°

INTENSITY VS. ANGLE ω FOR θ = 60°



Y-AXIS = 5 VOLTS/DIV

Rotation Angle is time base

Figure 22b - Oscilloscope Trace of Reflected Pattern at θ= 60°

* PHOTOS EXPOSED AT f = 5.6, DEVELOPMENT TIME = 32 SEC

INTENSITY VS. ANGLE ω FOR Θ = 67.5°

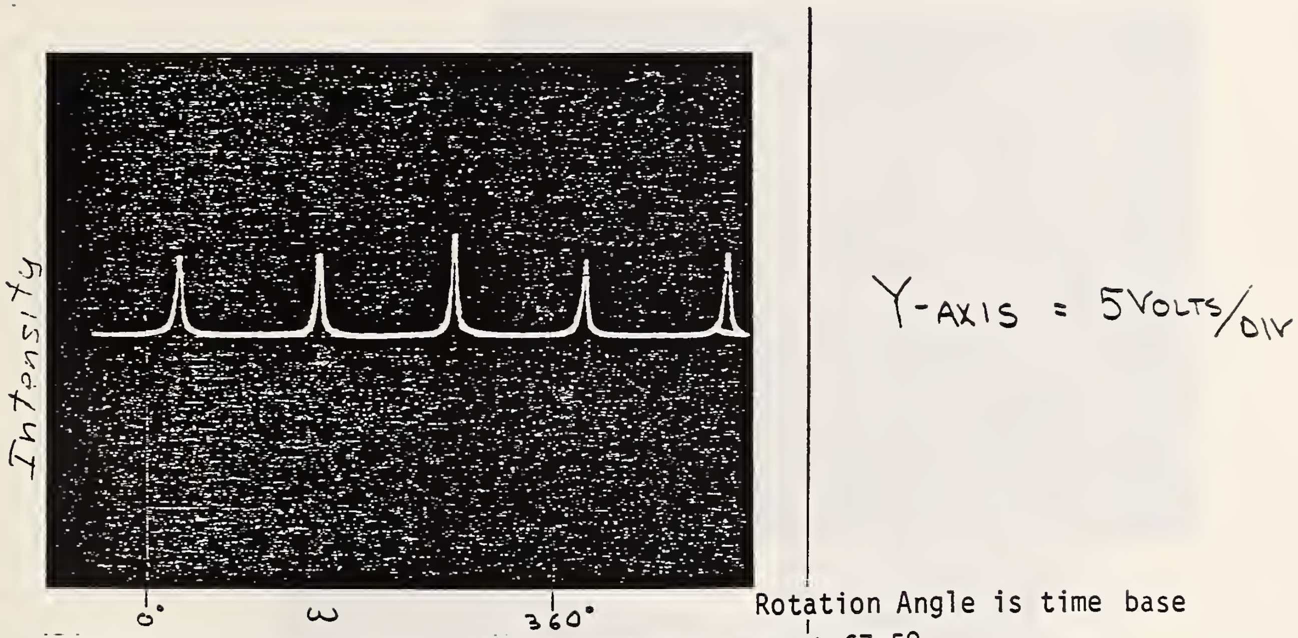


Figure 23a - Oscilloscope Trace of Reflected Pattern at 67.5°

INTENSITY VS. ANGLE ω FOR Θ = 70°

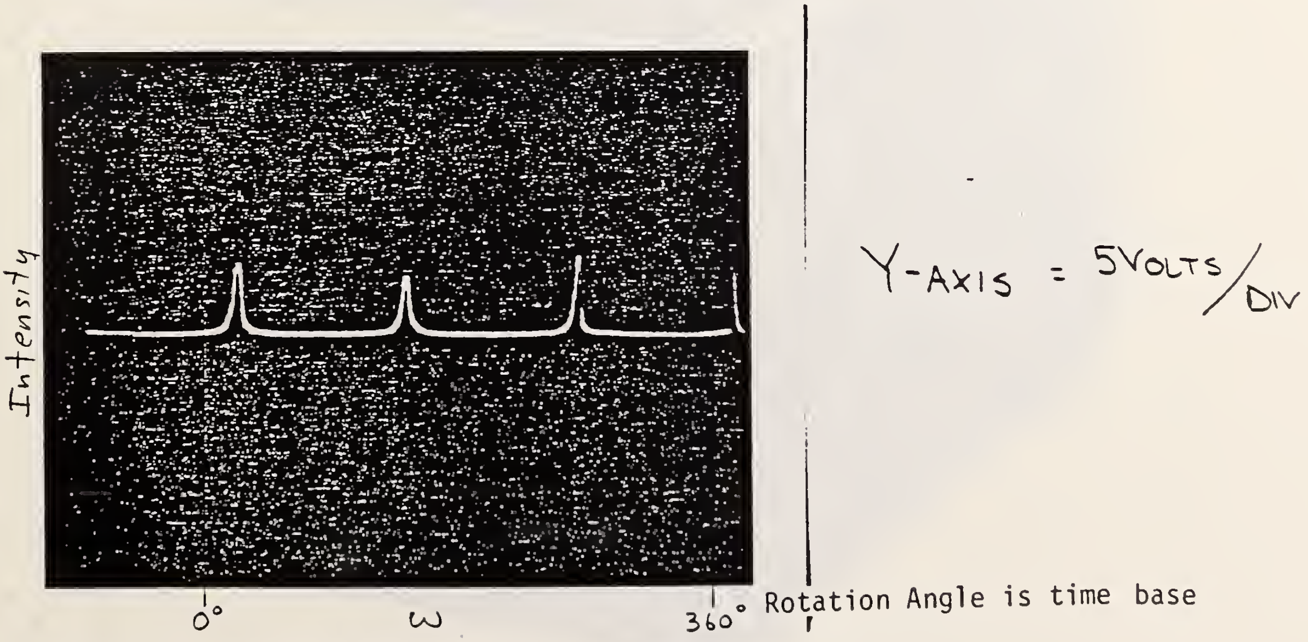
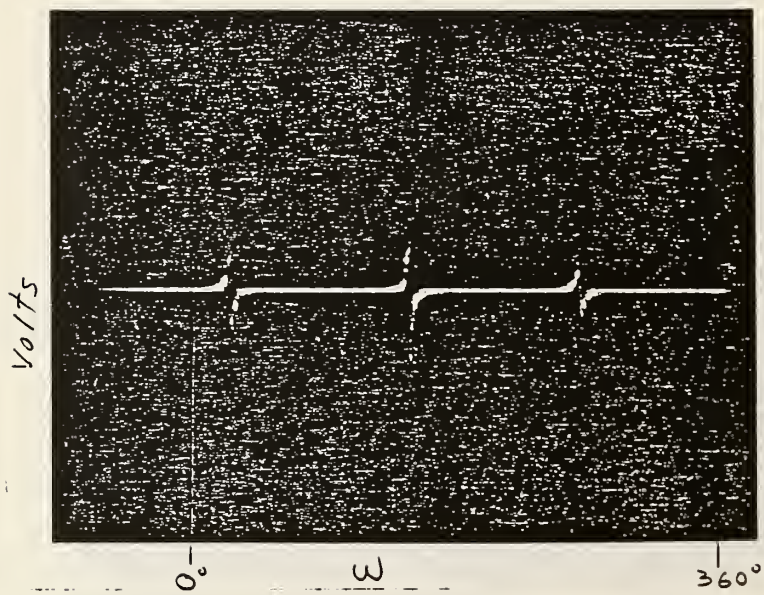


Figure 23b - Oscilloscope Trace of Reflected Pattern at 70°

* PHOTOS EXPOSED AT f = 5.6 DEVELOPMENT TIME = 32 SEC.

FIRST DERIVATIVE OF INTENSITY VS ω AT $\Theta = 67.5°$

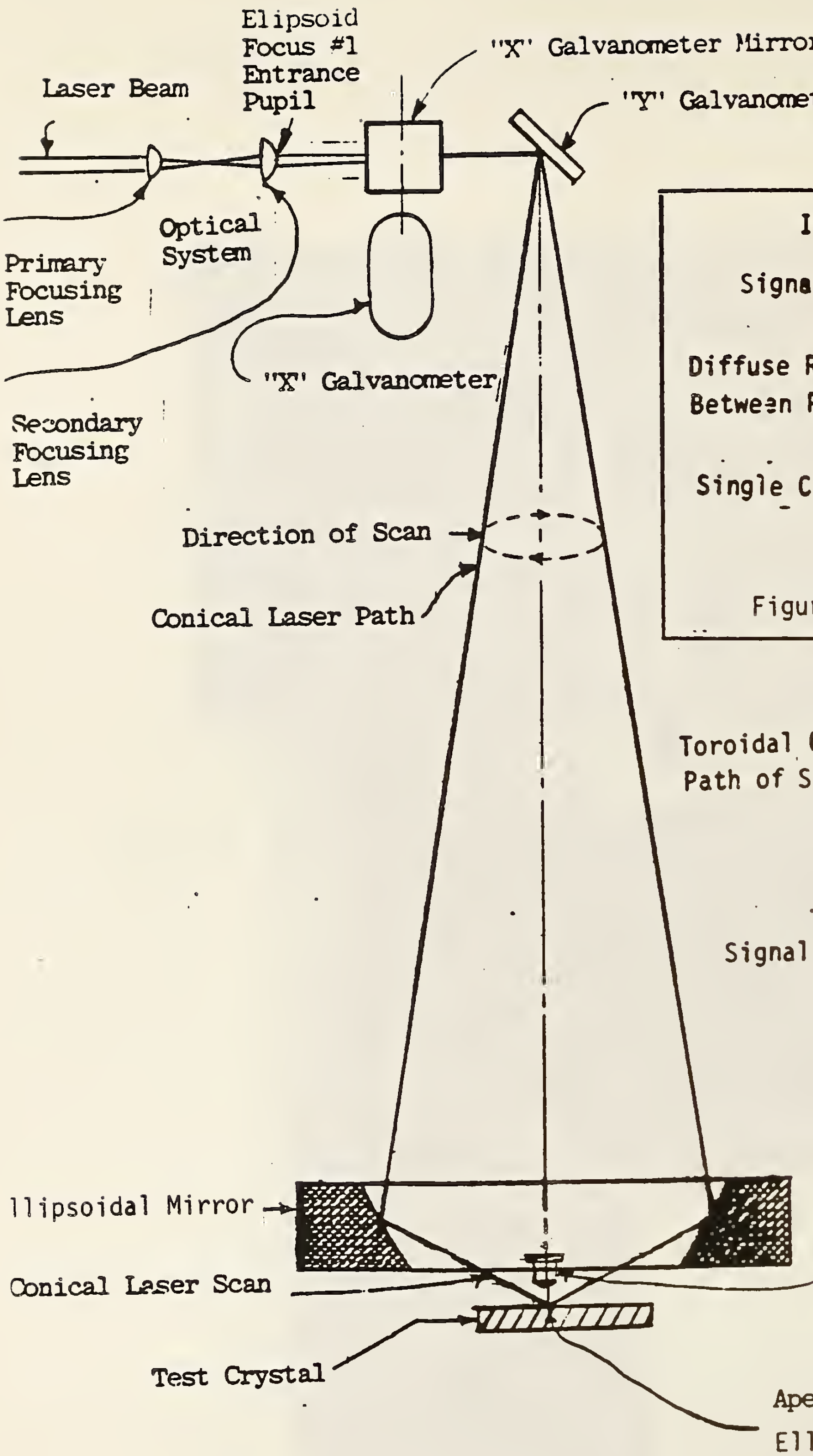


$$f(\omega) = \frac{dI}{d\omega}$$

Figure 24 - Oscilloscope Trace of First Derivative of Reflected Pattern at 67.5°

* PHOTO EXPOSED AT f: 5.6, DEVELOPMENT TIME = 32 sec

Figure 24 a Laser Scanner for Counting Bacteria Colonies



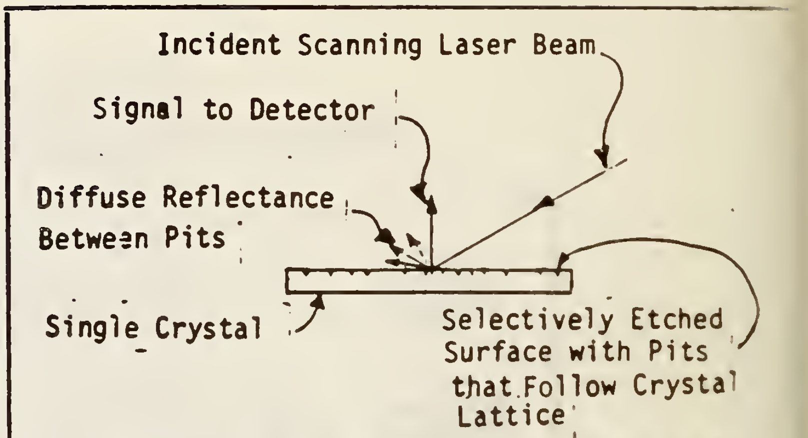


Figure 25 b Signal to Noise Enhancement

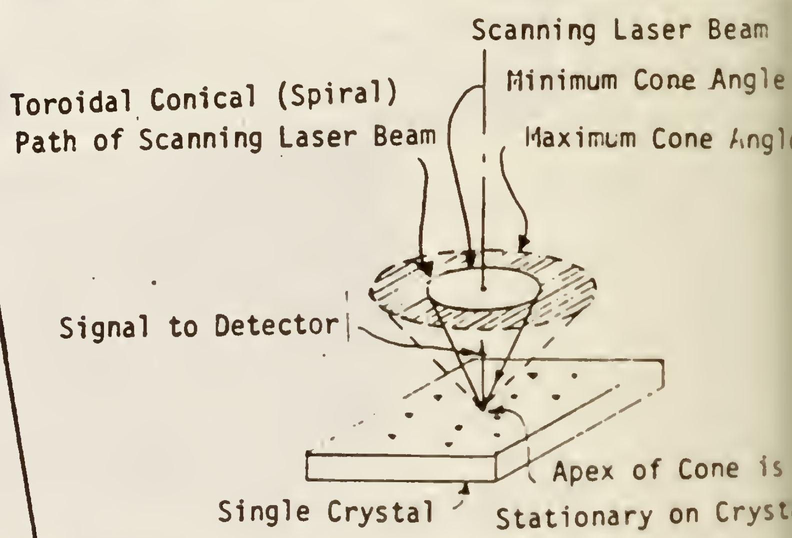


Figure 25c Dynamic Spiral Conical Toroidal Laser Scan

Figure 25 a Laser Scanner for Crystal Axis Orientation

Synchronizing this signal with an oscilloscope sweep yields a time based display of this pattern. The driving signals for the galvanometers can also be used to drive the "X" and "Y" axes of the oscilloscope to get a polar pattern. Connecting the detector output to the "Z" axis of this oscilloscope displays the spatial patterns of the reflected light from the crystal surface.

The design of this instrument included a goniometric stage to mount the crystal so that it can be mapped for orientation over its entire surface. This may be accomplished by a simple polar translation for wafers. However, since it would also be desirable to map the surface of the boule to improve the yield, a system for translating and rotating the goniometer stage in cylindrical coordinates was devised. Sample mapping display techniques were explored to facilitate analysis of this information. A typical crystal distribution for a boule is shown in Figure 26a. A representation of the cylindrical map of the surface of the boule is shown in Figures 26b and 26c. A goniometric mount having two rotational axes and one translation axis with the appropriate power supplies was used to map the crystal suface. The goniometer is controlled by signals received on either an RS-232 serial or an IEEE 488 parallel data bus.

The design of the laser scanner is shown in Figures 27, 28, and 29. A vertical adjustment table was designed to mount the goniometer so that it can be focused on both the end and the circumference of the boule. This adjustment is manual but it can be automated in the future.

A hardware version of a simplified pattern recognition algorithm was designed and built using 960 shift registers to count 360 degrees. This gives a potential accuracy of approximately 0.3 degrees for location of the lobes of the reflected pattern. The algorithm selected for the three lobed pattern was to "and gate" the signals every 120 degrees using the clock frequency of the laser scanner to synchronize the clock of the pattern recognition system. Detection of these patterns shown in Figure 30 is indicated by lighting a diode. This scheme was easily extended to the 1,0,0 plane which has a four lobed pattern and to the 1,1,0 plane which has a two lobed pattern. The schematics for this pattern recognition system and associated circuitry are contained in Figures 31, 32, 33, and 34.

This scanner was demonstrated to the Project Monitor as a breadboard model on October 24, 1985 with a 1,1,1 cadmium telluride crystal and a 1,1,1 silicon crystal. The signal to noise ratio of this scanner is so good that it can pick up the reflection from silicon far outside of the optimum reflection angle for this material, where it cannot even be seen by the human eye.

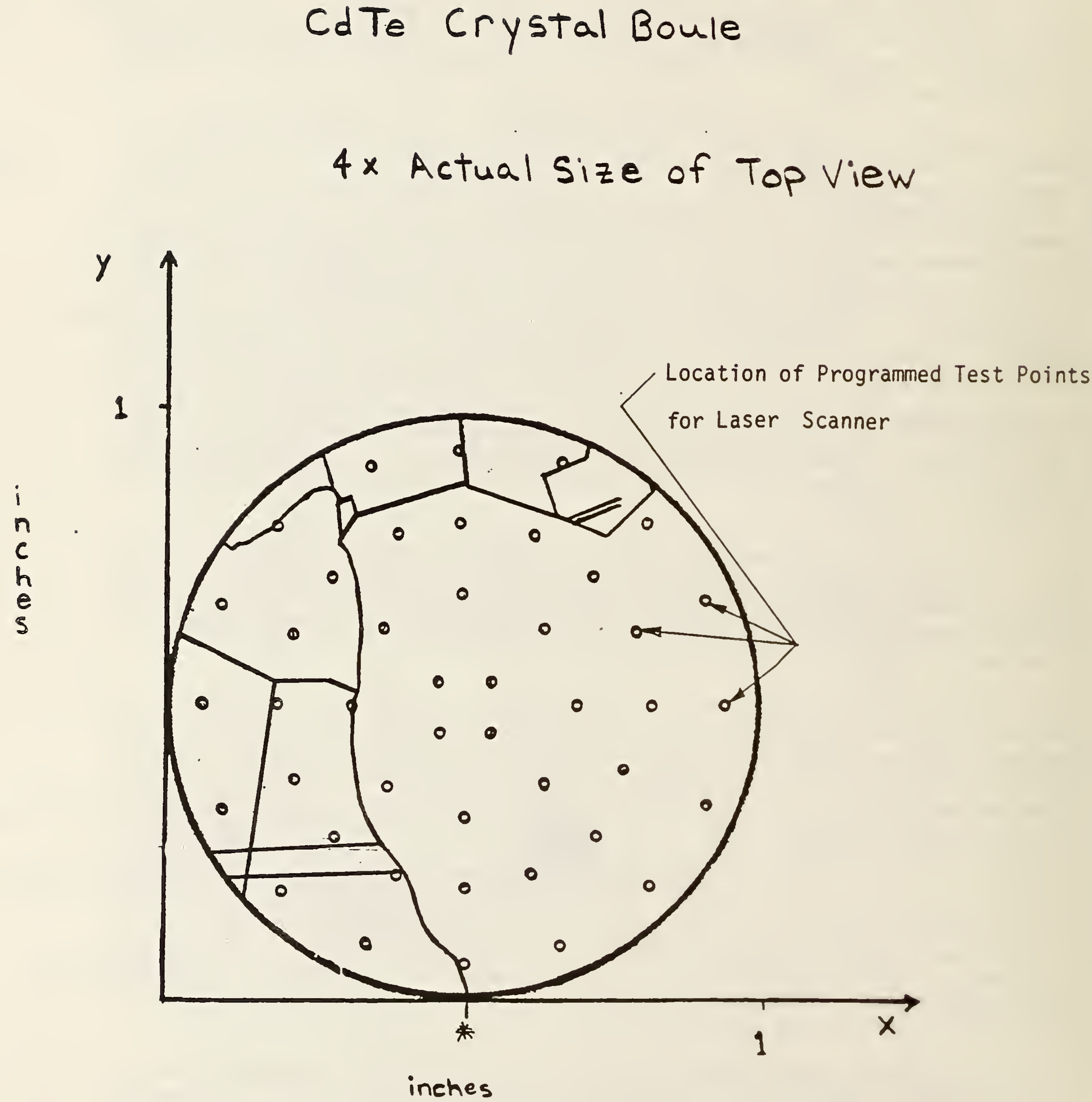


Figure 26a Typical Crystal Structure for the end of a Boule or a Wafer of CdTe

*: This is the zero Reference point

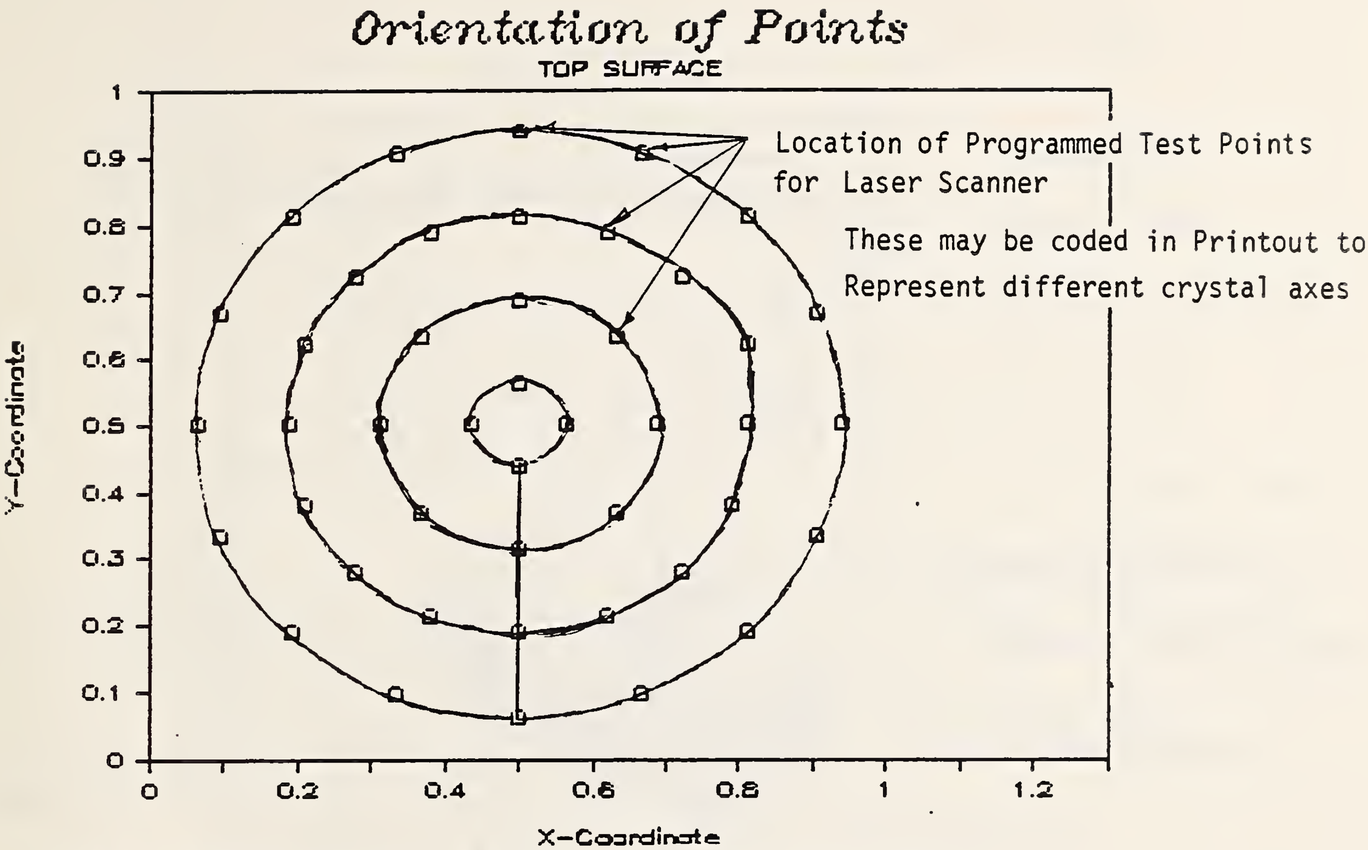


Figure 26b Mapping Display for Round Wafer or End of Boule

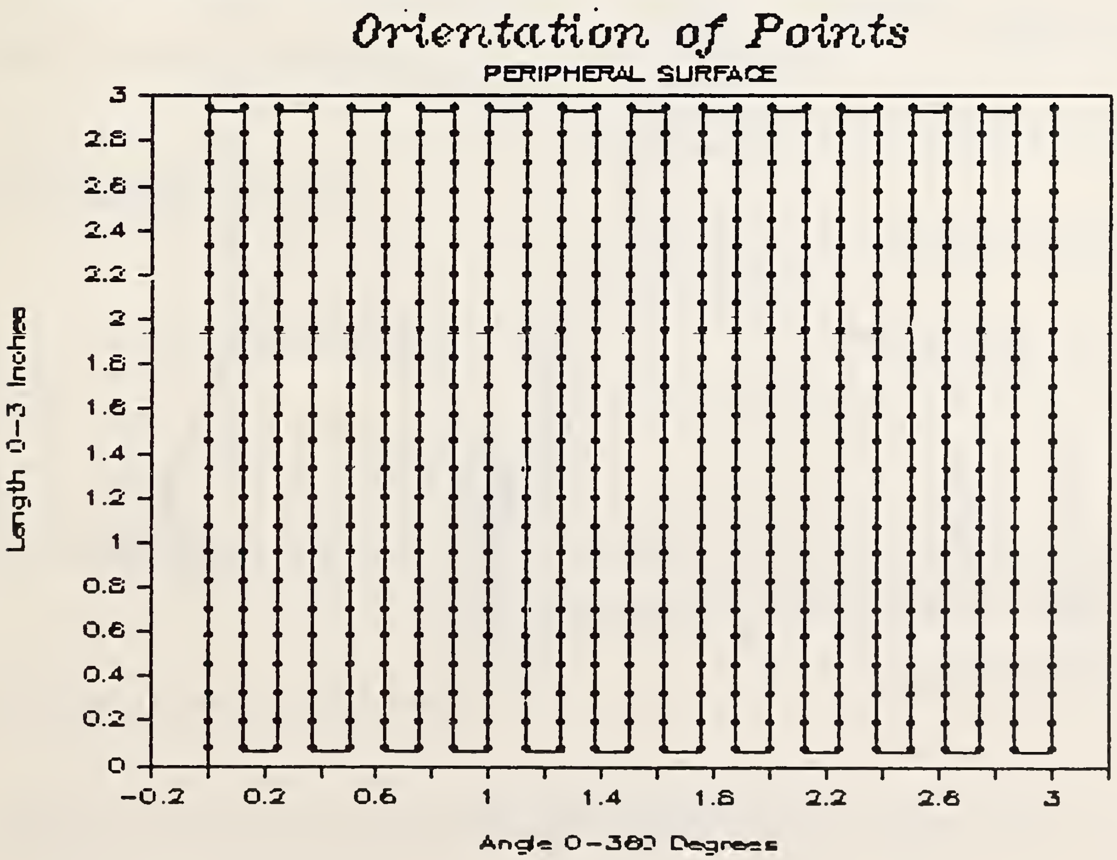


Figure 26c Mapping Display for Cylindrical Surface of a Boule

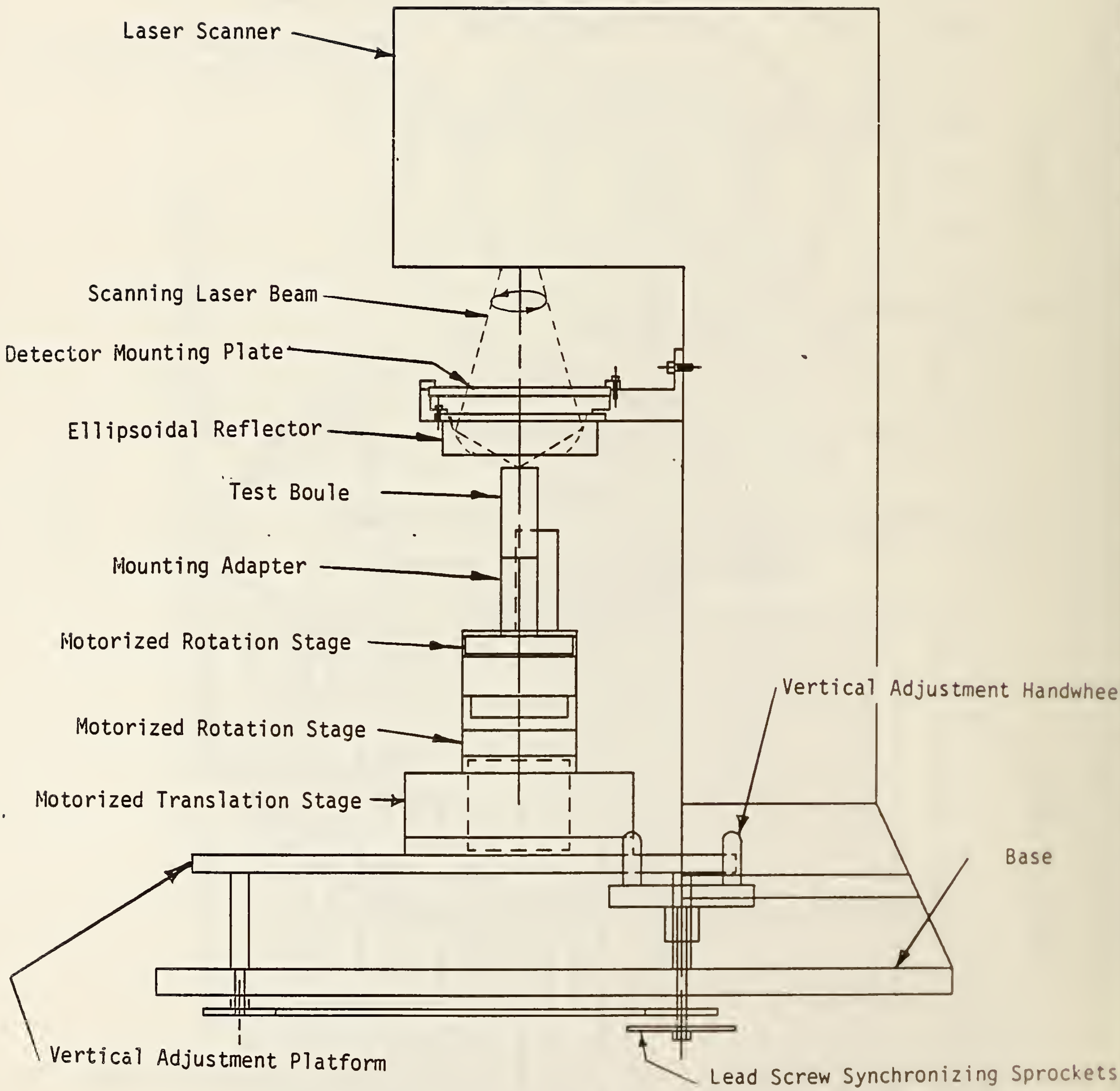


Figure 27 - Side View of Toroidal Laser Scanner

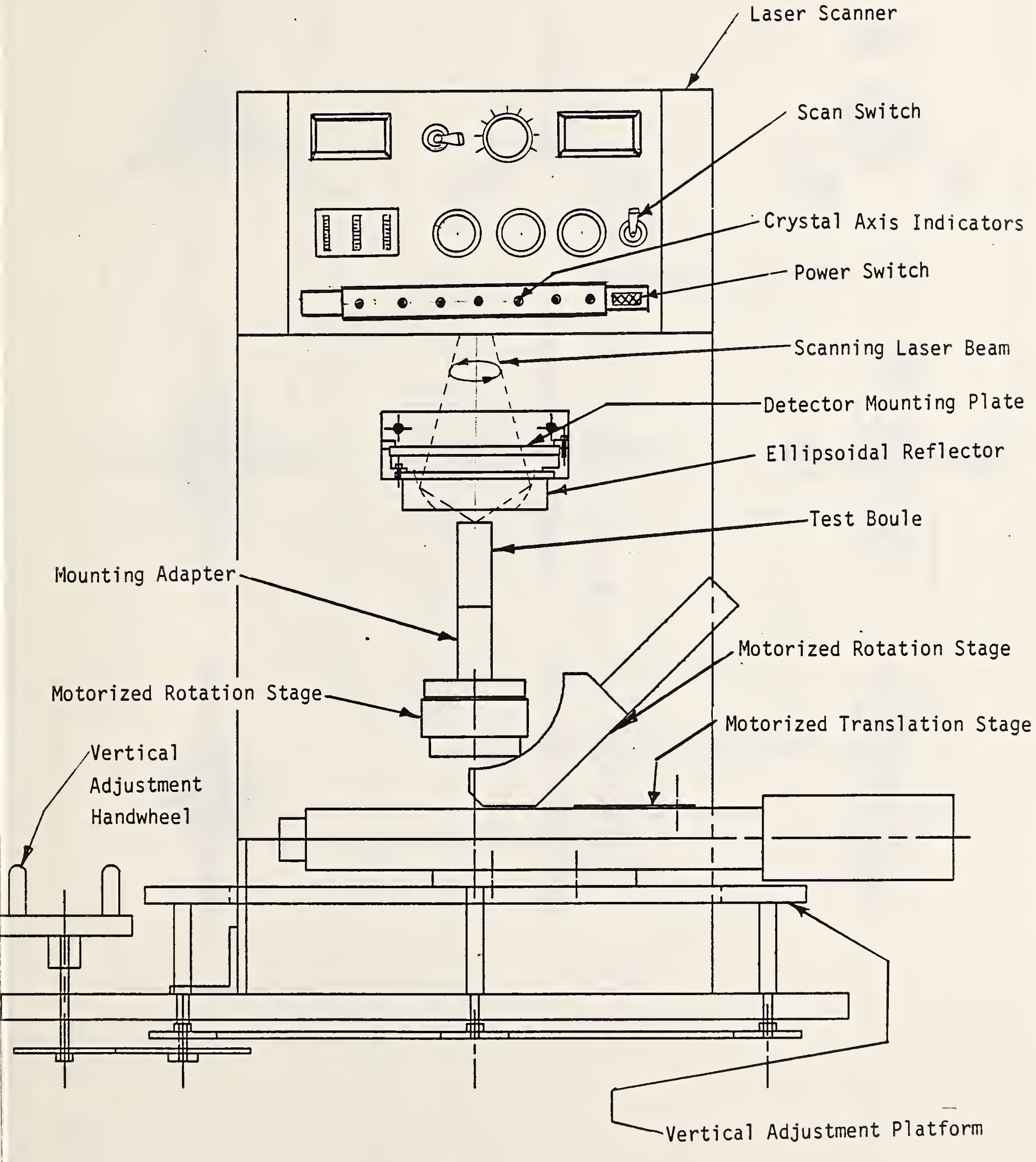


Figure 28 - Front View of Toroidal Laser Scanner

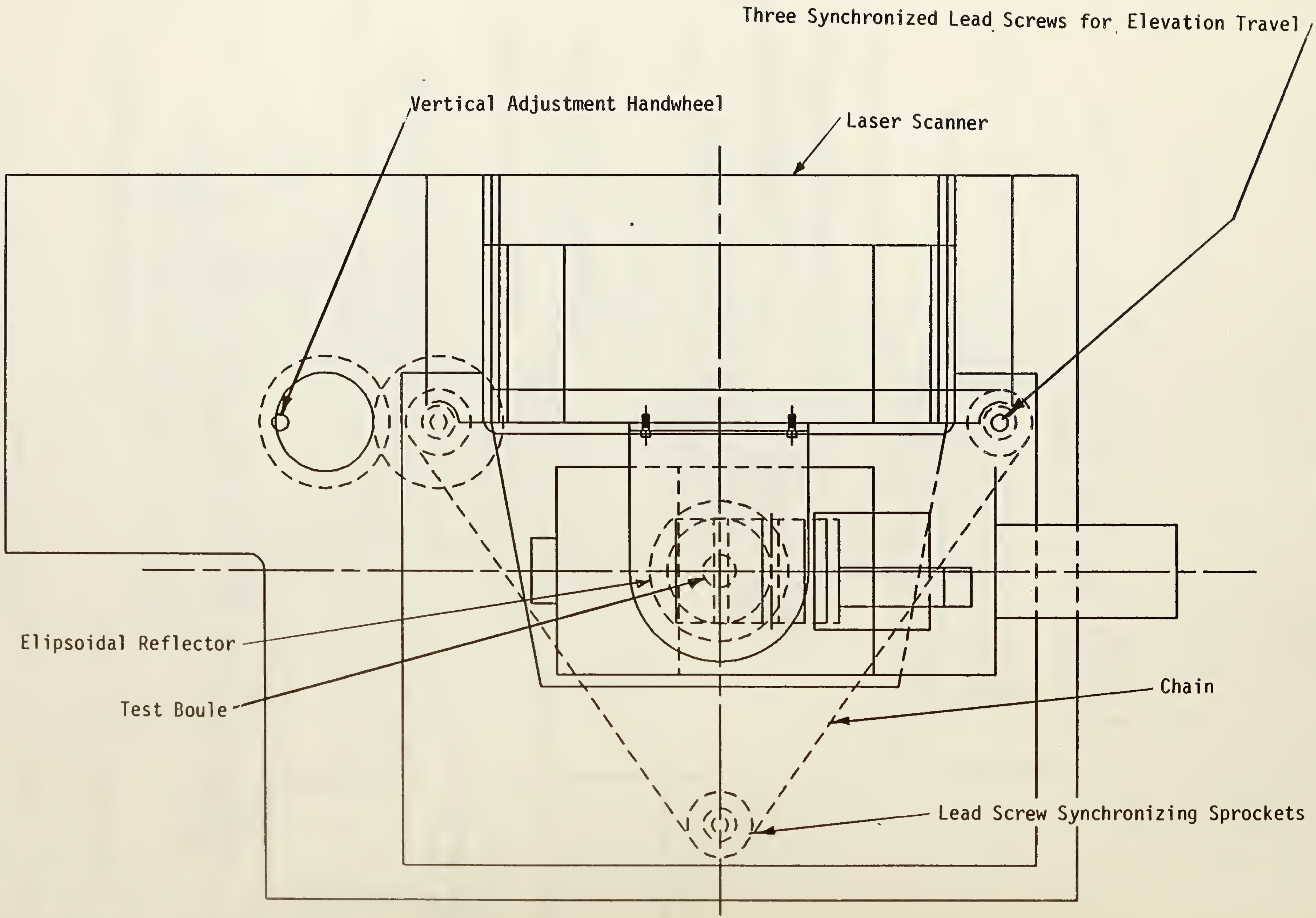


Figure 29 - Top View of Toroidal Laser Scanner

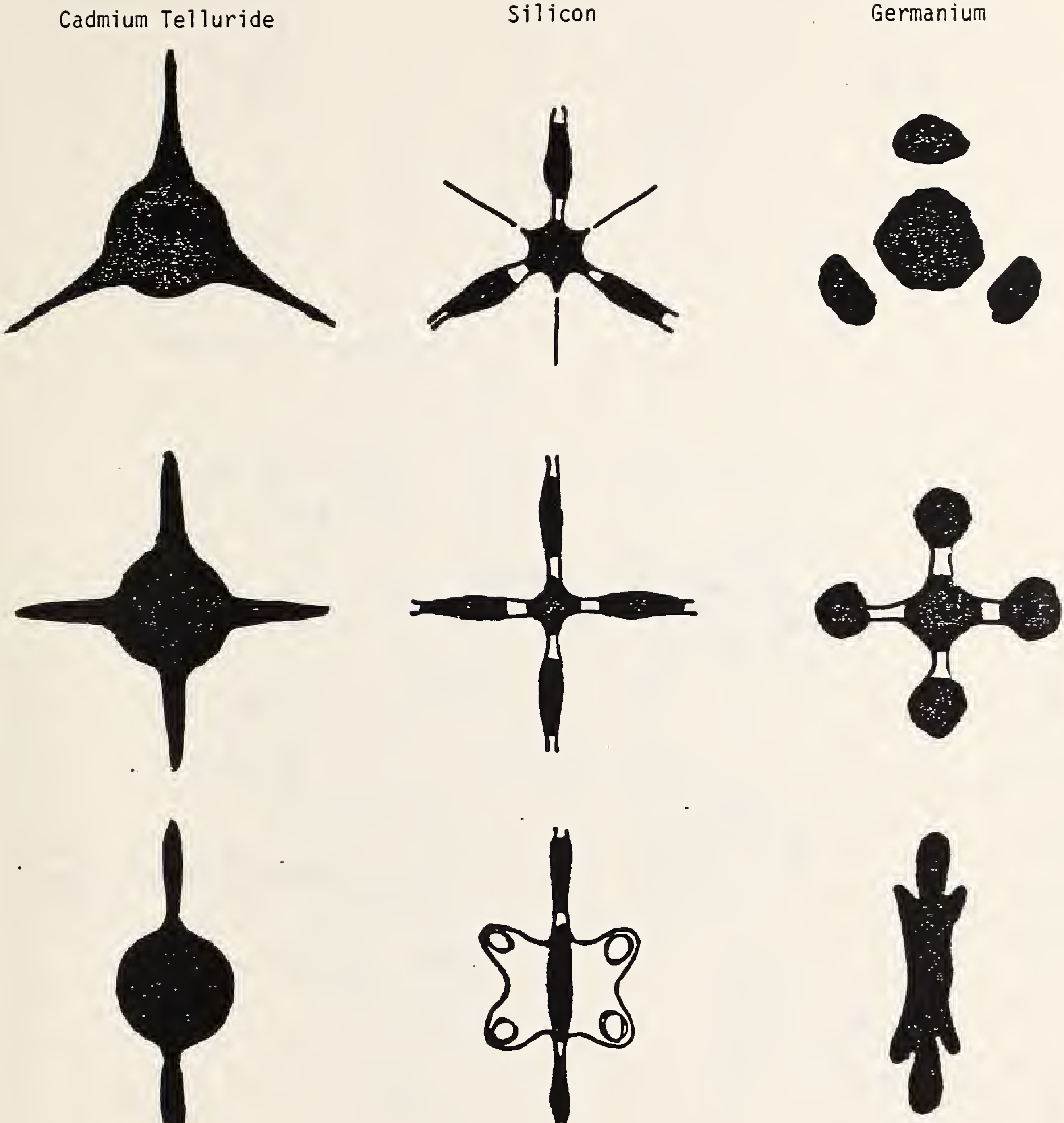


Figure 30 Typical Geometric Patterns Produced by Scanning Crystal with Laser

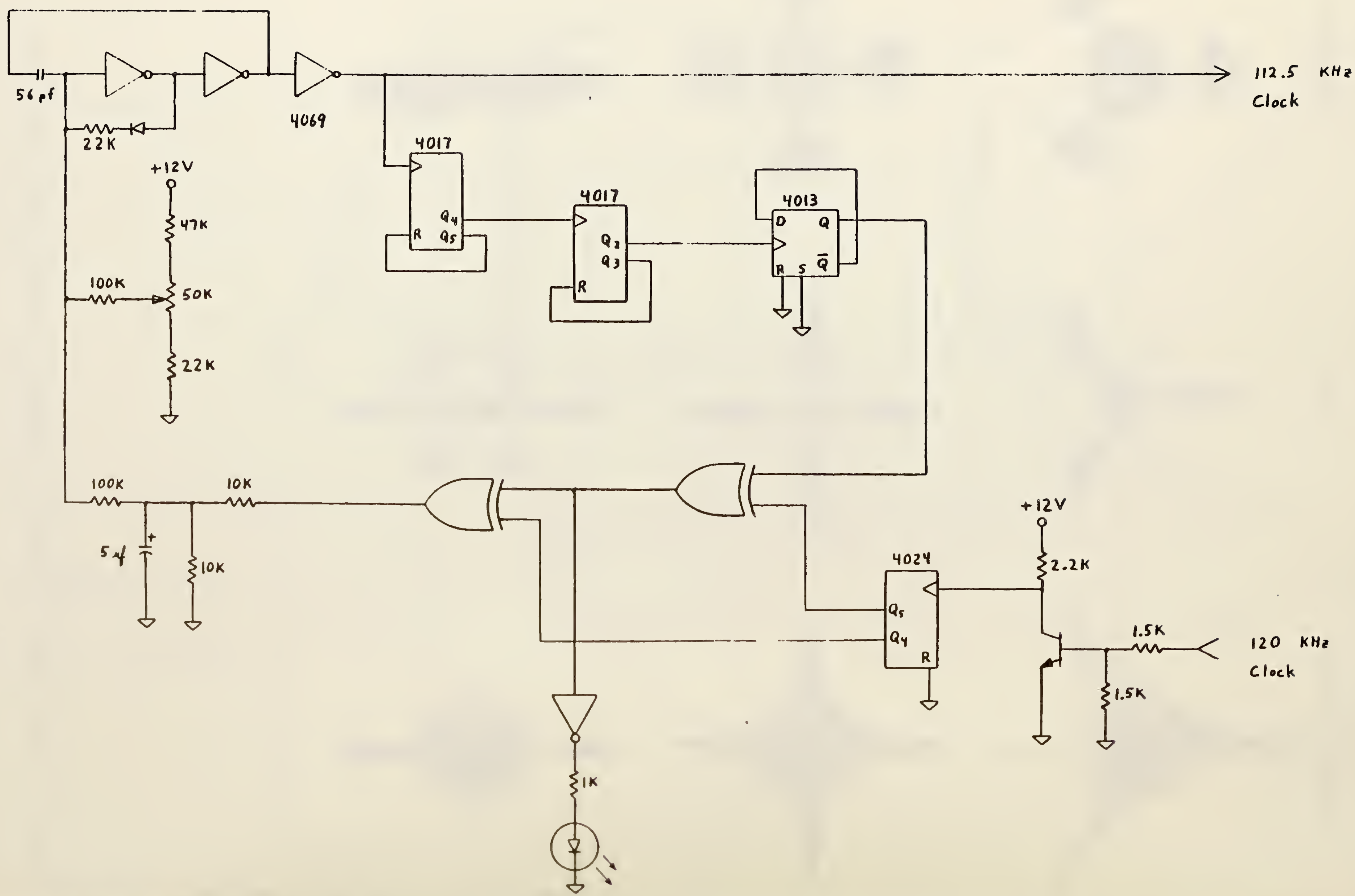


Figure 31 Schematic of Clock Circuitry for Laser Scanner

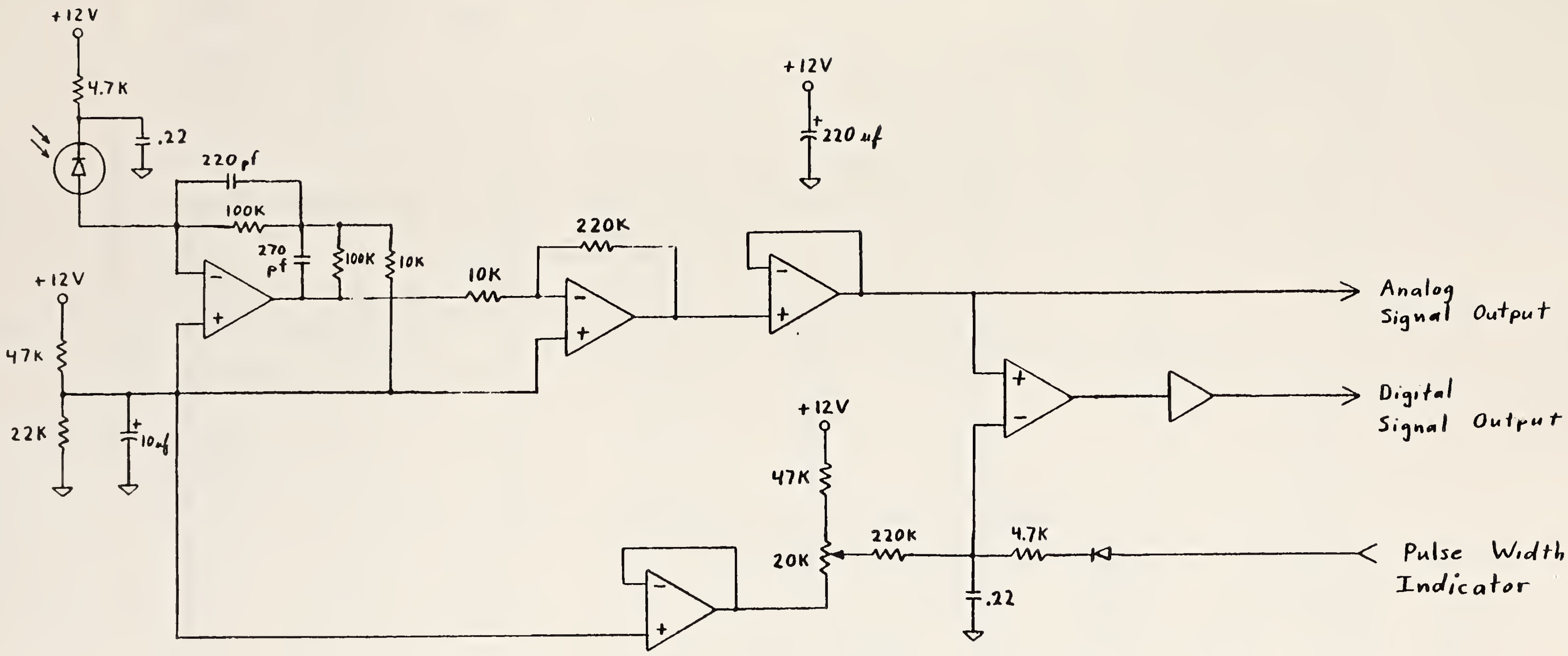


Figure 32 Schematic of Signal Amplifier Digitizer for Laser Scanner

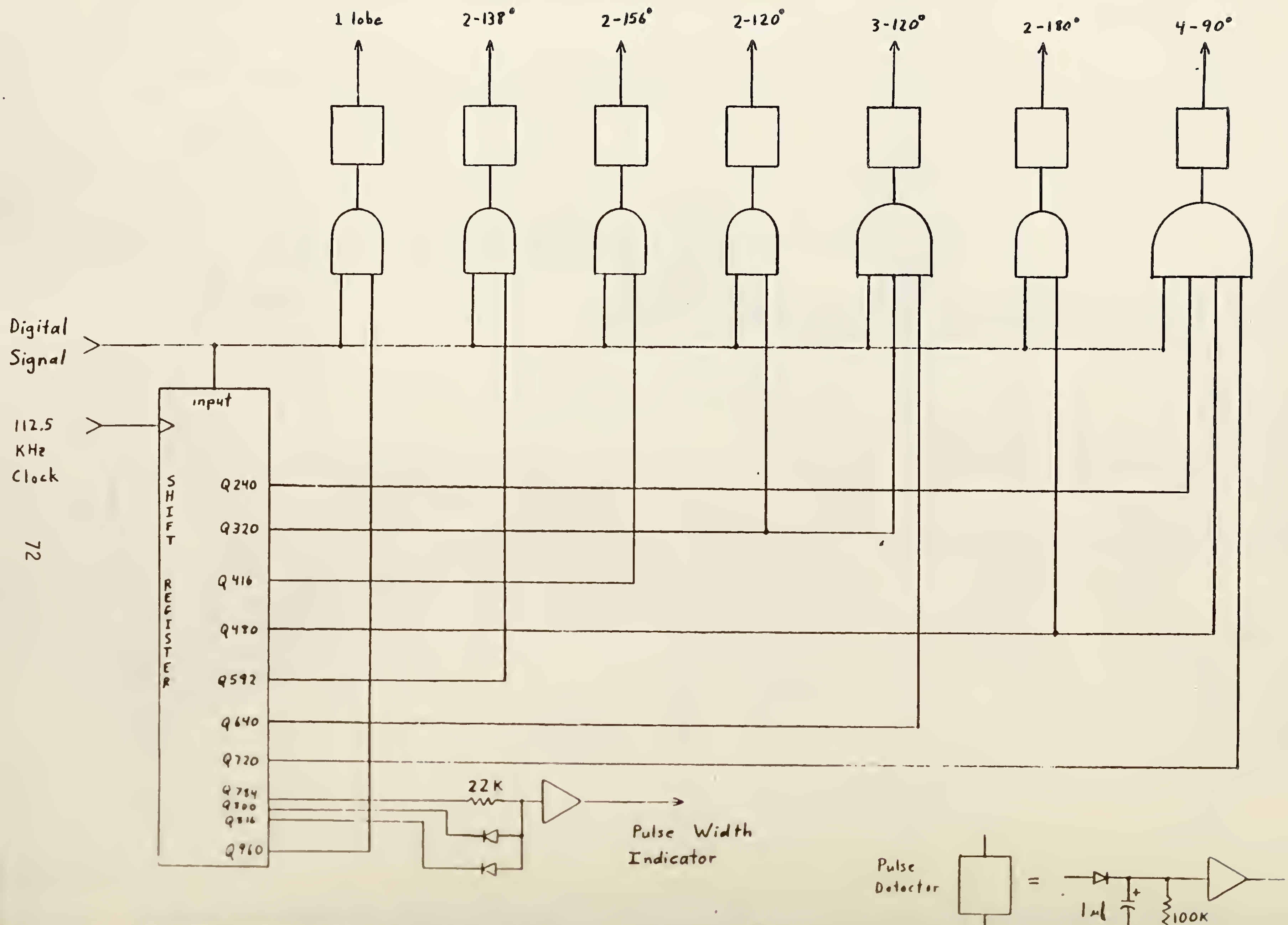


Figure 33 Schematic of Pattern Recognition Circuitry for Laser Scanner

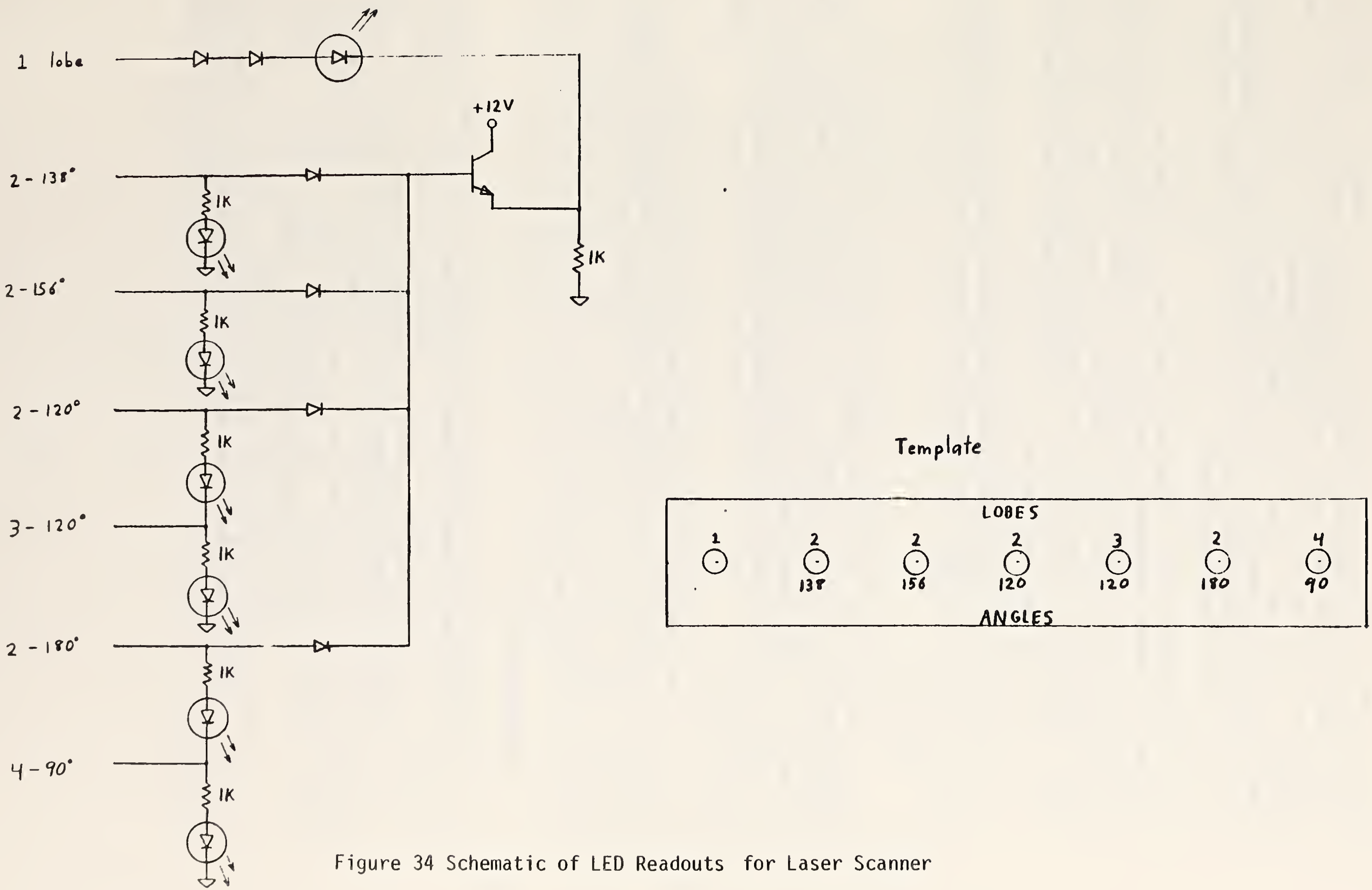


Figure 34 Schematic of LED Readouts for Laser Scanner

Since there were no samples of 1,0,0 cadmium telluride available, much time was spent mapping the sample boules using X-ray techniques to locate other crystal orientations to test the scanner. A selectively etched crystal of 1,0,0 silicon was however, obtained from the NBS Center for Electronics and Electrical Engineering. This crystal was immediately identified by the laser scanner pattern recognition system as having a four lobed pattern.

This breadboard has been upgraded to a prototype model by automating the scanning circuitry, extending the pattern recognition to seven different crystal orientations and packaging the circuitry and the displays inside the instrument. This instrument has been developed far beyond the breadboard model called for contractually. The goniometric mount has also been completed and assembled to the scanner.

The Night Vision Laboratory has provided a computer to automate this scanner. This has not yet been interfaced due to expiration of funding.

IV. Results

The feasibility of this scanner has been successfully demonstrated using a number of crystalline samples. The potential accuracy is good since the sensitivity is doubled by reflecting the laser beam from opposite sides of the sample. In addition the very favorable signal to noise ratio of this scanning system improves its sensitivity to small angular deflections.

While further development should be done on this scanner it is presently usable for experimental work. Crystals of cadmium telluride and silicon have been tested and characteristic patterns have been identified in real time. Crystals of gallium arsenide have also been tried and show some favorable pattern indications.

V. Recommendations

The successful demonstration of this laser scanner for crystal axis orientation shows a great reduction in testing time: mapping a one inch wafer in 3 to 4 minutes instead of 4 hours. In addition the automated pattern recognition of the 1,0,0 and 1,1,0 planes as well as the 1,1,1 plane give a 300 percent potential improvement in yield. The mapping of the boules can therefore help to provide lower cost material. This toroidal laser scanner also has the potential for higher angular accuracy due to its high signal to noise ratio.

It is recommended that work on this scanner be continued to include more advanced software algorithms for pattern recognition, automating of the coordinate mapping program and automating the logging of data and the printing of maps.

Appendix I
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Appendix 2

Field Trips and Conferences

Date	
January 14, 1985	Conference at Night Vision Laboratory Fort Belvoir, VA and Visit to Laboratory Facilities to Observe HgCdTe Fabricating Processes.
January 24, 1985	Conference at NBS on Ellipsometry of Thin Films
January 29, 1985	Conference at NBS on Non Destructive Testing Applied to HgCdTe InfraRed Detectors
February 5, 1985	Conference at Night Vision Laboratory Fort Belvoir, VA on Materials Growth and Fabrication for HgCdTe Infrared Detectors.
March 7, 1985	SME Workshop on Machine Vision in Baltimore, MD
March 19-20, 1985	SME/RE Seminar on Robotics in the Clean Room, San Jose, Calif.
March 21, 1985	Conference Santa Barbara Research Division Hughes Aircraft Company, Santa Barbara, Calif.
April 17, 1985	Conference at NBS on Non Destructive Testing of HgCdTe
April 19, 1985	Conference at NBS on Crystal Axis Measurement on Cd Te substrates.
May 1, 1985	Presentation of Progress at Night Vision Laboratory, Fort Belvoir, Va.
May 13, 1985	Presentations of Program status at Night Vision Laboratory Fort Belvoir, VA.
July 10, 1985	Presentation by GMF on Robots for Night Vision Laboratory at NBS.
August 1, 1985	Conference at NBS on Automated Inspection of Cd Te Substrate Crystals and Substrates, Dr. Santos Mayo.
August 9, 1985	Conference with Dr. Mayo on Photographing Cd Te Substrate Crystals.
August 21, 1985	Presentation of Status of Project at Night Vision Laboratory to William Garrett and Raymond Balcerak, Fort Belvoir, VA.
October 24, 1985	Demonstration of NBS Breadboard Model of Laser Scanner-Goniometer for Substrate Crystal Axis

	Determination Under Phase II of Contract to William Garrett and Raymond Balcerak.
November 19, 1985	Conference at Texas Instruments on Status of Work on HgCdTe Contract. Dallas, Tx.
November 21, 1985	Conference at Santa Barbara Research Division of Hughes Aircraft Corp. on HgCdTe Contract at Santa Barbara, CA.

Appendix 3

* Process Suitable for Automation

Detailed Process for Fabricating HgCdTe IR Detectors Arrays

1. Prepare Cd Te Substrate

A. Material Growth

1) Refine Cd and Te into ingots
*2) Divide Cd and Te into small pieces or granules suitable for precision alloying
3) Weigh each material for proper alloying
4) Make quartz ampule
5) Carbon coat (or other non stick method) interior of quartz ampule
6) Load ampule with seed and Cd and Te, evacuate and seal.
*7) Load ampule into vertical Bridgman furnace, melt alloy and grow crystal boule (14 days) or equivalent process.
8) Zone refine and anneal boule
9) Break quartz ampule and remove boule.

B. Substrate Preparation

1) Cut off ends of boule and cut into several cylinders
2) Sandblast ends and outside of cylinder.
*3) Map cylinder to find 1,1,1 axis and others if possible
*4) Cut cylinders to recover 1,1,1 cyrstals (additional yield may be derived from 1,0,0 and 1,1,0 axes)
*5) Recheck 1,1,1 orientation
*6) Slice wafer on 1,1,1 axis
*7) Polish wafers mechanically
*8) Polish wafers chemically
*9) Clean wafers
*10) Dice wafers into 1/2" x 1" substrates

C. Substrate Evaluation and Testing

*1) Flatness
*2) Resistivity
*3) Etch pit density
*4) Te precipitates
*5) Orientation
6) Hall effect measurement
*7) IR transmission measurements

2. Grow Epitaxial Layer on Substrate (LPE)
    *A. Clean Substrate
        1) Remove grease
        2) Etch

    *B. Furnace Loading

    C. LPE layer growth, anneal and cool

    D. Furnace unloading

    *E. FTIR--Spectrophotometer Mapping
        *1) Cutoff wavelength
        *2) Epitaxial layer thickness

    *F. Defect Counting

    G. Hall effect measurement

    *H. Surface roughness

    *I. Minority-carrier lifetimes

    *J. Other Measurements
        *1) Etch pit density

3. Array Photo Lithography

    *A. Optical Inspection (material defects, pits, burrs, scratches)

    *B. Mount chip on carrier

    C. Plasma clean

    *D. Etch (general clean up)

    *E. Deposit zinc sulfide

    *F. Apply photo resist

    *G. Bake

    *H. Expose

    *I. Develop

    *J. Rinse in DI water

    *K. Optical Inspection (check for sharpness of pattern, underdeveloped areas)

    L. Plasma strip

    *M. Etch (to take off ZnS)

*N. Etch (to clean surface)

*O. Implantation

*P. Plasma strip

*Q. Remove photo resist

*R. Etch (remove remaining ZnS)

*S. Remove chip from carrier

*T. Plasma strip (chip and carrier)

*U. Anneal

*V. Remount chip

*W. Etch (clean the surface)

*X. Etch (neutralize the surface)

*Y. Deposit ZnS

*Z. Apply photo resist

*aa. Expose

*ab. Soak in chlorobenzene

*ac. Develop

*ad. Rinse in DI water

*ae. Optical inspection (mask alignment, underdeveloped areas)

*af. Etch (remove zinc)

*ag. Metallization (zinc metal)

*ah. Lift Off

*ai. Optical Inspection (check to see if metal is removed from undesired areas)

*aj. Apply photo resist

*ak. Expose

*al. Soak in chlorobenzene and bake

*am. Develop

*an. Rinse in DI water

*ao. Optical inspection (check alignment of masks, underdeveloped areas)

*ap. Metallization (bonding pads)

*aq. Lift Off

*ar. Optical inspection (check if metal was removed from undesired areas)

*as. Bonding

*at. Testing

4. Hybrid Array Assembly and Test

A. Dicing

B. Silicon readout hybridization

C. Wafer characterization

D. Current-- voltage test

*E. Spectral response

F. Active area

G. Radiometric tests

5. Bond Leads

6. Final Test

A. Nominal area

B. Applied voltage

C. Noise bandwidth

D. Individual element tests--electrical

E. Individual element tests--spectral

F. Individual element tests--conversion status

G. Test summary

NBS-114A (REV. 2-8C)

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4. TITLE AND SUBTITLE

"Study of the Feasibility of Introducing Automation into Critical Manufacturing Processes for Producing Mercury Cadmium Telluride Detector Arrays."

5. AUTHOR(S)

Sidney Weiser

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
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U.S. Army Night Vision and Electro Optics Laboratory
Attention DELMV-R-FP
Fort Belvoir, Va. 22060-5677

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The task was divided into two phases.

Phase I was a systems study of the existing process and recommendation of a plan for automation. Since this process is complex, with over 100 steps, three options were proposed for implementation:

Option 1 Automation of eight critical subprocesses at a Laboratory level.
Option 2 Automation of five critical subprocesses in an existing production line.
Option 3 Automation of the complete process in a new facility.

Approximate costs were prepared for each of these options as required by the contract.

Phase II was to implement a near term demonstration of automation in infrared fabrication. This was directed to the development of a more efficient way for the measurement of the crystal axis orientation of cadmium telluride substrates used in this infrared detector. A breadboard model of a toroidal laser scanner, with pattern recognition was developed. This instrument will reduce the mapping time for a substrate from 4 hours to 4 minutes. The scanner can identify three different crystal orientations and characterize four others in a fraction of a second which can improve the yield by 300%. A goniometric mount controlled by a dedicated computer is planned for fully automating this inspection process. (Bibliography consists of twelve references)

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Automation; Clean Room Applications; Crystal Axis Measurement; Fabrication processes; Infrared Sensor Arrays; Laser Scanner, Mercury Cadmium Telluride Detectors; Robotics

13. AVAILABILITY

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