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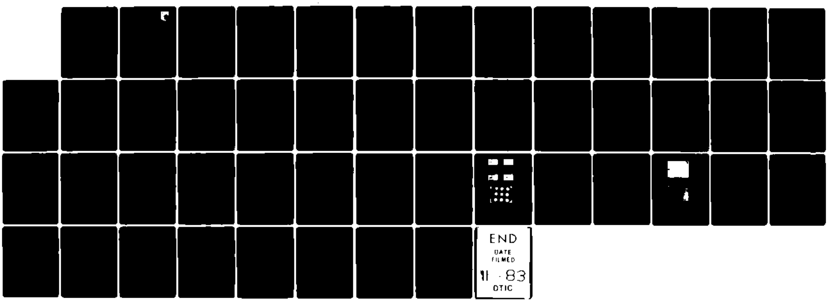

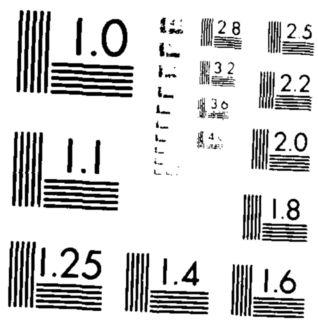

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SILICON MILLIMETER WAVE DEVICES BY MBE

Frederick G. Allen
School of Engineering and Applied Science
University of California, Los Angeles
Los Angeles, CA 90024

MAY 1983

Final Report for Period September 1981 - December 1982

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This 15-month program investigated the fabrication of millimeter wave silicon avalanche diode wafers using the growth process of molecular beam epitaxy (MBE). It was the objective of this effort to apply MBE's exacting depth control and arbitrary dopant deposition capabilities to achieve near-ideal IMPATT profiles. As such, the goal of this effort was directed at achieving good doping level control with sharp, well-defined layer transitions and very thin layer thicknesses for the 100 GHz frequency region.

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A number of silicon wafers were grown during the course of this effort with diode fabrication and electrical testing being accomplished at two industrial laboratories who have extensive millimeter wave IMPATT experience. Early wafer growths and subsequent diode fabrication/testing indicated that although the thickness and doping levels achieved were about right, all of the p-n junctions were far too leaky in reverse bias, and they exhibited soft and often too low of breakdown voltages. In addition, it was found that silicon MBE often etched much more rapidly than bulk silicon and sometimes revealed a milky film. These properties have been previously experienced in non-MBE materials and were attributed to possible high dislocation densities or polycrystalline films. Subsequent wafer growths were made but exhibited the same disappointing results and at this point, no remedy has been found.

While the specific cause contributing to poor p-n junction performances have not been isolated to date, there is no reason apparent at present why this problem cannot eventually be solved by better control of impurities and/or dislocations during the MBE growth process. Emphasis must now be given to solving these problems before further attempts are made to produce MBE devices.

PREFACE

This work was performed in the Electrical Engineering Laboratories of the University of California at Los Angeles. The principal investigator was Professor Frederick G. Allen. The experimental work was performed by Robert Metzger, Dwight Streit, Robert Ostrom and Ali Esraghi, all graduate students in the UCLA Electrical Engineering Department. Mesa diodes with UCLA-grown wafers were fabricated and tested at Hughes Aircraft Laboratories in Torrance, California, and by TRW, Inc. Laboratories, Redondo Beach, California.

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SECTION I. INTRODUCTION

A. Background

Future millimeter wave source requirements necessitate the use of solid state components to meet limitations on power and space and to provide high reliability. For these requirements, development is needed of solid state device technology which can provide improved rf sources in the 44 to 240 GHz frequency region.

GaAs and silicon are the dominant materials for rf diodes in different parts of this frequency range. To improve performance and optimize silicon devices at the higher end of this frequency range requires improved silicon growth techniques. Better control of doping levels is needed with sharp, well-defined transitions with very thin layer depths, down to a few tens of angstroms.

B. Molecular Beam Epitaxy for Silicon Devices, (MBE)

1. Drawbacks of Other Growth Methods

None of the currently used silicon growth tehcniques can provide the precise dopant control for arbitrary profiles required for optimum millimeter wave diodes. Diffusion, vapor phase epitaxy (VPE) and ion implantation all result in smearing of profiles by thousands of angstroms. The technique of metal organic chemical vapor deposition (MOCVD) is almost competitive with MBE for control of arbitrary doping profiles in silicon, and may ultimately win out on the production line. But it does not provide the extreme depth control nor the surface analytical capability of MBE desirable during development and optimization of new diode profiles.

2. Description of the MBE Process

In Molecular Beam Epitaxy, single crystal silicon substrates of any desired orientation are mounted in an ultra high vacuum station with background pressure below 10^{-10} Torr. The surface, previously polished and cleaned, is made atomically clean by removing any oxide film in vacuum either by heating it above 1000°C for several minutes, or by argon ion bombardment and annealing to $\sim$ 800°C, or by galliation[1] involving heating to 850°C in the presence of a gallium beam. Surface conditions are examined by LEED and Auger analysis before and after growth and by RHEED during growth.

A beam of ultra-pure silicon is then evaporated onto and grows epitaxially upon the silicon substrate which is held at 600°C to 750°C. The silicon source is a small molten pool of silicon completely surrounded by solid pure silicon in the crucible of an electron gun, located about 20 cm beneath the substrate. Growth of the crystal is precisely monitored by a vibrating quartz plate gauge placed close to the substrate.

Dopants can be evaporated from two effusion ovens beside the e-gun source - gallium for p-type and antimony for n-type in our present station at UCLA. Dopant control is effected by precise effusion oven temperature setting based on previous calibration runs together with shutters to turn the beams on or off abruptly.

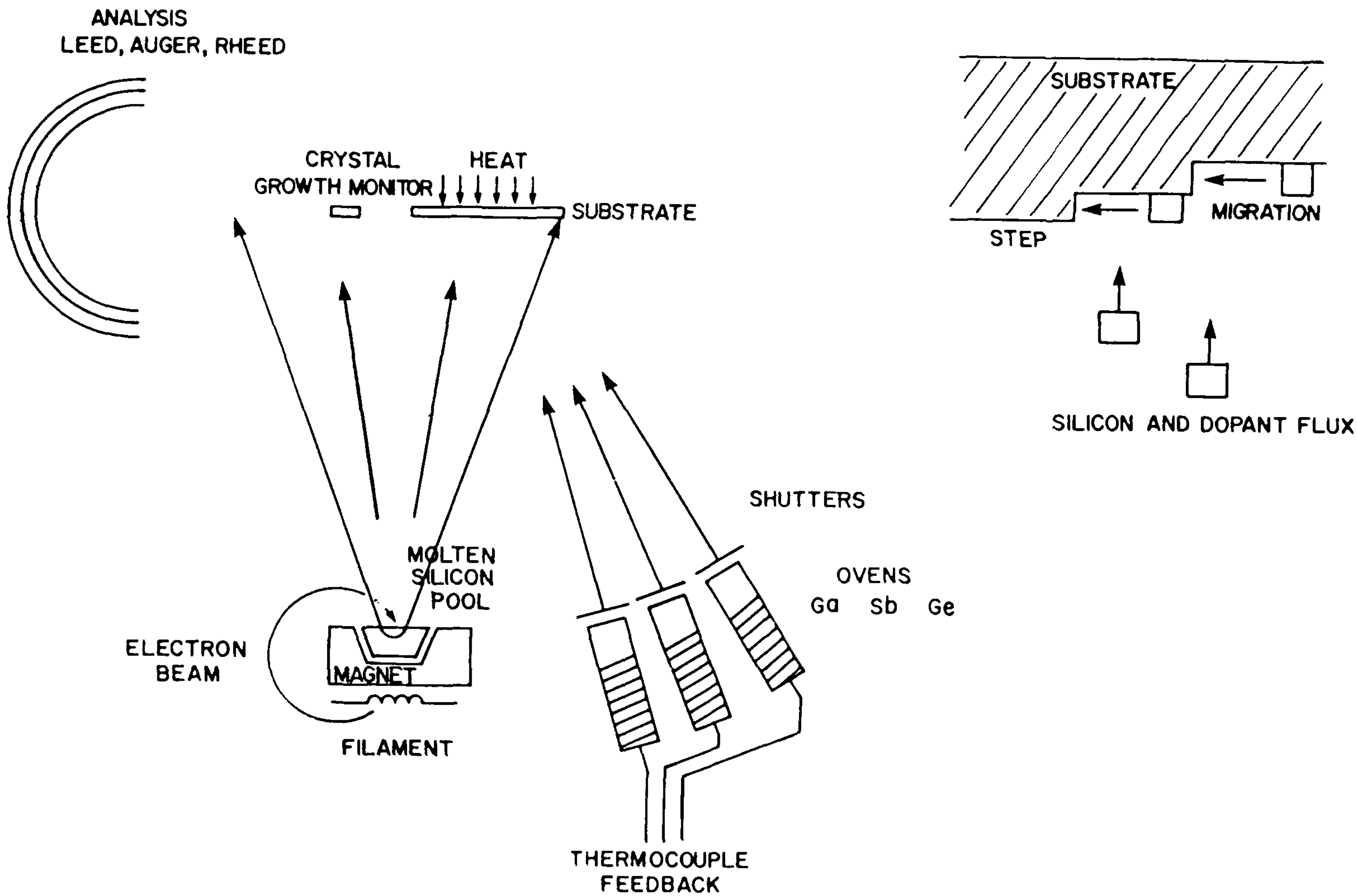

Fig. 1 PROCESS SCHEMATIC O ... MBE GROWTH

A more ideal dopant control has been demonstrated by Bean[2] and Ota[3] using low energy ion imbedding. Ion imbedding doping is not yet available at UCLA.

Liquid nitrogen cooled shrouds cover all heated surfaces except the beam openings and keep background pressure in the 10^{-9} Torr range during growth.

Silicon is grown at about 1 monolayer per second in the UCLA station, but Bean is now growing at $\sim$ 10 layers/sec, and higher rates are possible.

3. Advantages of MBE for Silicon mm Wave Devices

This method is ideal for silicon mm wave devices because:

1) at 750°C substrate temperature, no appreciable diffusion of dopants occurs during a run of many hours (a few angstroms at most),

2) p, i, or n material can be grown in any sequence by turning on or off doping beams; doping levels can be determined from previous calibration, or by direct measurement of ion current to the sample.

3) growing at only a few monolayers per second allows ample time to turn the silicon or the dopant beams on or off and effect transistions as sharply as desired.

4) the vibrating quartz plate thickness monitoring can be exact to within a few monolayers, providing the ultimate in thickness control.

4. Quality of MBE-Grown Silicon

At the start of this contract, (September, 1981) data from Bean[4,5] and Ota[3] at Bell Telephone Laboratories and from several Japanese[6] laboratories gave reason to believe that high quality silicon material and p-n junctions for devices could be grown by MBE. Results of the UCLA group[7] showed that MBE could indeed produce the sharp and arbitrary doping profiles needed.

But none of these sources had yet produced by MBE working p-n junction devices that competed favorably with the best commercial devices grown by conventional methods. Bean's[4] report of an MBE-grown hi-lo p-n junction with a reverse current density of only 2 nano amperes/cm^2 at 2 volts reverse bias with a derived carrier lifetime of $\sim$ 30 microseconds, does indicate that device quality junctions can be grown by MBE. But a bipolar transistor grown by MBE later by Schwarz et al at Bell Laboratories[8] showed that high interface recombination velocity at the junction could be a problem in MBE.

C. Goals of this Effort

1. Statement of Objectives

The objectives, as stated in our proposal of April 17, 1981, were:

1) To grow near-ideal millimeter wave device profiles in silicon in the 100 GHz frequency region that could be fabricated and tested in various industrial laboratories, using thermal dopant evaporation tech-

niques. Specifically, UCLA undertook to grow ten or more diode wafers of different designs for testing by outside laboratories designated by the Air Force - namely, Hughes and TRW.

2) To strengthen the UCLA capabilities for "thermal" MBE by the addition of a mass spectrometer, a larger e-gun evaporator, and a load lock. These would enable us, respectively, to analyze the thermal dopant flux for better dopant control, (particularly for antimony), to grow films more rapidly, and to achieve a shorter turn-around time.

3) To implement the addition of a low energy dopant ion embedding capability for use during MBE. This would permit simpler and more exact dopant control than with the "thermal" techniques, and would ensure high dopant levels into the 10^{19} and $10^{20} cm^{-3}$ range for both n^+ and p^+ layers.

2. <u>Failures and Successes of This Program</u>

1) <u>Failed</u> in the <u>first</u>; only eight diodes were delivered to Hughes and TRW for testing and fabrication, during the contract period and all of these had inferior p-n junctions. A solution has not yet been found, so the balance of two samples was not delivered.

2) <u>Succeeded</u> in the <u>second</u>. The goal of achieving a reliable silicon MBE station with rapid turn-around has been accomplished. Valuable scientific data on antimony doping have been obtained.

3) Partially accomplished the third. The critical equipment for ion imbedding doping has been purchased but not yet incorporated into our station.

We present below a report of our technical activity in pursuit of these three objectives. To avoid repetition, we shall discuss our MBE system development, Objectives 2 and 3 first, and the diode effort, Objective 1, last.

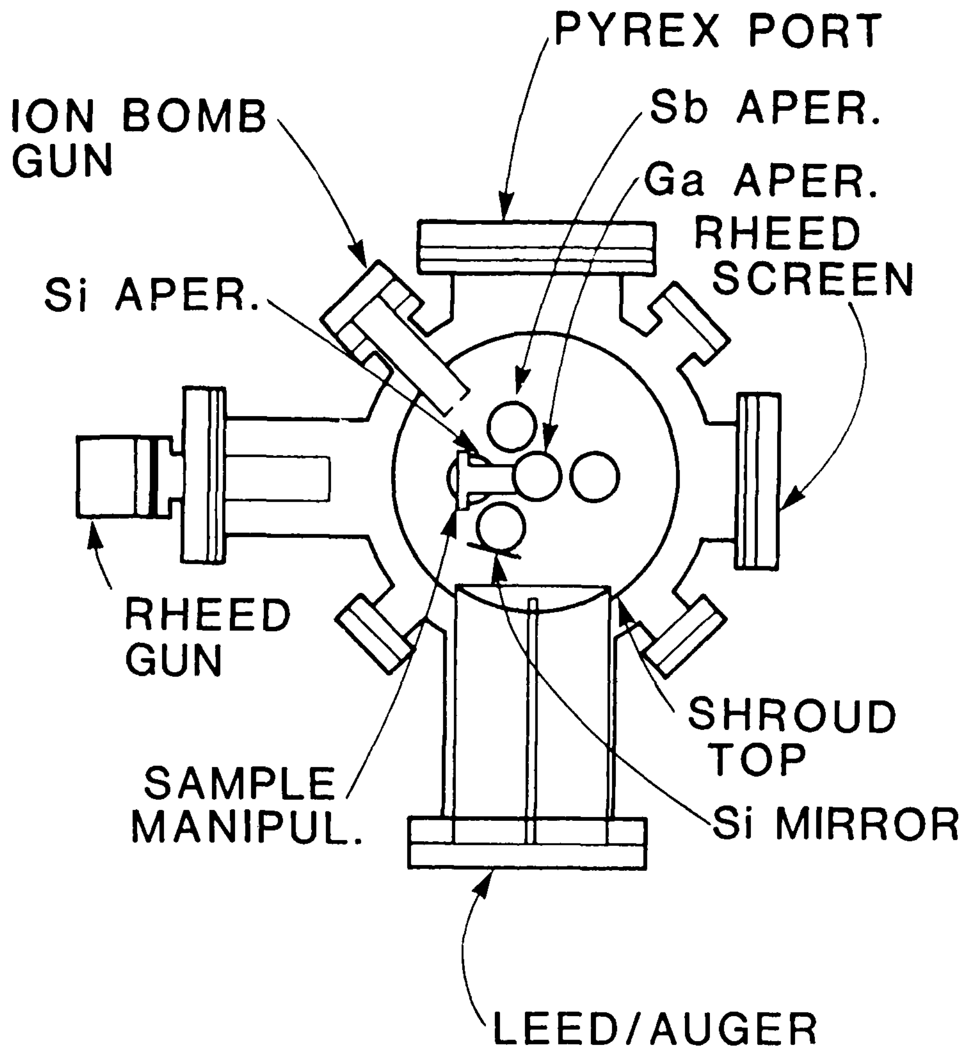

Fig. 2 UCLA SILICON MBE SYSTEM as of 9/10/81

SECTION II. DEVELOPMENT OF THE UCLA SILICON MBE CAPABILITY

A. UCLA MBE Station at the Beginning of the Period - September 1981

1. Vacuum System

The basic station is an all stainless steel 12" diameter Varian ultra-high vacuum system with a total pumping speed of 225 ℓ/sec (consisting of five separate 45 ℓ/sec pump elements) controlled by a Varian pump power supply (921-0066). Additional pumping is available with a titanium sublimation pump (Varian 922-0032) and a set of vacsorb pumps (Varian 941-6501) for use during initial pumpdown.

2. Analytical Tools

The station has several analytical surface tools. For use before and after growth to check surface cleanliness and crystalline quality a LEED/Auger system is present consisting of a Varian 4- grid LEED/Auger Optics (981-0127) coupled with a Varian electron gun (981-2145). For monitoring sample surface structure during growth a Physical Electronics SKU RHEED system (PHI-04-015) is available.

3. MBE System - Effusion Ovens

The heart of the MBE station consists of the liquid nitrogen shroud, ovens, and e-gun assembly. Two effusion ovens are present for either Sb or Ga doping. These ovens were designed and fabricated at UCLA. (See Fig. 3.) The ovens consist of forty-eight turns of 10 mil tantalum wire spring wound against four ceramic posts held in a tantalum can. This can is wrapped by five layers of tantalum foil and encased in an outer tantalum can to which a ceramic base

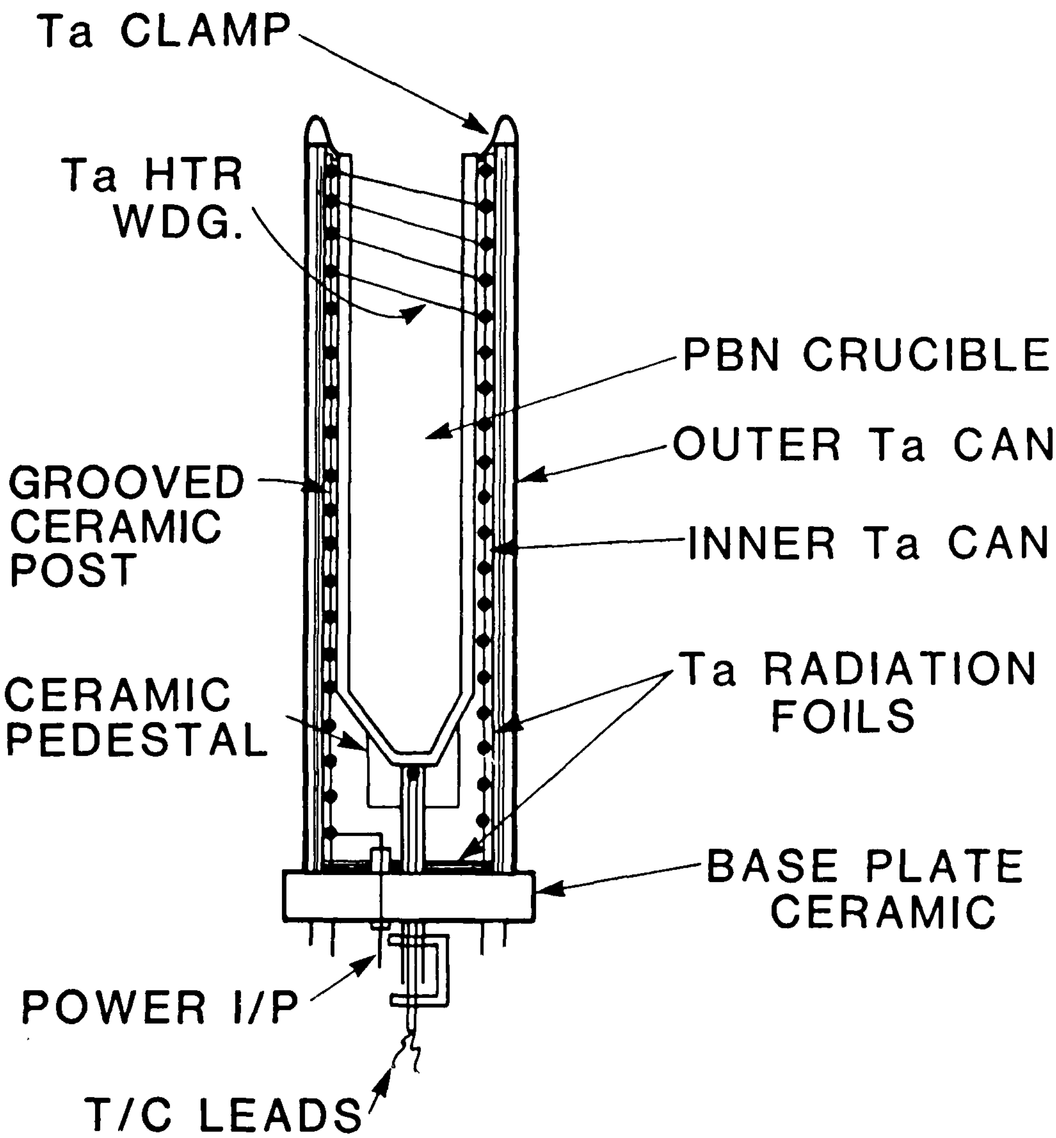

Fig. 3 SCHEMATIC OF UCLA EFFUSION CELLS

plate is attached. The base plate has feed-throughs for both the power and thermocouples. The crucibles within the ovens are made of pyrolytic boron nitride. These ovens can range from room temperature to 1000^{o}C and are controlled by a Eurotherm digital temperature controller (Model 990). Both these ovens are inserted into shuttered stainless steel cans which are attached to the underside of the liquid nitrogen shroud.

4. <u>E-Gun</u>

Beneath the oven-shroud assembly is a modified ultra-high vacuum Airco Temescal e-gun (FIH-270) with a water cooled crucible (molybdenum insert in copper block) which can hold 7 cc of silicon. This gun is powered by an Airco Temescal supply (ES-6) capable of 6 KW of power. Actually, during Si growth, only 500 watts has been used.

5. <u>Thickness Monitor</u>

Growth of Si, and Ga and Sb flux are monitored by a Sloan Digital Thickness Monitor (Model 200), with a vibrating quartz plate.

6. <u>Sample Mount</u>

The sample itself is mounted directly to a Varian high precision sample manipulator (981-2523) which permits movement in X, Y, and Z direction coupled with full 360^{o} rotation and 90^{o} flip. (See Figs. 5, 7)

The silicon sample is rectangular, 1.3cm x 1.3cm x .05cm, and is held at both of its ends by molybdenum spring clamps, (Fig. 5). The sample is heated for initial cleaning to 1250^{o}C

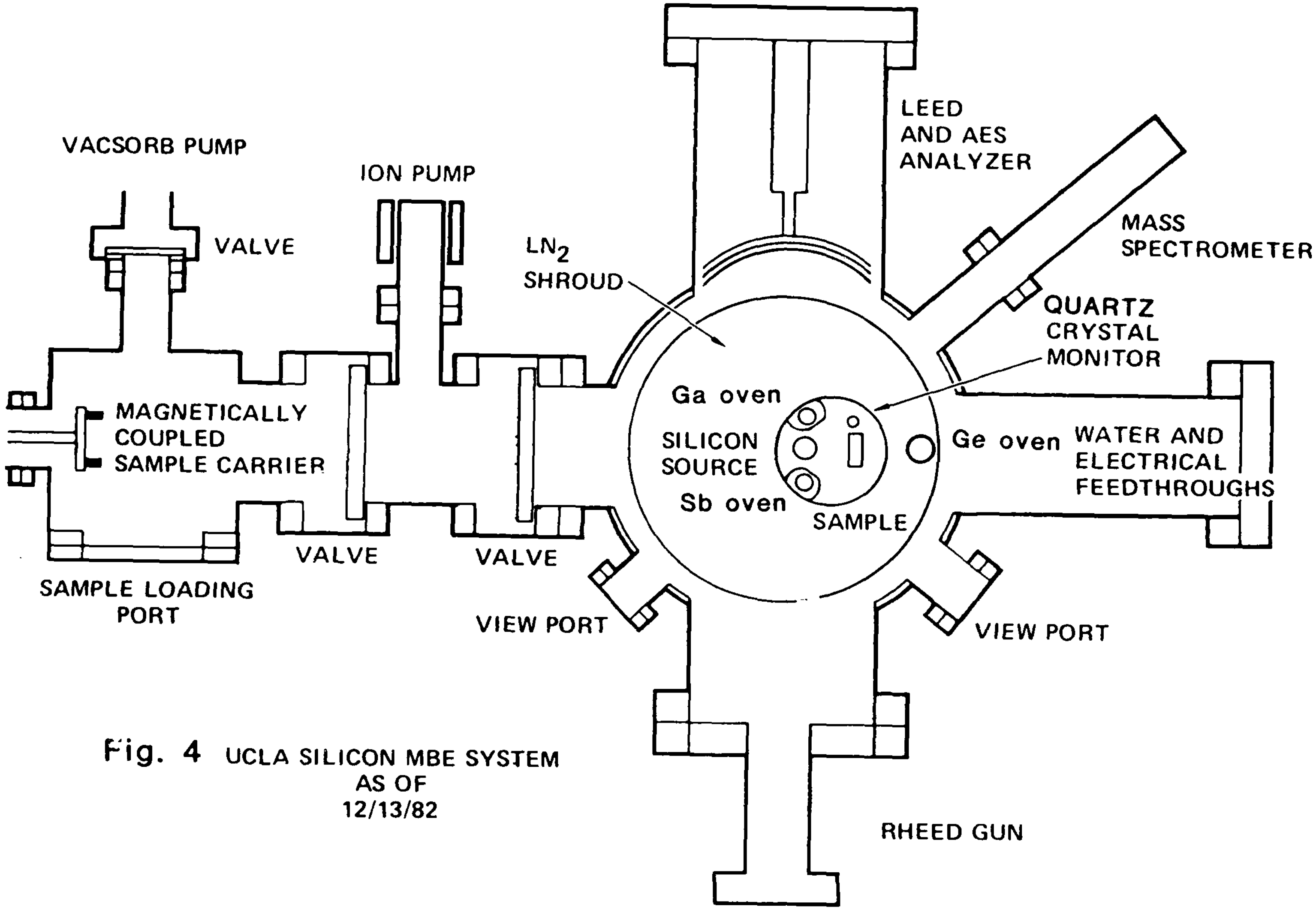

Fig. 4 UCLA SILICON MBE SYSTEM AS OF 12/13/82

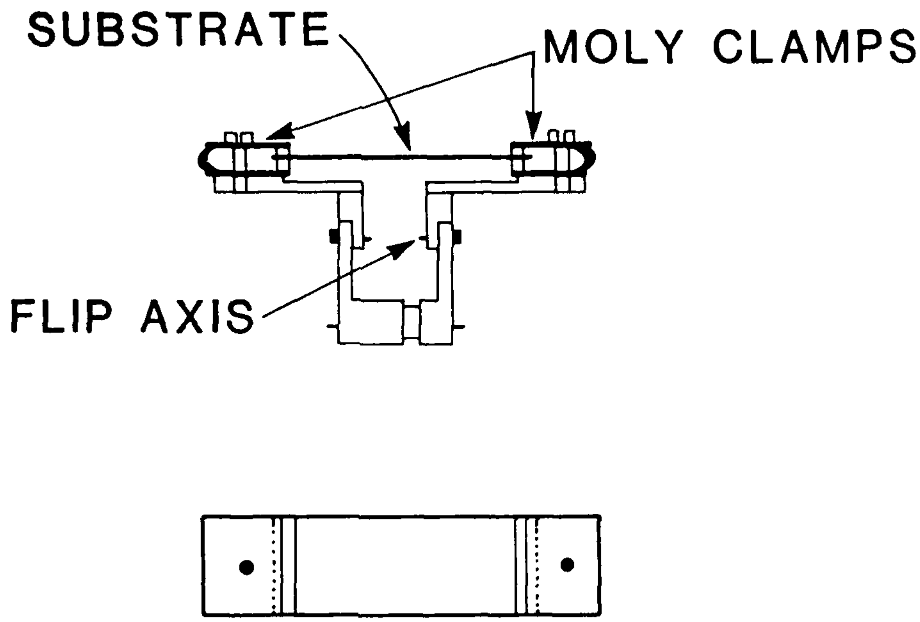

Fig. 5 SILICON SAMPLE HOLDER FOR RESISTIVE HEATING

or held at growth temperatures of 650 -750°C by passing heating current from the clamps directly through the silicon sample. This is advantageous in requiring minimum heated surfaces and a rapid thermal time constant. But it is disadvantageous in that: 1) some mechanical stress is always present in the sample, causing dislocations and plastic yielding when the sample is hot, 2) hot spots develop at the end contacts so that temperature sometimes varies across the sample by as much as 100°C.

At the beginning of this period, before a load lock had been installed, due to the necessity of breaking vacuum for each sample which then requires the entire system to be baked out at 200°C for 24 to 36 hours, (Varian bakeout 981-0052), the turn-around time between samples was on the order of two to three days.

B. <u>UCLA Si MBE Station at Present</u>

In the past fifteen months several system modifications have taken place. Both Sb and Ga ovens were replaced as well as the liquid nitrogen shroud. The LEED/Auger system was rebuilt and now offers greater sensitivity. The bottom half of the station was replaced due to fatiguing welds and a resulting leak. All other equipment and functions remain the same with the addition of the two major components below, (Fig. 4).

1. <u>Mass Spectrometer</u>

The first is a UTI quadrupole mass spectrometer (Model 100C) with specially modified pole pieces to obtain mass detection in the range of 2 to 500 atomic mass units. The mass spectrometer can be utilized in two modes as both a residual gas analyzer to monitor background gases as well as a detector for thermal desorption spectroscopy.

2. Load Lock

The greatest modification has been in the addition of a load lock (Thermionics - custom design), which permits sample loading without the breaking of vacuum which had necessitated a bakeout. The sample is loaded onto the sample holder on the bench and then attached to the sample carrier in the loading port. The loading port is roughed down to 10^{-4} Torr with vacsorb pumping at which point the first gate valve is opened resulting in the ion pump lowering the loading chamber pressure to 10^{-7} to 10^{-8} Torr. When this pressure is obtained the second gate valve is opened and the sample carrier is inserted into the main station where the sample holder is then transferred to the sample manipulator. The sample carrier is removed and gate valves are closed. During transfer the main chamber pressure rises to the mid 10^{-9} Torr and recovers to the 10^{-10} Torr range within minutes of closing the gate valves. This addition has changed sample turn-around time from several days to only several hours. (See Figs. 4, 7)

3. Radiant Sample Heater - 2" Diameter Wafers

The radiant sample heater shown in Fig. 6 has been designed, fabricated, and has passed its initial testing.

Tantalum filaments supported on a boron nitride disk lie in a plane parallel to and just behind the silicon sample. Radiation shields of tantalum foil keep the boron nitride disk cool. The 2" diameter sample is supported loosely at three points in the 10 mil thick tantalum can in a 2.01" diameter hole in its front surface. This can carries the sample from the loading station outside the vacuum system, through the load locks and then is twisted into a locked position on the boron nitride disk. The entire sample and heater can be flipped 90^{o} by the Varian flip stem so that the sample is vertical, for inspection or LEED-Auger analysis, or horizontal during growth. (Fig. 7)

The sample can be heated up to 1000^{o}C readily by about 280 watts. For initial cleaning to 1250^{o}C, electron emission from the tantalum filaments is accelerated to the silicon sample with 2000 volts to provide an extra 100 to 150 watts. Alternatively, the silicon sample can be cleaned by argon ion bombardment with a Varian ion gun in the station; in this case initial cleaning temperatures need not exceed 805^{o}C for annealing and outgassing the argon.

The heater assembly has been designed for rapid outgassing, with low thermal mass. Special attention was paid to ensuring that no metal surface protrudes beyond the silicon surface to act as a contaminant source during cleaning or growth.

This radiation heater is now ready but has not yet grown any samples. It should eliminate any remaining problems

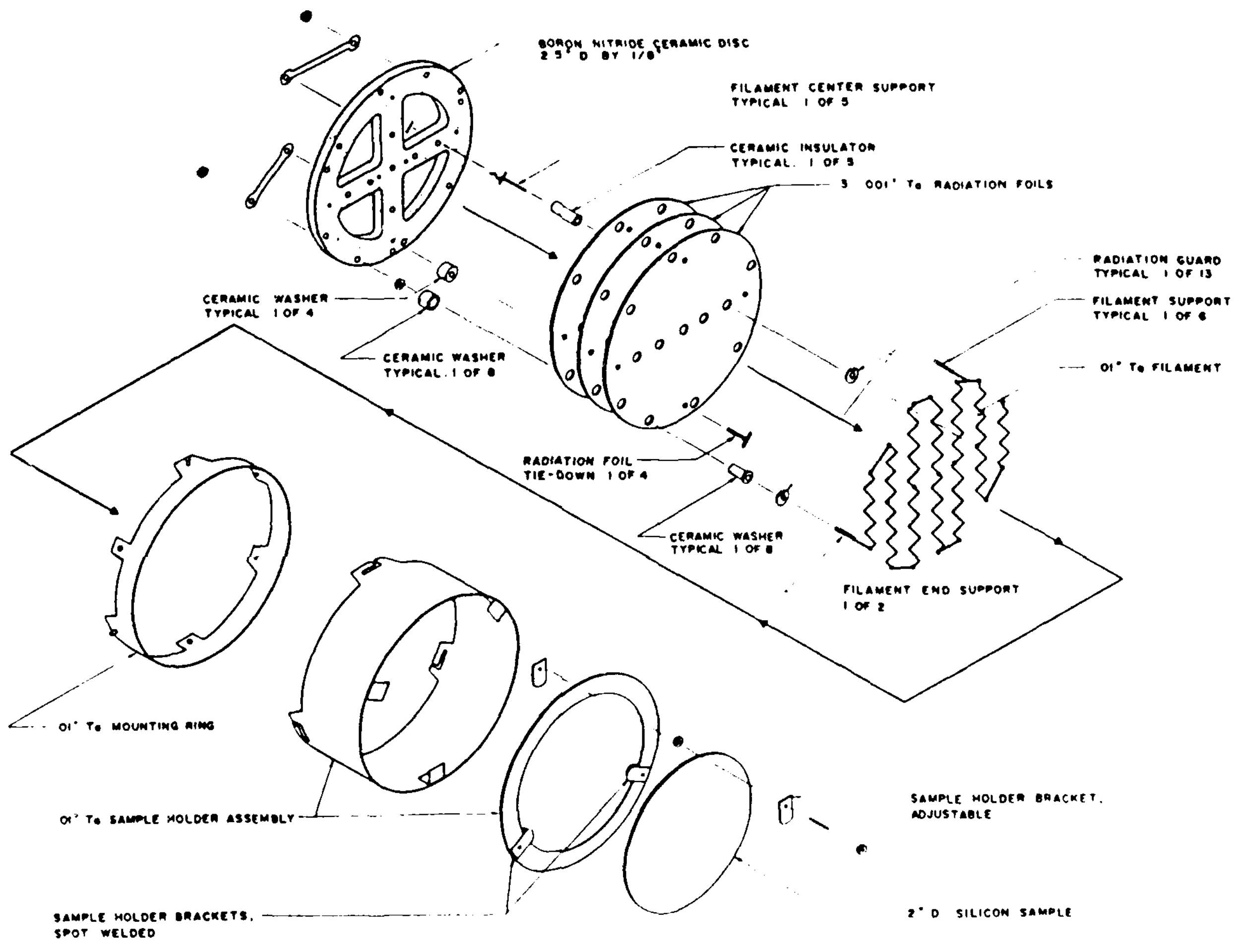

Fig. 6 SILICON WAFER RADIATION HEATER

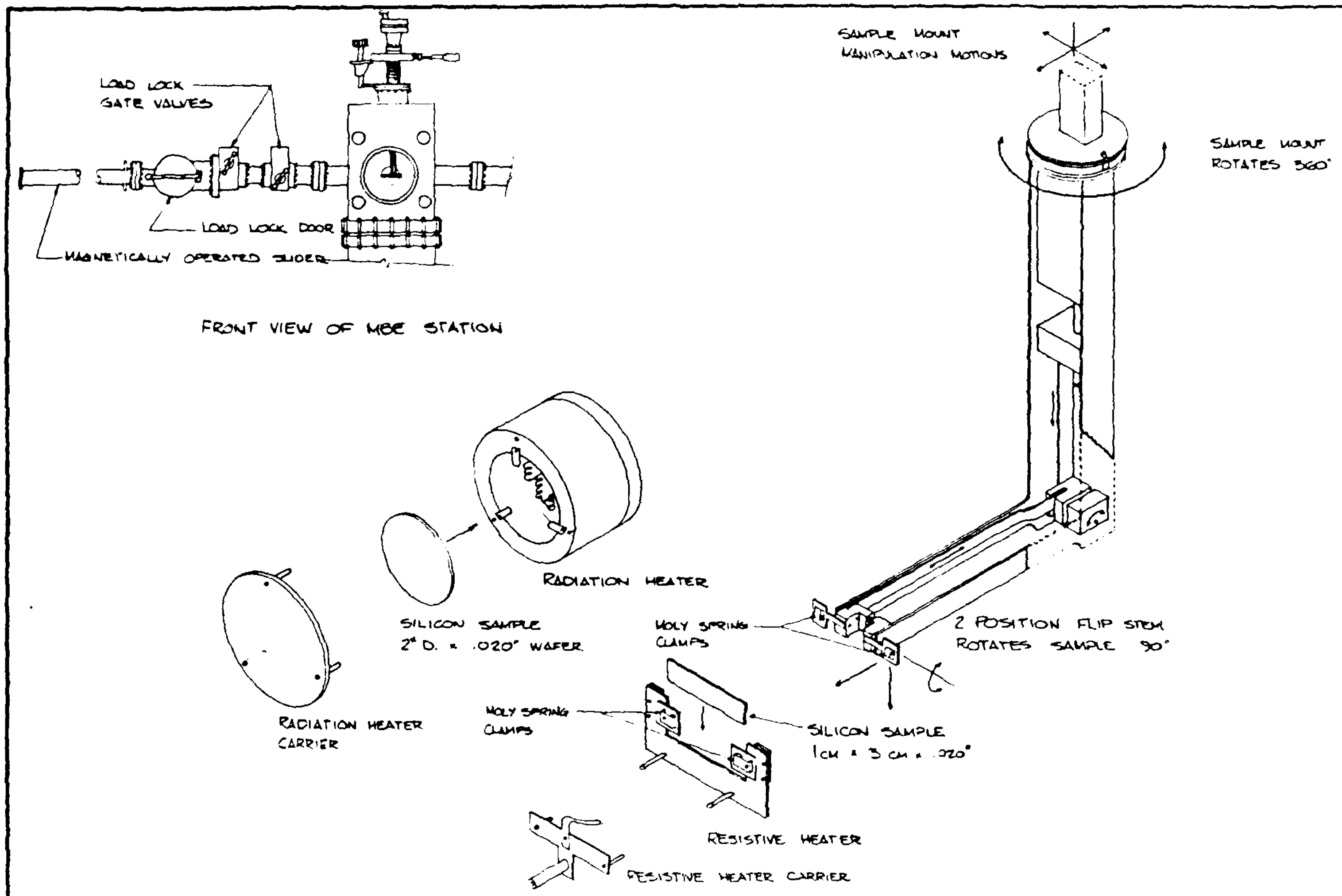

Fig. 7 SAMPLE MOUNTING, HEATING, POSITIONING, AND CHANGING. UCLA SILICON MBE SYSTEM

we suffer from dislocations using our present spring clamps, and provides a more uniform sample temperature.

In addition, interaction with industrial production lines will be far simpler with the standard 2" wafer, than it was with our rectangular sample.

C. Hall Mobility Measurement System

An important addition to the UCLA capability during this contract period has been the Hall mobility measurement system shown in Fig. 8. We now routinely measure mobility of MBE grown films by isolating them from the substrate with a p-n junction. We cut from our wafer square Van der Pauw samples about 1cm x 1cm, and then press and sinter indium contacts on the four corners; we then place the sample in a holder in the magnet to measure Hall voltage and resistivity.

When this contract began, we had never measured the mobility in our MBE grown films. Results are presented later.

D. Vacuum Component Test Station

A small (14" diameter) auxiliary vacuum station has been assembled from surplus parts in order to outgas and vacuum test components to be used in the MBE station. The Turbo molecular pump (Item #8 in Appendix 1) bought for later use with the Colutron Ion gun is being used to pump this station.

Boron nitride elements for effusion ovens, and for the radiation heater have been outgassed and baked in this station, and the radiation heater assembly has been tested in it.

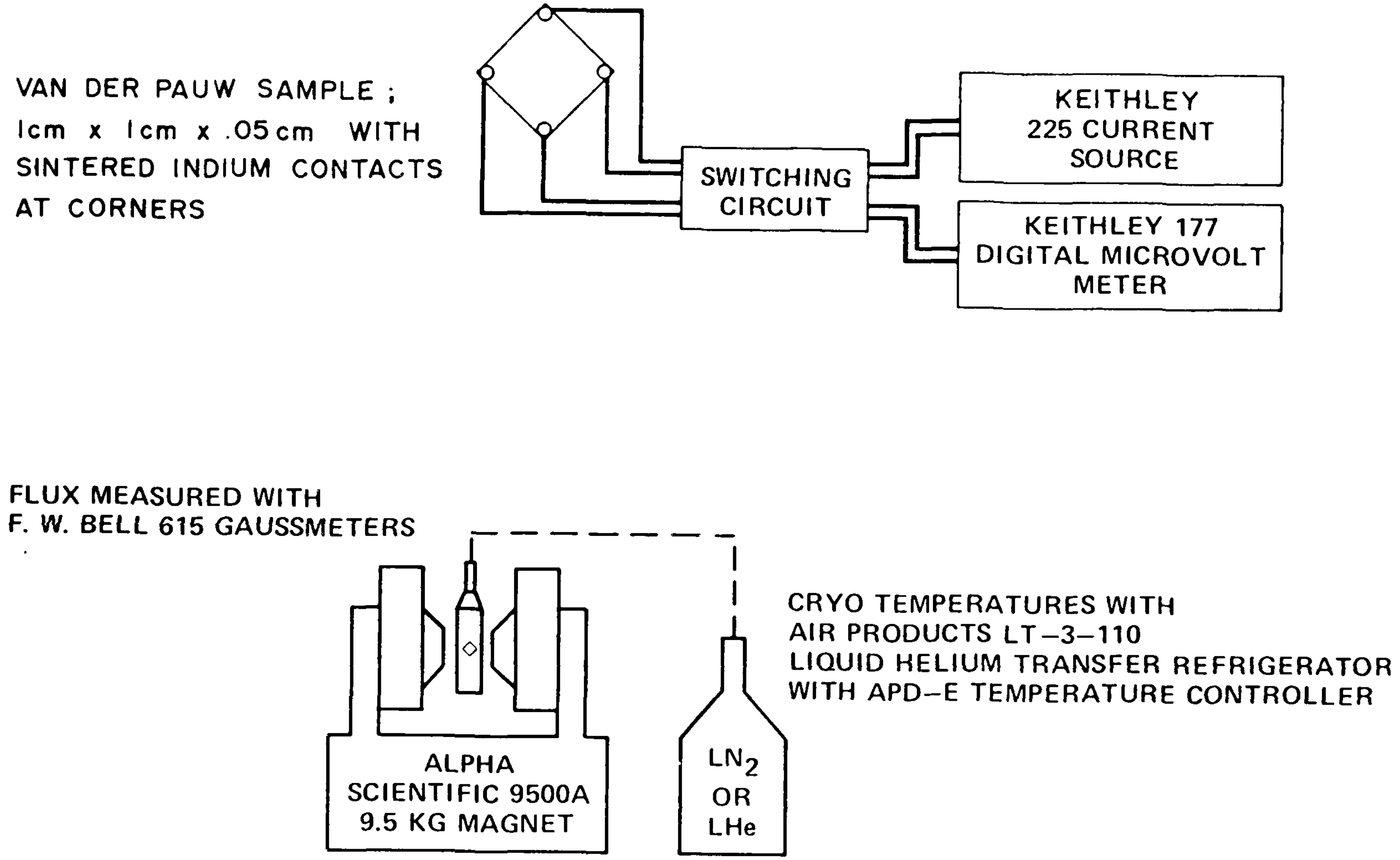

Fig. 8 UCLA HALL MOBILITY MEASUREMENT SYSTEM

E. Back-Up MBE Station

A large high-vacuum pump, obtained from surplus, has been combined with an MBE station custom machined and welded to our order to provide a second back-up station to our principal station. No major components for this station have been purchased on the present contract.

F. Adaptor Flange Assembly

An 18" diameter adaptor flange assembly was welded to our design on this contract by Thermionics, Inc., to increase the available operating space in our present station. This is ready but has not been used as yet.

G. Ion Imbedding Doping

The principal components for doping our MBE films by low energy ion imbedding, have been bought on this contract. Thus, the Colutron ion source and its power supplies are on hand.

Considerable shop work will still be necessary to mount this ion beam on either our principal or our back-up MBE station, and considerable electronic work is needed to get a focussed controlled ion beam.

Despite the desirability of ion imbedding doping, we expect to postpone putting this system into operation until more contract support is found.

SECTION III. GROWTH AND TEST RESULTS OF MILLIMETER WAVE DIODES

A. Early Results

The present Air Force Contract began in September of 1981, with the agreement to deliver a total of ten diode wafers to TRW and Hughes by December 13, 1982. Five diodes were grown by UCLA and delivered to Hughes and TRW for testing between 11/30/81 and 1/11/82.

Results of electrical tests made at Hughes and TRW on these early diodes were reported to UCLA from four to eight weeks after delivery. All results on the early diodes showed that although the thickness and doping levels were about right, all p-n junctions were far too leaky in reverse bias and had soft and often too low breakdown voltages. In addition, it was found that the MBE silicon often etched much more rapidly than bulk silicon and sometimes revealed a milky film. TRW reported this had previously been found to correspond to high dislocation density or even polycrystalline films.

B. 94 GHz Simple Profile Test Diodes

As a result of the poor diode characteristics and etching behavior of early diodes delivered by UCLA to TRW and Hughes, it was agreed with WPAFB that UCLA should grow a simple 94 GHz diode profile by MBE which had already been proven by Hughes and TRW. For that purpose we grew two identical samples with the profile shown in Fig. 9. These were grown on May 21, 1982 and transmitted to Hughes and TRW on May 29, 1982. In each case, the (111) n^+ substrate, doped with $N_D = 5 \times 10^{19} cm^{-3}$, and with front surface prepared by chemical-mechanical polish, was cleaned at UCLA by a standard chemical pre-cleaning treatment* then mounted in our molybdenum spring clamps through the load lock and heated to 1200°C for 1 minute until a sharp 7 x 7 LEED pattern was seen.

The sample, heated to 650°C by joule heating through the clamps, was then exposed to the silicon e-gun. Silicon growth rate was 70 Å/min, and a uniform MBE film 4500 Å thick was grown. The goal was a n-type doping level of $2 \times 10^{17} cm^{-3}$ of Sb.

C. Test Results from Hughes and TRW on 94 GHz Diodes

Due to the need to modify their process to handle the geometry of the UCLA rectangular wafer, results of electrical tests from TRW and Hughes were not available at UCLA until July 15th and August 10th, respectively. In each case these laboratories diffused a thin (about 1500 Å) p^+ layer into the 4500 Å MBE n-film, applied metal contacts, etched mesa diodes and then tested them by C-V techniques.

The results were disappointing. Hughes laboratory reported that their test diodes had a "soft" breakdown of 1 or 2 volts and were too "leaky" in reverse bias to get a readable profile by C-V.

TRW laboratory made C-V runs on eight different diodes evaporated on different regions of the rectangular sample. The TRW results on the UCLA diodes showed:

1. All diodes were very leaky in reverse bias;

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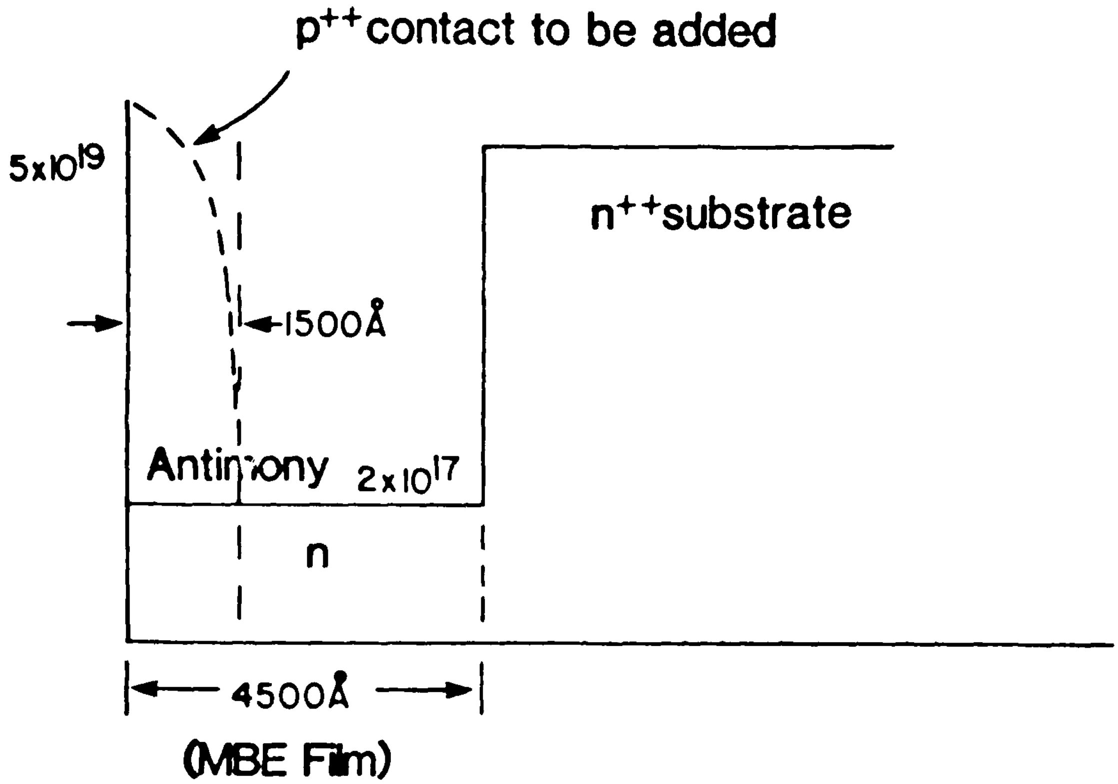
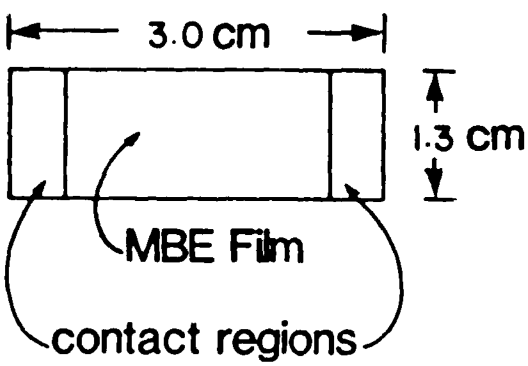
*APPENDIX A



Doping profile



Sample Shape

Fig. 9 94 GHz test diode profile supplied to Hughes and TRW

2. Breakdown voltages were soft, not sharp, and varied from 4.2 to 8.0 volts over the sample; (ideal value should have been 8 to 12 volts);

3. The doping level was about $1 \times 10^{17} cm^{-3}$; (design value was $2 \times 10^{17} cm^{-3}$).

There was also some evidence that TRW p^+ diffusion had penetrated the MBE film faster than for a conventional film, suggesting dislocations.

D. Second 94 GHz Sample Supplied to TRW

Because of evidence of rapid diffusion of the p-dopant from TRW in the first sample, UCLA then grew a second diode sample for TRW identical to the first but with a total MBE film depth of ∿1 micron instead of 0.45 microns. This was grown on 5/21/82 and delivered to TRW on 5/25/82.

E. Results on Second 94 GHz Sample from TRW

TRW diffused a p^+ layer (boron) about 0.25 microns into the surface of the n-type MBE film and made mesa diodes as before for C-V testing. The results, communicated to UCLA on September 17, 1982, were again disappointing. All diodes were very leaky in reverse bias; they had breakdowns which were soft and varied from 4 - 5 volts (as opposed to 8 - 10 volts); the doping level measured $2.5 - 3.5 \times 10^{17} cm^{-3}$. Again, the etching behavior of the MBE film was abnormal, possibly indicating high dislocation content.

F. Non-Delivery of Further Contract Samples

As of September, with only 3 months of the contract remaining, it was clear that the cause of the problem had to be found before delivering further samples.

So an in-house mesa diode fabrication and testing program was begun at UCLA to give us rapid answers on results of changes in our process. As of this time (March,1983) a remedy for the leaky diodes has not yet been found. Consequently, the remaining diodes could not be delivered. Since this contract ended on December 13, 1983, no further deliveries will be made. Nevertheless, the UCLA effort to find the problem and produce good diodes is continuing.

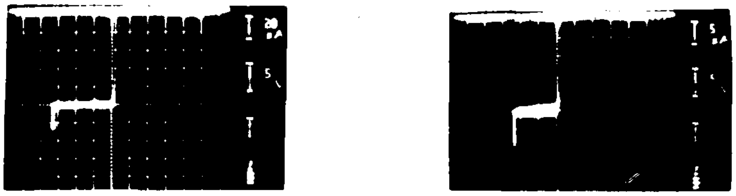
G. UCLA In-House Mesa Diode Testing Program

Starting in October the UCLA group started growning MBE wafers which it could fabricate into a matrix of 10 mil diameter mesa diodes for rapid in-house testing. The first two such matrices had been made and tested by October 15th. Details are given in the Fifth quarterly progress report[11]. (See Fig. 10)

Results from the first matrices of diodes showed that although the MBE grown films and junctions could be grown to produce the expected breakdown voltage, these breakdowns were nearly always "soft", rather than sharp. Furthermore, the reverse current on all diodes was far higher than could be expected for good quality silicon junctions.

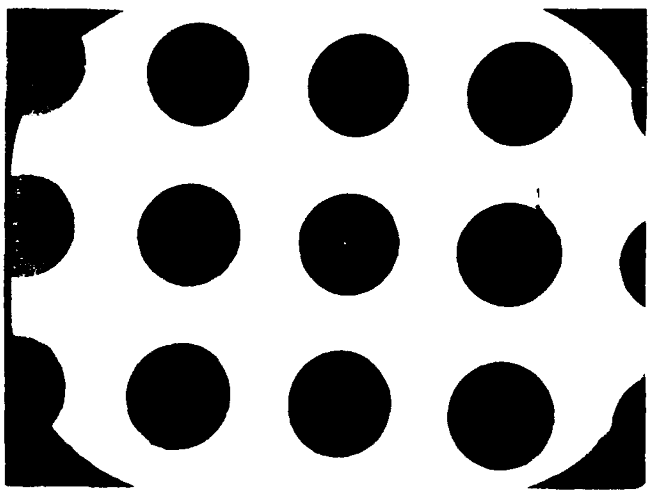
Up until March, five different MBE diode wafers have been grown, fabricated and tested; but all diodes continue to display leaky reverse characteristics.

Examples of our best MBE diodes are shown in Fig. 10. Our best leakage currents are on the order 5×10^{-7} amps for 10 mil diodes at several volts reverse voltage, which is



(a) Diode near the edge of sample #1. $V_{BD}=17V$

(b) Diode near the center of sample #1. $V_{BD}=12V$



(c) Portion of the 10 mil dia.mesa diode array.

Fig. 10 10 MIL MESA DIODES FABRICATED AT UCLA FROM MBE GROWN FILMS. 12/29/82

REVERSE CURRENT = 5×10^{-7} amps

$V_r = -10$ v AREA = 5×10^{-4} cm^2

a current density of $\sim 10^{-3}$ amps/cm^2. They should be 10^{-9} to 10^{-11} amps, corresponding to a reverse current density of 2×10^{-6} to 2×10^{-8} amps/cm^2.

The minority carrier effective lifetime near the junction, τ_e can be calculated either from the reverse current density using the relation

$$J_{rev} = \frac{q n_i W}{\tau_e} \qquad (1)$$

where q = electron charge, n_i = intrinsic concentration, W = depletion width

or from the forward current, at very low forward bias, from the relation for recombination - generation current,

$$J = J_{rec} e^{qV/nkT} = \frac{1}{2} \frac{q n_i}{\tau_e} W e^{\frac{qV}{2kT}} \qquad (2)$$

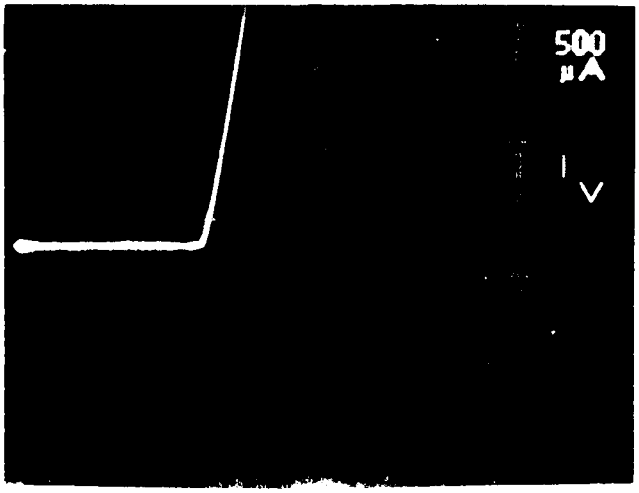
where V = forward bias, n = ideality factor and kT = thermal energy. Using these relations for our best MBE-grown diodes we derive an effective lifetime near the junction of $\tau_e \sim 3 \times 10^{-9}$ secs. Good material should show $\tau_e \sim 10^{-6}$ secs.

We have also grown diffused diodes at UCLA in this effort, for comparison with MBE diodes to check our techniques. Phosphorous was diffused into 15 ohm-cm p-type substrates to form n^+ - p junctions about 0.4 microns deep. The breakdown voltage of these diodes checks the expected value (35 volts) and the breakdown is relatively sharp. The reverse leakage current, 1.8 nanoamperes, or 3.6×10^{-6} amps/cm^2 at 4 volts reverse bias, is about 300 times better than our best MBE grown diodes. (See Fig. 11)

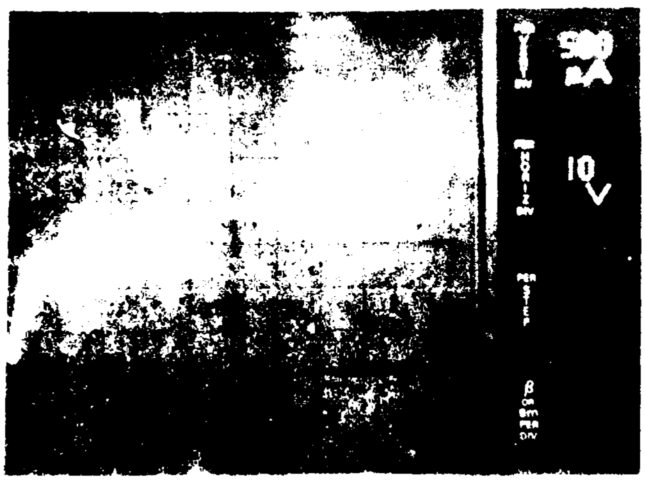
TRW[10] reports that a good, but typical diffused mm wave silicon diode etched and mounted in its cavity, has a sharp breakdown voltage of 38.5 volts, and a reverse current density at 5 volts reverse bias of $\sim 1.8 \times 10^{-6}$ amps/cm^2. This is comparable to our own diffused diode, but better than our best MBE diodes by a factor of 500.

H. Reasons for Poor Quality Junctions

The large reverse leakage current and soft breakdown of the UCLA MBE grown diodes must be due either to deep level impurities or crystal imperfections. We are actively pursuing each of these possibilities at present, with well developed techniques, but cannot state which is our problem at this time. We see no reason why either source cannot be controlled during MBE growth once it is identified. Again, the silicon p-n junction grown by MBE using resistive heating by J. C. Bean[5] had a reverse current density of only 2×10^{-9} amps/cm^2 at a reverse voltage of 2 volts; this is a factor of several hundred better than for the diffused junctions TRW finds satisfactory for mm wave diodes.



a.



b.

Fig. 11 I-V Characteristics for UCLA Diffused Silicon Diodes. a. Forward; b. Reverse breakdown. Reverse current = 2.5×10^{-9} amps at $V_r = -5$ v. Area = 5×10^{-4} cm^2.

SECTION IV. RELATED RESEARCH RESULTS

A. Hall Mobility Results

Since putting our Hall measurement system into operation we have measured the carrier concentration, type, and mobility on a wide range of our p-type Ga-doped, and n-type Sb-doped silicon MBE films. Cumulative results of all our data so far are shown in Figs. 12 and 13 respectively. Despite the considerable scatter in the data, it is evident that our mobility values are close to good bulk values over the full range of both n- and p-type doping covered except for high Sb doping levels about $10^{18}cm^{-3}$. For these, mobilities are only $\sim$50% of good bulk values. Taken with a brownish appearance of such MBE films, this probably means we have very poor crystal quality - perhaps many grain boundaries - at such high Sb levels.

The bulk value of mobility at all other dopings indicates we cannot have very serious dislocation densities - probably not $> 10^4cm^{-2}$. Some evidence from TEM and SIRTL etching leads us to believe some of our MBE silicon films have very low dislocation densities, while on the other hand, we have seen high disloc.. ion densities near the edges of our sample where the spring contacts are.

B. Sticking Coefficient for Sb Dopant on Si

By calibrating the incident Sb flux and then measuring the resultant doping density in the grown MBE films, R.A. Metzger has accumulated data on the sticking coefficient of Sb on Si. A complete analysis of his results on the kinetics

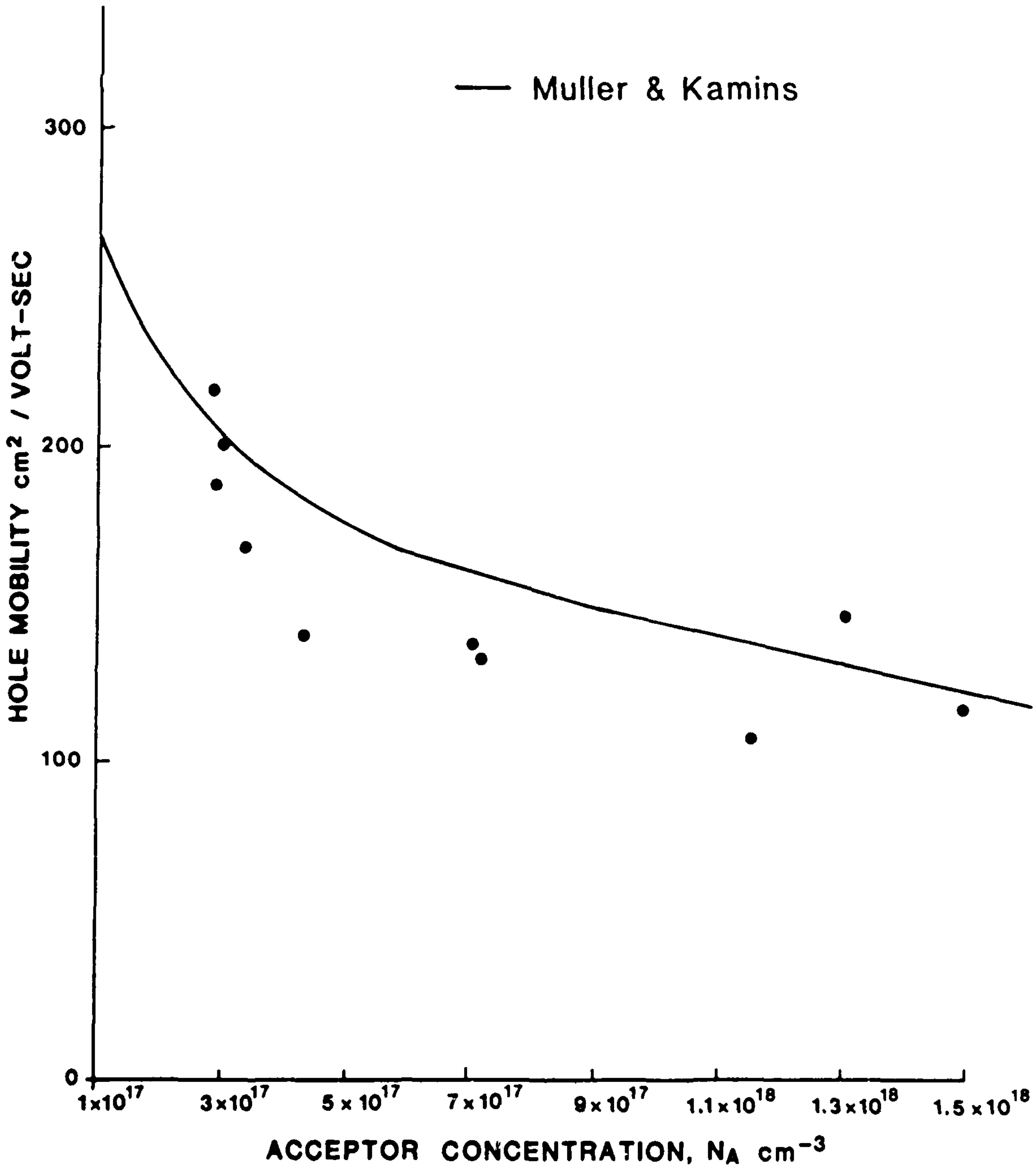


Fig. 12 HOLE MOBILITY VS. ACCEPTOR CONCENTRATION FOR ALL Ga DOPED SILICON MBE FILMS GROWN AT UCLA TO DATE.

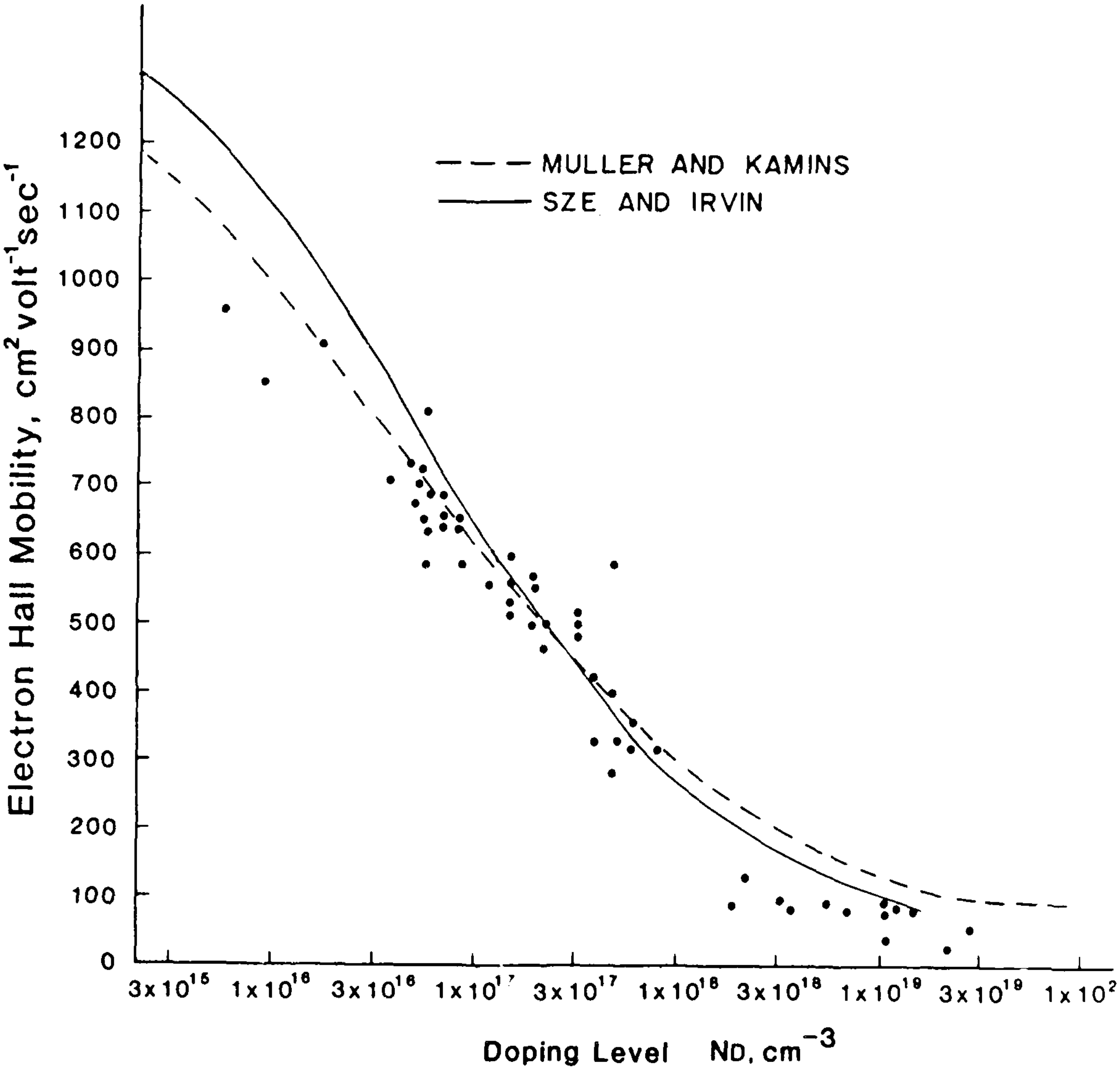


Fig. 13 ELECTRON HALL MOBILITY vs. DONOR CONCENTRATION FOR ALL Sb-DOPED MBE SILICON GROWN AT UCLA TO DATE.(3/15/83)

of Sb on Si will be published and presented in a Ph.D thesis[12]. The sticking coefficient data are summarized in Fig. 14 where Metzger's data for Sb on Si is combined with previous results of Iyer's data of Ga on Si[8]. It is see that from 700 to 850°C, Sb has a sticking coefficient that varies from $\sim 10^{-3}$ to 3×10^{-5}.

C. Computer Simulation Study of Si mm Wave Diodes

Mr. Nelson Lee has carried out a study, under the supervision of Professor Dee-Son Pan of the Electrical Engineering Department of UCLA, of the electron and hole motion in silicon impatt and tunnett type diodes in the 30 to 100 GHz frequency region. This study anticipated the need to find optimum design profiles to be achieved by MBE growth. Despite much progress, the program is not yet ready to predict power output efficiencies from arbitrary profiles. Work on this program continues under other sponsorship and results will be published in the literature as they become available.

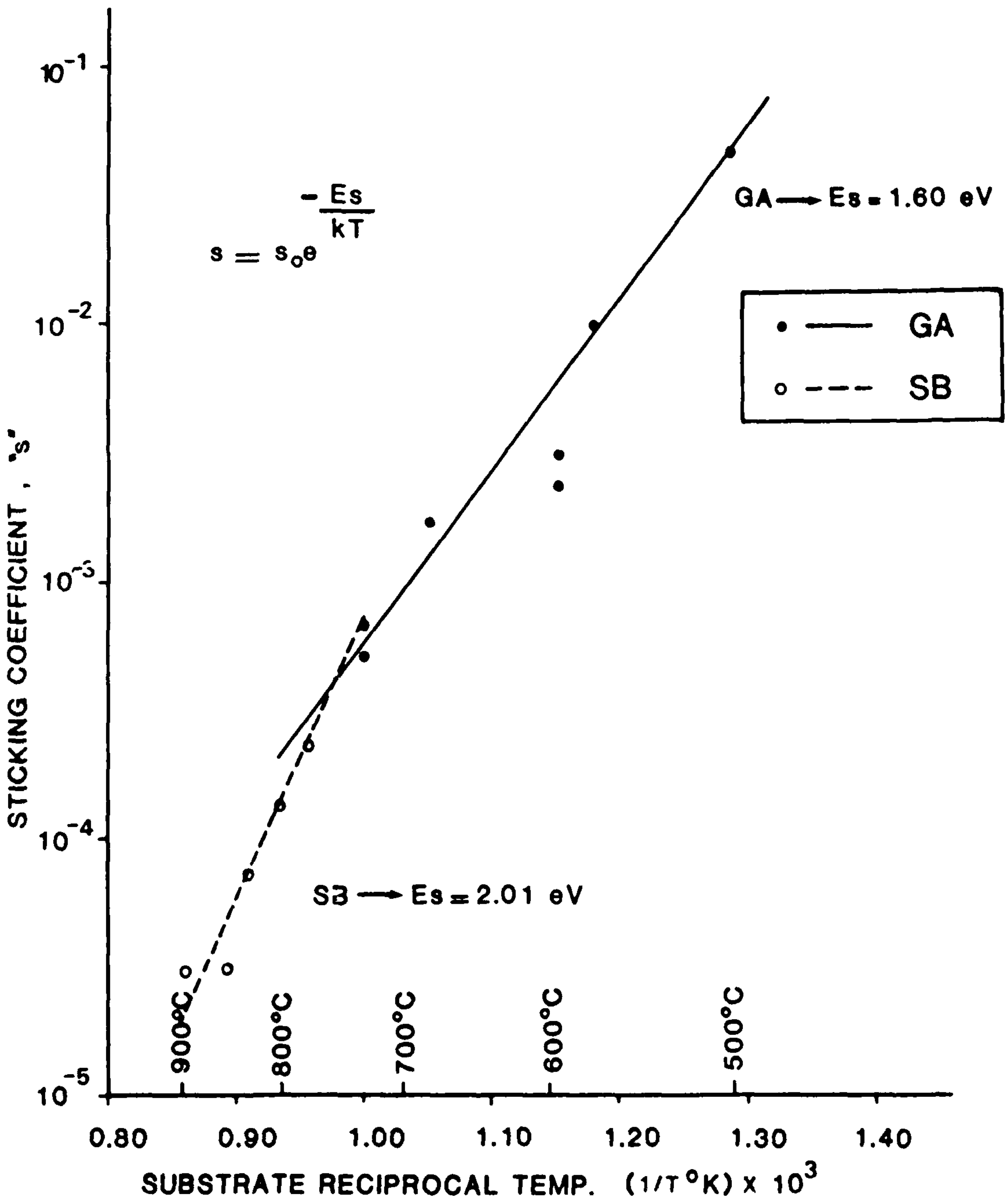


Fig. 14 STICKING COEFFICIENT AS A FUNCTION OF TEMPERATURE Ga AND Sb ON SILICON

SECTION V. CONCLUSIONS AND RECOMMENDATIONS

Silicon molecular beam epitaxy has the potential of growing mm wave devices with better dopant control, in very thin layers for prescribed arbitrary doping profiles, than any other growth method. This program has confirmed that the expected doping control in arbitrary profiles can be achieved by MBE. It has also confirmed that bulk mobility values can be achieved over a large range of doping densities for both Ga (p-type) and Sb (n-type) dopants. However, the p-n junctions grown by MBE in this program have all been far too leaky in reverse bias to serve as useful mm wave diodes. While we do not know the specific causes yet for this, there is no reason apparent at present, why this problem cannot eventually be solved by better control of impurities and/or dislocations during the MBE growth process. Emphasis must now be given to solving these problems before further attempts are made to produce MBE devices.

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   See Also EDL-3 (5), p. 138, (1982).
9. Five quarterly progress reports have been submitted to Wright-Patterson Air Force Base covering the period of this contract, September 10, 1981 through December 13, 1983.
10. Private Communication, from TRW.
11. R.A. Metzger, UCLA Ph.D. Thesis, to be published.

APPENDIX A

Chemical Cleaning treatment used at UCLA to prepare silicon MBE sample surfaces.

1. TCE
2. Acetone
3. Methanol
4. D. I. Rinse
5. 10 sec dip in 10% H.F. acid
6. D. I. Rinse
7. 5 min soak in 5:1:1 $H_2O:H_2O_2:NH_4OH$
8. D. I. Rinse
9. 5 min soak in 6:1:1 $H_2O:H_2O_2:HCl$
10. D. I. Rinse
11. Dry with N_2

APPENDIX B

Major Equipment Purchases on this Contract

1. Thermionics Lab Inc.

   Order 9/11/81

2 8 pm Inst. F.T. FEP-8	$ 650.00
2 10" Stroke Linear/Rotary F.T. FLR-1000	1,100.00

   Purpose: part of adapter flange assembly

2. Varian Assoc.

   Order 9/11/81

2 20pm Inst. F.T. 954-5116	900.00

   Purpose: part of adapter flange assembly

3. Thermionics Lab Inc.

   Order 9/11/81

Adapter Flange ULMAC O	5,200.00

   Purpose: increase volume of 12" diam. station

4. Huntington Mechanical Lab Inc.

   Order 9/11/81

10 Mini Rotary F.T. UF-106	2,950.00

   Purpose: part of adapter flange assembly

5. MDC Man. Co., Inc.

   Order 9/11/81

1	8"	Window	UP-600	485.00	
2	3/4"	Window	UP-150	220.00	
20	1 1/3"	Blank	F133000	220.00	
30	2 3/4"	Blank	F275000	420.00	
8	8"	Blank	F800000	800.00	
20	1 1/3"	Blank	F133050R	220.00	
30	2 3/4"	Blank	F275150R	420.00	
3	I.U.F.T.		MMC-150	210.00	
3	H.U.F.T.		MC-150	240.00	
2	Flexible Couplings		150-X	210.00	
					3,445.00

   Purpose: part of adapter flange assembly

6. Thermionics Lab Inc.
Order 10/19/81

60 Clamp-Wheeler Flange GWS-100	1,200.00

Purpose: part of adapter flange assembly

7. Environment Assoc.
Order 11/16/81

E-Beam Power Supply EB15-2	19,500.00

Purpose: control up to 3 E-guns in two separate stations

8. Leybold-Heraeus
Order 2/9/82

Turbomolecular Pump Turbovac 150	4,570.00

Purpose: additional pumping for ion gun

9. Industrial Vacuum Engr.
Order 2/24/82

E-Gun FIH-270-2	3,450.00

Purpose: expand Silicon source

10. Coulutron Research Corp.
Order 3/18/82

Ion Gun Model G-2-D	13,550.00

Purpose: ion doping

11. Dunaway Stockroom
Order 6/10/82

4 Rebuilt pump elements	1,900.00	
1 pump 50L/sec 7R245	1,250.00	
1 power supply 721-0012	700.00	
		3,850.00

12. Hewlett-Packard
Order 8/26/82

3 Power supply 600 2A	4,950.00	
3 HB-IB interface	1,650.00	
		6,600.00

Purpose: misc. power supply use: oven control direct interface to HP-85 computer

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