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A FEASIBILITY STUDY OF THE APPLICATION OF ION AND ELECTRON BEAMS TO SEMICONDUCTOR DEVICE FABRICATION

by

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ABSTRACT

Ion and electron beam technology provides a possible solution to resolution problems encountered in reducing the size of microelectronic circuit elements.

The thesis explores the improvement of resolution that might be obtained by replacing presently used photolithographic techniques for fabricating semiconductor circuits by ion implantation and electron beam machining and alloying.

The basic theory of charged particle beams is presented with emphasis on their application to the fabrication of semiconductor circuits. Experimental research is reported, which demonstrates the feasibility of the above and it is concluded that an improvement of resolution by a factor of 300 should be possible.

Finally, a method of overcoming the problem of dispersion in low energy ion beams is proposed.

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TABLE OF SYMBOLS

A is the cross sectional area of a beam of charged particles

C is the impurity concentration in atoms per cubic meter

E is the electric field measured in Volts per meter and Z directed

h is Planck's constant

I is the beam current in Amperes

J is the current density in Amperes per square meter

L is the junction depth in meters

m is the mass of the charged particle in kilograms

N is the number of impurity atoms

P is the power density in Watts per square centimeter

Q is the total charge of N ions

q is the charge of the particle in Coulombs

r is the beam diameter measured in meters

r_m is the minimum beam diameter measured in meters

s is the spacing between Z resolved points

t is time in seconds

v is the velocity of a particle in meters per second

V_o is the potential at the emitter in Volts

V is the acceleration potential in Volts

w is the volume of the junction in cubic meters

x is the spacing between the acceleration electrodes in meters

z is the length of the drift space in meters

z_o is the initial displacement in meters

ε_o is the permitivity of free space

λ is the electromagnetic wavelength in meters

INTRODUCTION

The transistor was invented in 1948 and ever since then researchers have been reducing the physical size of semiconductor elements with resulting savings in cost and improved reliability. The first integrated circuits containing 2, 3, and 4 input logic gates were developed in 1960 and were in production by 1962. Presently extensive research is being done on Large Scale Integration of circuits. These circuits contain more than 50 logic gates. One of the major drawbacks with large scale integration is that integrated circuits are only economical if produced in large quantities, and there are few complex circuits that are widely used and require large quantity production.

At present, photolithography is the only economical way to define the various patterns associated with the manufacture of integrated circuits. The expense involved in making the photolithographic masks requires mass production of integrated circuits to make them economical. Researchers are also approaching the optical limit of resolution of the photolithographic technique. Junctions 3 micrometers in width are being produced using this technique. The technique of using photolithography followed by thermal diffusion is satisfactory for producing transistors and simple integrated circuits, but it is inadequate for the production of sub-micron Devices and new processes are required.

Such a process was suggested in 1961 by K. R. Shoulders, (Ref. 1) but had the disadvantage of requiring a substrate to be transferred between several vacuum chambers with the associated registration and contamination problems. In 1962 G. S. Glinski et al. (Ref. 2) proposed an improved system in which the construction and inspection of a microcircuit was performed in a single vacuum chamber and in which the circuit configuration could be controlled by electronic techniques. Experimental work was performed under G. S. Glinski at the University of Ottawa with a "Multipurpose Microelectronic Processor." In this device, the following operations are performed:

1. Ion beam deposition of thin films.
2. Electron beam micromachining.
3. Inspection and testing of the microcircuit with a scanning electronic microscope.

Results were published by G. S. Glinski et al. in 1963 (Ref. 3) and by W. R. Samaroo in 1965. Ref. 4.

Initial work on a duoplasmatron ion source for the processor was reported by W. J. Jirafe in 1966 (Ref. 5) and continued by C. C. Tsai (Ref. 6) and M. Master under O. Celinski. At the time of writing, the processor is being further developed by K. Ramachandran working under G. S. Glinski.

The techniques developed for the processor can be adapted to the fabrication of junction microelectronic devices in Silicon, and this thesis is concerned with the improvement of resolution in the fabrication of small junction devices. In particular it explores the feasibility of electron beam microalloying of junctions and ion beam implantation of junctions at resolutions much higher than is presently possible by photolithographic methods.

The basic theory of beams of charged particles is presented with emphasis on the application of these beams to the production of semiconductor devices.

The experimental part of the research leads to the conclusion that electron beam micro-junction fabrication and testing is feasible. Electron beam bombardment as a practical means of producing an ion beam is demonstrated in the experimentation. It is concluded that this provides a means of producing junctions 300 times smaller than the smallest junctions produced today.

The introduction of a second electron beam into the system is proposed as a method of overcoming the problem of dispersion of low energy ion beams. Finally a system for the generation of such beams is suggested.

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CHAPTER ONE

THEORY OF BEAMS OF CHARGED PARTICLES

Resolution of Beams:

At the present time a great deal of research is being done on the production of high intensity ion beams. It is much more difficult to produce a high energy density beam with ions than with electrons. The reasons for this are as follows:

1) Every pure substance will produce more than one type of ion, and there is no simple device which will produce an intense beam of ions of one particular type with a reasonable efficiency.
2) Since the velocity of charged particules in an electric field is proportional to $m^{-\frac{1}{2}}$ an ion will have a much slower velocity than an electron in the same electric field. As an example the mass of a proton is 1.67×10^{-27} kilograms; 1840 times the mass of an electron and its velocity will be 43 times less for the same field. This slower velocity means that the space charge repulsion will be much greater for the ion beam, and hence it is at present impractical to produce an ion beam of high energy density.

3) When a beam of positive ionsstrike a target the ions release secondary electrons which accelerate back along the path of the ion beam. The result of this is an additional current drain on the high voltage power supply and possible damage to the ion emitting source.

4) Some focusing devices used with electrons are of little use with ions. In particular, magnetic lenses are not very suitable for ion beams because the focal length varies inversly as the mass of the charged particle. Electrostatic lenses are used, but suffer from the disadvantage that if they are struck by any of the ions a considerable flux of secondary electrons is formed. Ref. 7.

For these reasons the resolution of an ion beam is poor compared with that of an electron beam.

The resolution of beams of charged particles may be examined from the viewpoint of quantum mechanics. It is well known that the behavior of charged particles is similar to that of an electromagnetic wave of a defined wavelength. The expression for this wavelength is

$$\lambda = \frac{h}{mv} \qquad \text{..........(1)}$$

Where h is Planck's constant

m is the particle mass

v is the particle velocity

The velocity of the particle, is dependent upon the accelerating voltage and the mass of the particle. The equation for non relativistic velocities is

$$v = \sqrt{\frac{2qV}{m}} \qquad ....(2)$$

If this value for the velocity is substituted into formula (1) the resulting equation for the wavelength of a charged particle as a function of its mass is:

$$\lambda = \frac{h}{\sqrt{2qVm}} \qquad ....(3)$$

This equation shows that if the charge and the electric field remain constant the wavelength will decrease as the mass of the charged particle increases. For example, the theoretical wavelength of a hydrogen ion beam will be 43 times less than that of an electron beam of the same energy.

It is also well known that the resolution of an optical system is theoretically limited by the wavelength of the radiation and is given by

$$s \approx \lambda$$

s is the spacing between 2 resolved points

Thus, if the wavelength is decreased the resolution is increased. Therefore if quantum mechanics is to govern the limit of resolution of the electron and ion beams, the ion beam would have a much higher resolving power than the electron beam.

At present it is not the quantum mechanical wavelength which limits the resolution of these beams but rather it is the spreading of the beam because of space charge repulsion. In order to compute this space charge repulsion effect of a beam of charged particles it is necessary to make several assumptions. The most restricting of these assumptions concerns the initial conditions of the beam. A beam of charged particles that originates from a realistic source, does not have a uniform current density across its cross section. The axial and radial velocities of the particles vary throughout the beam. In order to simplify the computation of the shape of the beam it is necessary to assume a uniform current density, and uniform axial velocity across the cross section. It follows that in this case the volume density is uniform, and the radial velocity of any charged particle of the beam is directly proportional to its distance from the axis. All paths are similar and the beam shape is determined by the path of the beam edge particle. A beam which satisfies these assumptions is called a laminar beam. It is also usual to assume the the beam divergence is small, which simplifies the determination of the space charge forces that are effective in the beam. Ref. 7

The nonrelativistic equations of motion are

$$\frac{md^2r}{dt^2} = q\frac{I}{2\pi r\dot{z}\varepsilon_o} \qquad \text{..........(5)}$$

$$\frac{md^2z}{dt^2} = qE \qquad \text{..........(6)}$$

E is the electric field measured in volts per meter and Z directed

I is the beam current measured in Amperes

r is the beam diameter measured in meters

q is the charge of the particle in Coulombs

m is the mass of the particle measured in kilograms

ε_o is the permittivity of a vacuum

where Gauss' theorem is used to determine the radial force caused by the space charge, and also where the magnetic force caused by the current is neglected.

Integrating equation 6

$$\dot{z} = \frac{q}{m}Et + \dot{z}_o \qquad \text{..........(7)}$$

Substituting 7 into 5

$$\frac{d^2r}{dt^2} = \frac{qI}{2\,\pi\varepsilon_o mr(\frac{q}{m}Et + \dot{z}_o)} \qquad \text{..........(8)}$$

This equation describes the diverging effect attributable to space charge. Figure 1 illustrates the system described by equation 8. The beam originates at A and is accelerated by an electric field E to position B where it passes through a limiting aperture and drifts to C. If the electric field is zero the equation describes the spreading effect in a drift space that is region B to C. If E is a constant not equal to zero the equation describes the spreading effect in the acceleration space A to B.

Beam of Charged Particles in Drift and Acceleration Space

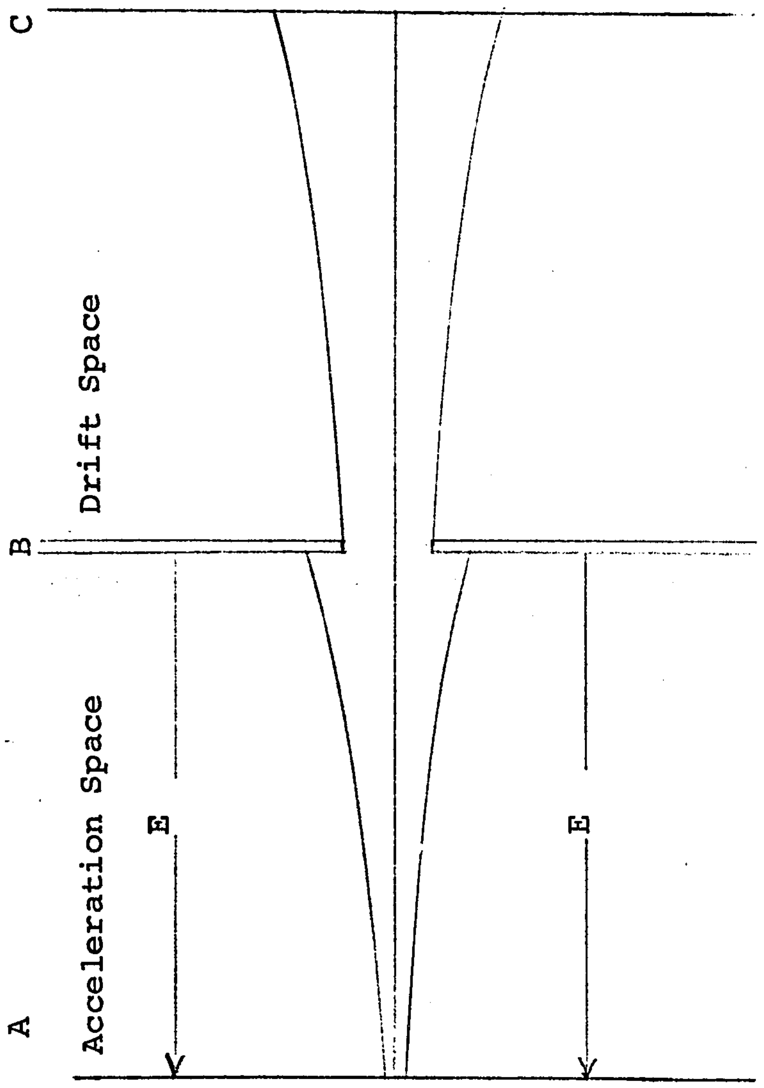


Figure 1

Behavior of Beams in Drift Space:

In the drift space E is zero and equation 8 reduces to

$$\frac{d^2r}{dt^2} \doteq \frac{qI}{2\pi\varepsilon_o m r \dot{z}_o} \qquad \text{..........(9)}$$

Integrating equation 9 once the result is

$$\frac{1}{2}\, m\dot{r}^2 = \frac{qI}{2\pi\varepsilon_o m r \dot{z}_o} \ln \underline{r} + c \qquad \text{..........(10)}$$

To solve for the constant c assume $\dot{r}$ is equal to zero at the minimum beam diameter r_m. Equation 10 becomes

$$\frac{1}{2}\, m\dot{r}^2 = \frac{qI}{2\pi\varepsilon_o m r \dot{z}_o} \ln \frac{r}{r_m} \qquad \text{..........(11)}$$

The assumption that $\dot{r}$ is zero is valid in 2 cases illustrated in figures 2 and 3. In figure 2, the first case, the beam is forced to converge to a minimum. In figure 3 the area of the aperture is small compared to the area of the emitter and the radial velocity is small compared with the axial velocity.

The origin of the time is taken when the charged particles pass the minimum cross section. Integrate equation 11

$$\int_{r_m}^{r} \frac{dr}{\left[\ln\left(\frac{r}{r_m}\right)\right]^{1/2}} = \int_{o}^{t} \left(\frac{qI}{\pi\varepsilon_o m \dot{z}_o}\right)^{1/2} dt \qquad \text{..........(12)}$$

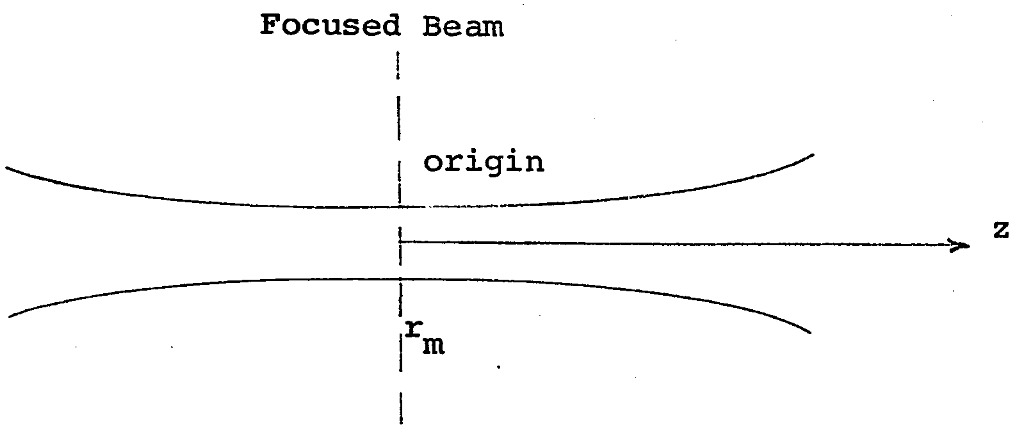


Figure 2

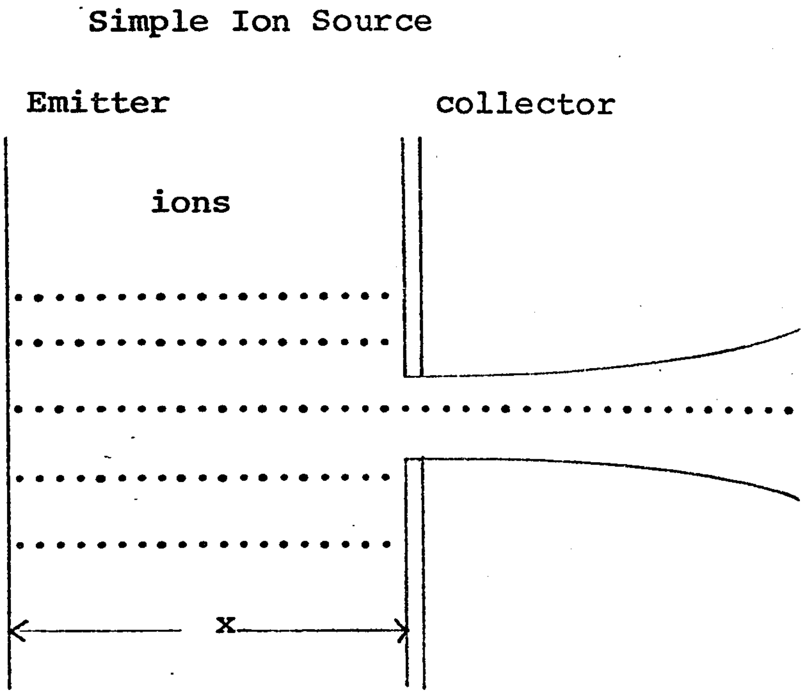


Figure 3

and letting

$$R = \frac{r}{r_m} \qquad \text{..........(13)}$$

and

$$z = \dot{z}_o t \qquad \text{..........(14)}$$

then

$$\frac{1}{R}\int_1^R \frac{dR}{(\ln R)}\,{}^{1/2} = \frac{t}{r}\left(\frac{qI}{\pi\varepsilon_o m\dot{z}_o}\right)^{1/2} = \frac{z}{r}\left(\frac{qI}{\pi\varepsilon_o m\dot{z}_o}\right)^{1/2}\frac{1}{\dot{z}_o} \qquad \text{..........(15)}$$

Using the transformations

$$w = \left(\ln R\right)^{1/2} \quad \text{or} \quad R = \exp\left(w^2\right) \qquad \text{..........(16)}$$

equation 15 becomes

$$\int_1^R \frac{dR}{\left(\ln R\right)^{1/2}} = 2\int_o^w \exp\left(w^2\right)dw \qquad \text{..........(17)}$$

An approximate expression for this integral was given in Ref. 1 in the form

$$2\int^{\left(\ln \frac{r}{r_m}\right)^{1/2}} \exp\left(w^2\right)dw \simeq 2.09\left(\frac{r}{r_m} - 1\right) \qquad \text{..........(18)}$$

Using the relation

$$\frac{1}{2}\,m\dot{z}_o^2 = |q|\,V \qquad \text{..........(19)}$$

equation 15 becomes

$$2.09\left(\frac{r}{r_m} - 1\right)^{1/2} \simeq \frac{z}{r_m}\left(\frac{qI}{\pi\varepsilon_0 m\dot{z}_0}\right)^{1/2}\frac{1}{\dot{z}_0} \quad \ldots\ldots\ldots\ldots(20)$$

which reduces to

$$r \simeq 0.292 \times 10^{10}\,\frac{z^2 I}{r_m V^{3/2}}\left(\frac{m}{q}\right)^{1/2} + r_m \quad \ldots\ldots\ldots\ldots(21)$$

Equation 21 shows the relation of the beam diameter to the various parameters. The diameter of the beam is dependent upon the mass of the charged particle. This is why ion beams are more difficult to focus than electron beams, and also explains the limitation on the resolution of beams of charged particles. If the space charge repulsion could be neutralized, the limiting factor would become the quantum mechanical wavelength, in which case an ion beam could have better resolution than an electron beam.

Optimum Aperture Size:

The optimum aperture size for the system shown in figure 3 is derived as follows. The beam diameter is related to the current density by the expression

$$J = \frac{I}{A} = \frac{4I}{\pi r^2} \quad \ldots\ldots\ldots\ldots(22)$$

J is the current density in Amperes per square meter

I is the current in Amperes

A is the cross sectional area of the beam r is the beam diameter in meters

Rearranging equation 22

$$r = \sqrt{\frac{4I}{\pi J}} \qquad \text{..........(23)}$$

Assume I to be constant, then r is a minimum when J is a maximum. The expression for J_{max} is derived as follows. For particles of charge q and mass m emitted with negligible velocity at the source.

$$V(x) = \left[\frac{2q(V_o-V)}{m}\right]^{1/2} \qquad \text{..........(24)}$$

V_o is the potential at the emitter

V is the potential at any point between the emitter and the collector

The profile of the potential function V(x) is related by Poisson's equation to the profile of the ion density N(x):

$$\frac{d^2V}{dx^2} = \frac{-Nq}{\varepsilon_o} = \frac{-J}{\varepsilon_o v} = \frac{J}{\varepsilon_o}\left[\frac{m}{2q(V_o-V)}\right]^{1/2} \qquad \text{..........(25)}$$

Equation 25 may be integrated after multiplying by $2\left[\frac{dV}{dx}\right]$ which gives

$$\left(\frac{dV}{dx}\right)^2 - \left(\frac{dV}{dx}\right)^2_{x=o} = \frac{4J}{\varepsilon_o}\left[\frac{m(V_o-V)}{2q}\right]^{1/2} \qquad \text{..........(26)}$$

The term $\left(\frac{dV}{dx}\right)^2_{x=o}$ is the square of the electric field at the ion source, E_o.

It is impossible for the value of E_o to be negative since this would mean that the current flow would be zero. The range of values for E_o is

$$0 < E_o < \frac{V_o}{x} \quad \text{..........(26)}$$

The upper limit is the pure electrostatic field which would prevail in the absence of any space charge, and which would be constant along the axial direction x. The lower limit is the space charge limited case, where the acceleration field has been just neutralized at the ion source by the distribution of the intervening charge. In this space charge limited case

$$\frac{dV}{dx} = 2\left(\frac{J}{\varepsilon_o}\right)^{1/2} \left[\frac{m(V_o-V)}{2q}\right]^{1/4} \quad \text{..........(28)}$$

which after integration becomes:

$$V = V_o - \left[\frac{3}{2}\left(\frac{J}{\varepsilon_o}\right)^{1/2} \left(\frac{m}{2q}\right)^{1/4} x\right]^{4/3} \quad \text{..........(29)}$$

The space charge limited current density is determined by inserting V=0 at $x=x_a$. Ref. 8

$$J_{max} = \frac{4\varepsilon_o}{9}\left(\frac{2q}{m}\right)^{1/2} \frac{V_o{}^{3/2}}{x^2} \quad \text{..........(30)}$$

Equation 30 has some similarities to equation 21. Equation 21 is the space charge repulsion equation for a beam of charged particles in a drift space, while equation 30 is the space charge limited current density of a source of charged particles in an applied acceleration field.

Substituting equation 30 into equation 23

$$r_m = 3x \left(\frac{m}{2q}\right)^{1/4} \left(\frac{I}{\pi \varepsilon_o}\right)^{1/2} \left(\frac{1}{V_o}\right)^{3/4} \quad \ldots\ldots\ldots(31)$$

which is the equation for r_m since J is a maximum and I is assumed constant. Equation 31 is therefore the equation for the optimum diameter of the aperture.

Calculation of beam Current:

If this beam is to be used to produce a semiconductor junction the relationship between the impurity concentration and the beam current must be determined. Figure 4 is a cross section view of the silicon substrate showing the incoming ion beam and the junction boundaries. The impurity concentration is

$$C = \frac{N}{W} \quad \ldots\ldots\ldots\ldots(32)$$

C is the impurities concentration in atoms per cubic meter.

W is the volume of the junction in cubic meters.

N is the number of impurity atoms.

Cross Section of Silicon Substrate

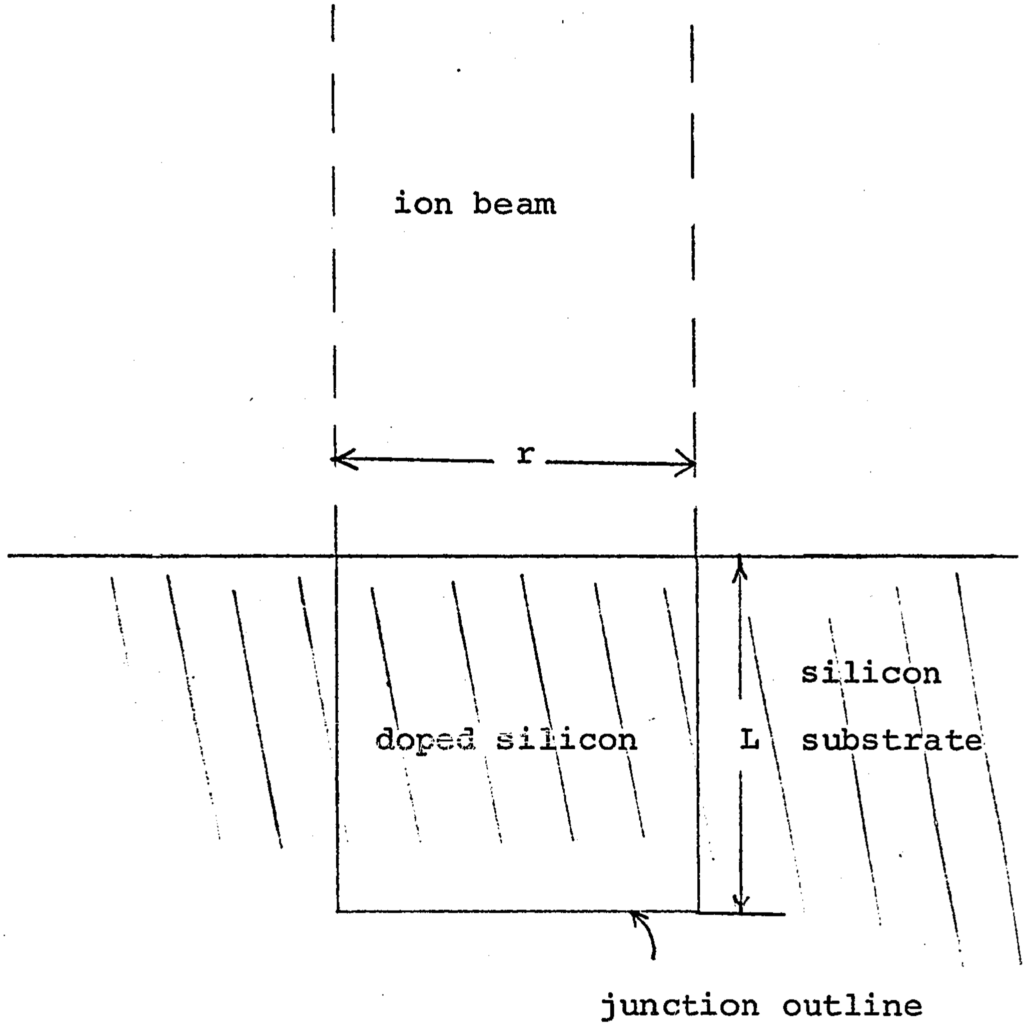


Figure 4

The net charge transfer for N impurity ions is given by

$$Q = Nq \qquad \ldots\ldots\ldots\ldots(33)$$

q is the charge on the individual ions.

Q is the total charge of N ions.

Therefore the beam current I is

$$I = \frac{dQ}{dt} = \frac{Q}{t} \qquad \ldots\ldots\ldots\ldots(34)$$

if I is a constant beam current.

Combining equation 32, 33 and 34 the beam current is

$$I = \frac{CWq}{t} \qquad \ldots\ldots\ldots\ldots(35)$$

System Design Equation:

Figure 5 is a diagram of the complete system for generating and using an ion beam to form semiconductor junctions. Region A to B is the ion source, in which the emitter located at A, has a positive potential V applied to it. The collector located at B is held at zero potential. The substrate at C also is held at zero potential and therefore there is no electric field between B and C which results in B to C being a drift space. The last region C to D is a cross section of the substrate showing the junction outline. One further assumption is made ie that the ions are positive Boron ions and the substrate is N type silicon.

Ion Beam System for Junction Formation

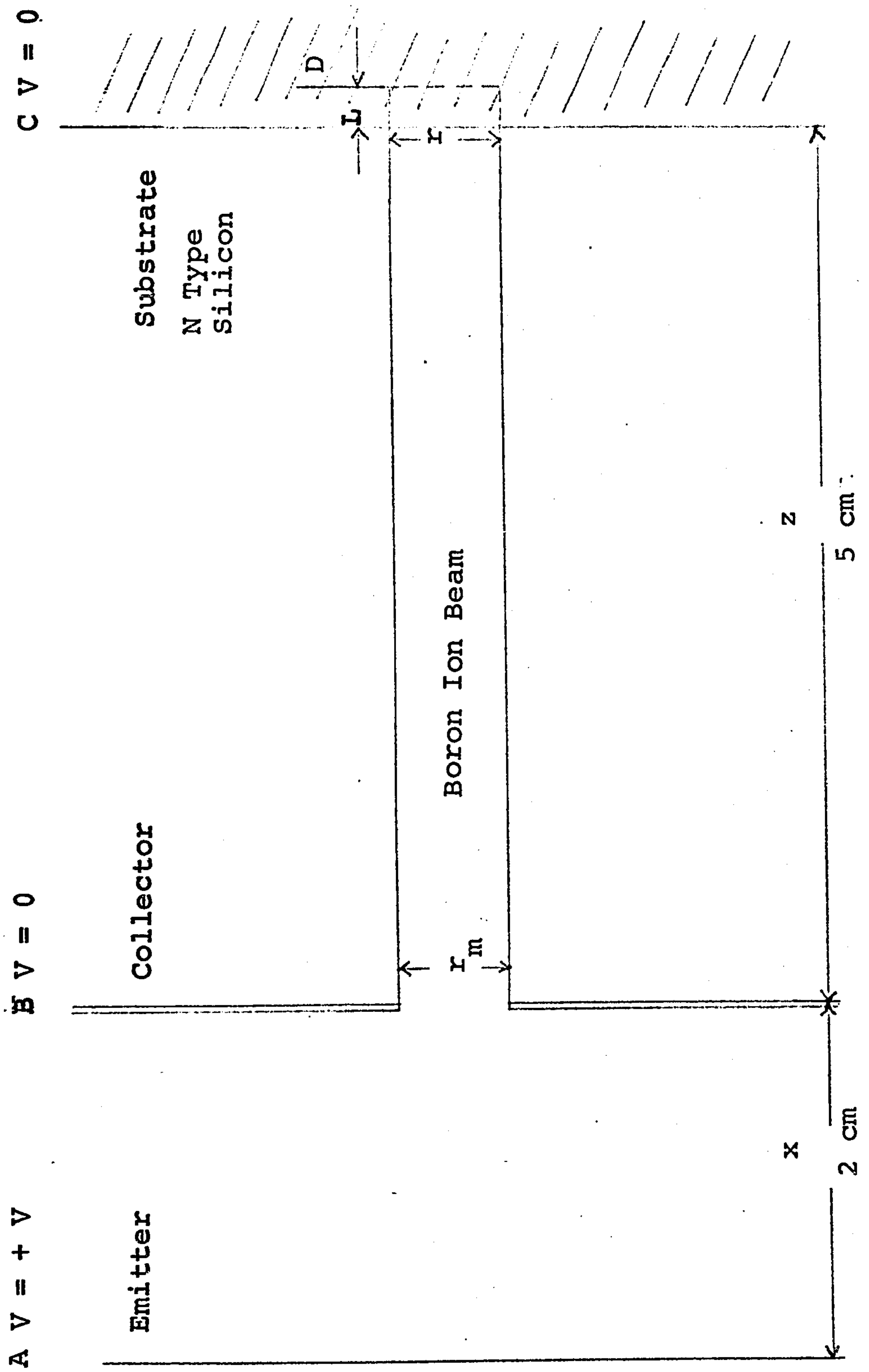


Figure 5

Equation 21 is the general equation for space charge repulsion of a beam in a drift space.

$$r \approx .292 \text{ X } 10^{10} \frac{z^2 I}{r_m V^{3/2}} \left(\frac{m}{q}\right)^{1/2} + r_m$$

The minimum beam diameter r_m is the collector aperture diameter and the optimum value is given by equation 31.

$$r_m = 3x \left(\frac{m}{2q}\right)^{1/4} \left(\frac{I}{\pi \varepsilon_o}\right)^{1/2} \left(\frac{1}{V_o}\right)^{3/4} \qquad \text{..........(31)}$$

Combining equations 21, 31, and 35 and letting V equals V_o.

$$r \approx 0.292 \text{ X } 10^{10} \frac{z^2}{r_m V^{3/2}} (mq)^{1/2} \frac{CW}{t} + \frac{3x}{V^{3/4}} \left(\frac{mq}{2}\right)^{1/4} \left(\frac{CW}{\pi \varepsilon_o t}\right)^{1/2} \qquad \text{....(36)}$$

Rearranging equation 36

$$r \approx 0.292 \text{ X } 10^{10} \frac{z^2}{r_m V^{3/2}} \left[(mq)^{1/2} \frac{CW}{t}\right]$$

$$+ \frac{4.78 \text{ X } 10^5 \text{ x}}{V^{3/4}} \left[\frac{(mq)^{1/2}}{V^{3/2}} \frac{CW}{t}\right]^{1/2} \qquad \text{..........(37)}$$

Letting $K^2 = \left(\frac{mq}{V^3}\right)^{1/2} \frac{CW}{t}$ ....(38)

equation 37 reduces to

$$r \approx 0.292 \text{ X } 10^{10} \frac{z^2}{r_m} K^2 + 4.78 \text{ X } 10^5 \text{ x } K \qquad \text{..........(39)}$$

Substituting equation 35 into 21

$$r \simeq \frac{0.292 \times 10^{10} \; z^2}{r_m V^{3/2}} \left[(mq)^{1/2} \; \frac{CW}{t} \right] + r_m \quad \text{.........}(40)$$

but

$$K^2 = \left(\frac{mq}{V^3} \right)^{1/2} \frac{CW}{t} \quad \text{..........}(38)$$

hence

$$r \simeq \frac{0.292 \times 10^{10} \; z^2 K^2}{r_m} + r_m \quad \text{..........}(41)$$

and

$$r \simeq \frac{0.292 \times 10^{10} \; z^2 K^2}{r_m} + 4.78 \times 10^5 \times K \quad \text{.........}(39)$$

therefore

$$r_m = 4.78 \times 10^5 \times K \quad \text{..........}(42)$$

Equation 39 can be further reduced to

$$r \simeq \frac{0.292 \times 10^{10} \; z^2 \, K^2}{4.78 \times 10^5 \times K} + 4.78 \times 10^5 \times K \quad \text{..........}(43)$$

or

$$r \simeq \frac{6.1 \times 10^3 \; z^2 \; K}{x} + 4.78 \times 10^5 \times K \quad \text{..........}(44)$$

If the power density of the beam at the substrate is too high it will melt it and destroy its crystal structure. To avoid this the power density must be kept below 10^6 Watts per square centimeter. Ref. 9 The equation for the power density is

$$P = \frac{VI}{A} \qquad \text{..........(45)}$$

P is the power density in Watts per square centimeter.

A is the cross section area in square meters.

Substituting I from equation 35

$$P = \frac{VCWq}{At} \qquad \text{..........(46)}$$

Substituting for W from figure 4

$$P = \frac{VCALq}{At} = \frac{VCLq}{t} \qquad \text{..........(47)}$$

Depth of Penetration:

The depth of the junction is determined by the depth of penetration of the bombarding ions. This depth will be determined by the energy level of the ions and hence by the acceleration voltage V.

The depth of penetration of ions into solids is determined from emperical data. The exact value depends upon several factors such as, crystal lattice orientation, the size of the bombarding ions and the substrate material. References conculted gave no figure for the depth of penetration of Boron into Silicon. Figures were shown for the penetration of Neon into Silicon dioxide. Neon is element 10 in the periodic table and Boron is element 5. This means boron would penetrate further than Neon because it is a smaller ion. These values for neon are: Ref. 10

Ion	Ion energy E(keV)	Effective Layer depth Angstroms
Ne^+	38.3	740 ± 4
Ne^+	43.9	850 ± 4
Ne^+	51.8	950 ± 5

From this data the assumption was made that for an energy level of 5×10^4 electron volts the depth of penetration of Boron into Silicon would be approximately 1,000 Angstroms.

CHAPTER TWO

APPLICATION OF DESIGN THEORY

Example one:

This is shown in figure 5 and the assumptions made are as follows:

1) The desired junction depth is 1,000 Angstroms.
2) The resistivity of the doped silicon is to be 1 ohm centimeter. The impurity concentration would have to be 10^{22} atoms per cubic meter Ref. 11
3) All ions which strike the substrate are absorbed.
4) The spacing between the electrodes A and B of the ions source is 2 centimeters.
5) The length of the drift space B to C is 5 centimeters.
6) The collector hole diameter is 1.0 micrometer.
7) The impurity ion is boron and the substrate is N type silicon.

For a depth of penetration of 1,000 Angstoms an energy level of 50×10^3 electron volts is required as was stated previously. Assuming the boron ions carry a single charge of 1.6×10^{-19} coulombs, the accelerating potential would be 5×10^4 volts.

Rearranging equation 42 and solving for K

$$K = \frac{r_m}{4.78 \times 10^5 x} \quad \ldots\ldots\ldots\ldots (48)$$

$$= \frac{10^{-6}}{4.78 \times 10^5 \times 2 \times 10^{-2}}$$

$$= 1.04 \times 10^{-10} \quad \frac{\text{kilograms}^{1/2}\ \text{Coulombs}^{1/2}}{\text{Volts}^{3/2}\ \text{seconds}}$$

From equation 44

$$r \approx \frac{6.1 \times 10^3\ z^2\ K}{x} + 4.78 \times 10^5 \times K \quad \ldots\ldots\ldots\ldots (44)$$

$$r \approx \frac{6.1 \times 10^3 \times (5 \times 10^{-2})^2 \times 1.045 \times 10^{-10}}{2 \times 10^{-2}}$$

$$+ 4.78 \times 10^5 \times 2 \times 10^{-2} \times 1.045 \times 10^{-10}$$

$$r \approx 1.08 \times 10^{-6} \text{ meters}$$

Thus a junction of 1.08×10^{-6} meters in diameter will be produced by the system shown in figure 5 under the above listed assumptions.

The time of formation of the junction is calculated using equation 38

$$K^2 = \left(\frac{mq}{V^3}\right)^{1/2} \frac{CW}{t} \qquad \ldots\ldots\ldots\ldots(38)$$

The volume W is

$$W = \frac{\pi D^2}{4} \times L$$

$$W = \frac{\pi}{4} \times (1.08 \times 10^{-6})^2 \times 10^{-7}$$

$$= 0.917 \times 10^{-19} \quad \text{meters}^{3}$$

from equation 38

$$t = \left(\frac{mq}{V^3}\right)^{1/2} \frac{CW}{K^2}$$

$$= \left(\frac{1.67 \times 10^{-26} \times 1.6 \times 10^{-19}}{1.25 \times 10^{14}}\right)^{1/2} \times \frac{10^{22} \times 0.917 \times 10^{-19}}{(1.045 \times 10^{-9})^{2}}$$

$$= 3.85 \times 10^{-7} \text{ seconds}$$

The beam current is calculated using equation 35

$$I = \frac{CWq}{t} \qquad \ldots\ldots\ldots\ldots(35)$$

$$= \frac{10^{22} \times 0.917 \times 10^{-19} \times 1.6 \times 10^{-19}}{3.85 \times 10^{-7}}$$

$$= 0.381 \times 10^{-9} \text{ Amperes}$$

The power density is checked using equation 47

$$P = \frac{VCLq}{t}$$

$$= \frac{5 \times 10^4 \times 10^{22} \times 10^{-7} \times 1.6 \times 10^{-19}}{3.85 \times 10^{-7}}$$

$$= 2.07 \times 10^{3} \text{ Watts per square centimeter}$$

The power density is below the maximum permissable value of 10^6 Watts per square centimeter.

It has been demonstrated that it is possible to use an ion beam to produce a semiconductor junction. In summary, the junction formed would be 1.08 micrometers in diameter, 0.1 micrometers in depth, and would be formed in 0.385 microseconds with the system described in example one.

With present day photolithographic techniques the smallest junction which can be produced is 3 micrometers in diameter. Ref. 12 The ion implantation technique described above improves this resolution limit by a factor of approximately 3.

The figure of 1.08 micrometers for the diameter of the ion beam at the substrate is made up of two terms. The first of these terms is the space charge repulsion term for the beam and is equal to 0.08 micrometers, and the second term is the minimum beam diameter governed by the physical limitation on the collector hole diameter of 1.0 micrometer.

Generation of Ions:

In the system described no explanation has been given regarding the method of generating the ions at the emitter electrode. One method of doing this is to use a device called a Duoplasmatron. Research on this method was started at the University of Ottawa by Professor G. Glinski and W. Jirafe (Ref. 5) and is being continued by Professor O. Celinski and M. Master.

Another method of generating an ion beam is by electron beam bombardment. The electron beam locally heats the substance and produces positive and negative ions. The positive ions accelerate back along the electron beam towards the cathode and may be separated from the electrons by a magnetic field.
The electron beam energy is dissipated in three ways:

1) heating the substance
2) generating negative ions
3) generating postive ions

Therefore, the ratio of positive ions to electrons is small and there remains a net negative charge in the beam. Because the ions have very little kinetic energy when they are first formed, they are drawn into the electron beam and held there by the negative charge while they are accelerating towards the cathode. See figure 6

A problem with the method of ion beam implantation, illustrated in example 1,is the restriction on the collector aperture diameter, which determined the minimum beam diameter. Using an electron beam, to generate the ion beam removes this restriction because the ion beam will have approximately the same diameter as the electron beam. Electron beams have been produced with diameters as low as 100 Angstroms which is 100 times smaller than the minimum beam diameter obtained in Example 1 of 10^{-6} meters.

Example II:

A possible system is shown in figure 7 . In the system

Production of Ion Beam by Electron Beam Bombardment

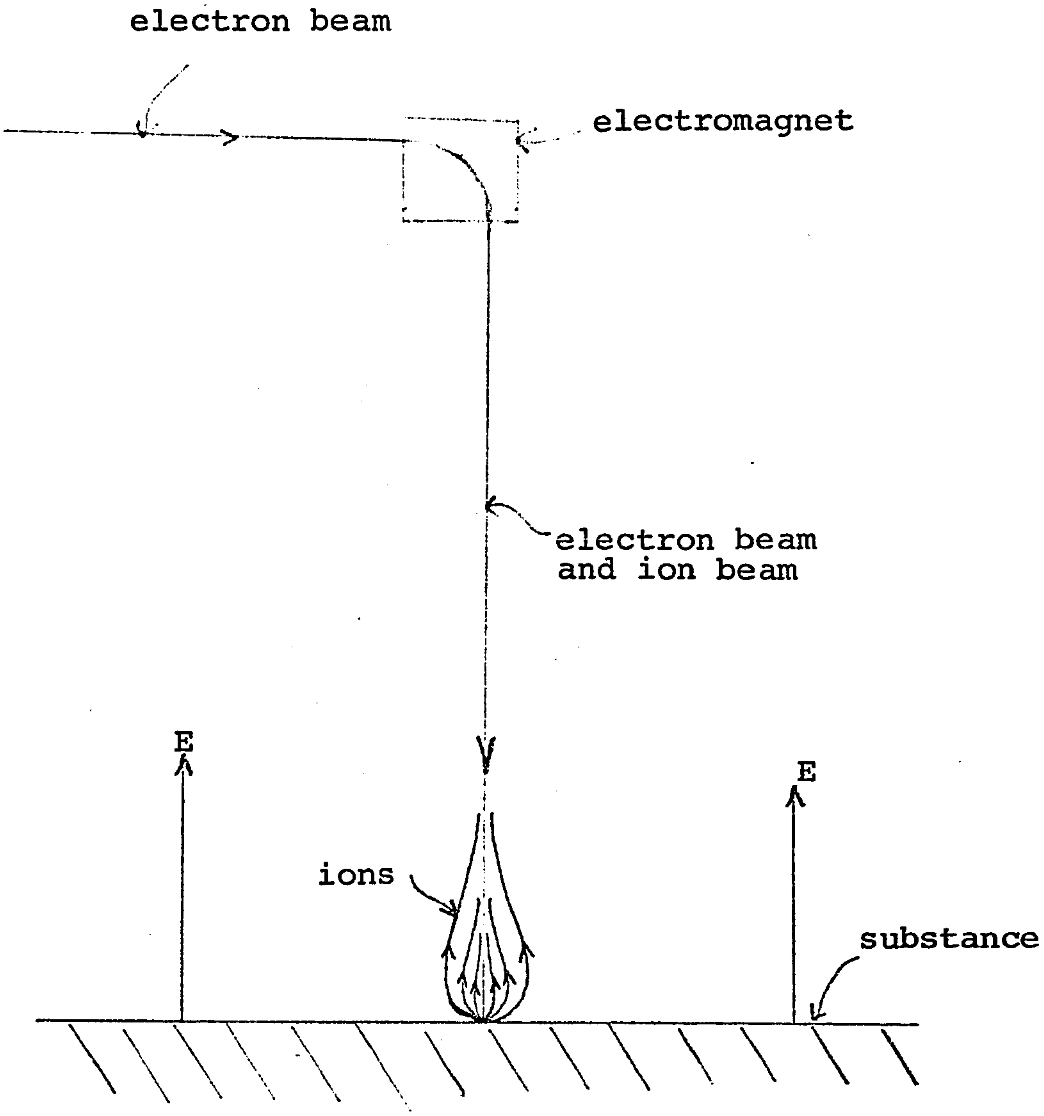


Figure 6

Electron Beam Bombardment System

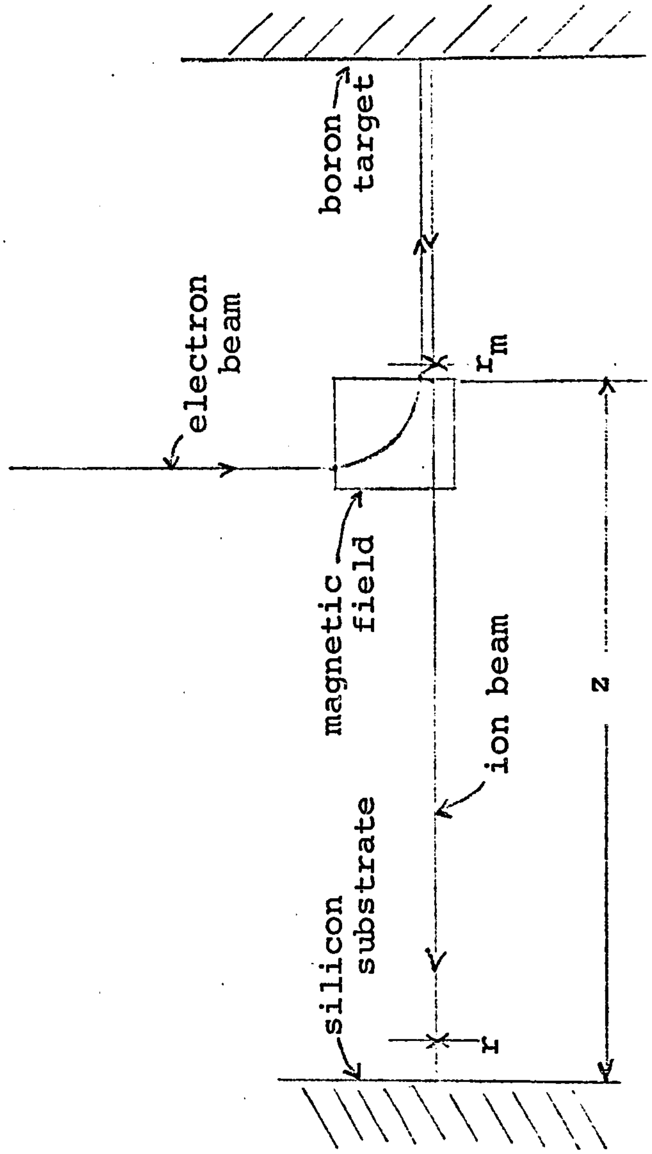


Figure 7

the electron beam is bent through 90 degrees by a magnetic field and then strikesthe boron. The positive boron ions return along the electron beam as far as the magnetic field where they are separated from the electron beam and continue as a pure ion beam. The assumptions made are as follows:

1) The desired junction depth is 1000 Angstroms.
2) the resistivity of the doped silicon is to be 1 ohm centimeter.The impurity concentration would have to be 10^{22} atoms per cubic meter. Ref. 11
3) All ions which strike the substrate are absorbed.
4) The length of the drift space B to C is 5 centimeters.
5) The impurity ion is Boron and the substrate is N type silicon.
6) The minimum beam diameter is 100 Angstroms.
7) The current density at the minimum beam diameter can be made equal to the value in example one.

$$J = \frac{I}{A} \quad \ldots\ldots\ldots(22)$$

$$= \frac{0.381 \times 10^{-9}}{\frac{\pi}{4} \times (10^{-6})^2} = 0.485 \times 10^{-21} \text{ Amperes per square meter}$$

The beam current is

$$I = JA$$

$$= 0.485 \times 10^{-21} \times \frac{\pi}{4} \times (10^{-8})^2 = .381 \times 10^{-13} \text{ Amperes}$$

The junction diameter is

$$r \simeq 0.292 \times 10^{10} \frac{Z^2 I}{r_m V^{3/2}} \left(\frac{m}{q}\right)^{1/2} + r_m \quad \ldots\ldots\ldots\ldots(21)$$

$$r \simeq 0.292 \times 10^{10} \left(\frac{(5 \times 10^{-2})^2 \times 0.381 \times 10^{-13}}{10^{-8}\ (5 \times 10^{4})^{3/2}}\right) \times$$

$$\left(\frac{1.67 \times 10^{-26}}{1.6 \times 10^{-19}}\right) + 10^{-8}$$

$$\simeq 1.08 \times 10^{-8} \text{ meters}$$

The power density

$$P = \frac{VI}{A} \quad \ldots\ldots\ldots\ldots(45)$$

$$= \frac{5 \times 10^{4} \times .381 \times 10^{-13}}{\frac{\pi}{4}\ (1.08 \times 10^{-8})^2} = 2.88 \times 10^{3} \frac{\text{Watts}}{\text{sq. centimeter}}$$

The time of formation of the junction is from equation 35

$$t = \frac{CWq}{I}$$

$$= \frac{10^{22} \times \pi\ (1.08 \times 10^{-8})^2 \times 1.6 \times 10^{-19}}{4 \times 0.381 \times 10^{-13}}$$

$$= 3.85 \times 10^{-7} \text{ seconds}$$

This example shows that by using the technique of electron beam bombardment to produce the ion beam it should be possible to produce a junction of approximately 100 Angstroms in diameter. This is three hundred times smaller than that obtainable by present day photolithographic techniques.

The Neutralized Beam:

When shallower junctions are required the acceleration potential must be reduced which results in greater spreading of the beam. For example, if it is desired to produce a junction with a depth of 100 Angstroms the acceleration voltage would be reduced to 5 kilovolts

In equation 21

$$r \approx 0.292\text{X } 10^{10} \; \frac{Z^2 I}{r_m \, V^{3/2}} \; \frac{m}{q}^{1/2} + r_m \qquad \text{..........(21)}$$

the first term is the space charge repulsion term and is proportional to $V^{-3/2}$. For example, in example 2, reduction of V by a factor of 10 increases the spreading term by 31.5 times. In example 2 the new junction diameter would be $3.52 \text{ X } 10^{-8}$ meters ie 3.25 times the original junction diameter. In the production of some semiconductor devices this amount of spreading is unacceptable.

If the electron density in the beam becomes equal to the ion density in a region free of external electric fields, there will be no overall space charge and the ions will travel in straight lines. If in particular the optical system which follows the source provide a parallel beam at the entry to the neutralized zone the beam will remain parallel throughout this zone. Intense beams can thus be transported over long distances without appreciable divergence. This provides a solution to the problem of space charge repulsion. This process of beam neutralization is impossible in the beam extraction region and within electrostatic lenses. Furthermore the electrons must be trapped in the useful zone and prevented from turning back towards the source. This can be done by the formation of a sufficiently deep negative potential well or a magnetic barrier at the extremities of the useful zone. Ref. 13

In a paper entitled "The Duoplasmatron As An Ion Or Electron Injector Of Very High Emission Current Density" M. von Ardenne also refers to the neutralized beam which he calls a plasma beam. In his description of the duoplasmatron he states that it can be used as a plasma injector. In this state positive ions and electrons are injected simultaneously with a high initial current density into a field free region. When guiding the electrons magnetically by means of an axial magnetic field it is possible to contain this plasma in a known manner in the form of beams through the electron space charge. Ref. 14.

Application of this technique should reduce the space charge repulsion term to an acceptable value and permit the formation of junctions of the same diameter at different depths.

CHAPTER THREE

EXPERIMENTATION

Outline:

The thesis as explained in the introduction, was a feasibility study of new techniques for the production of semiconductor junctions. The purpose of the experimentation was to perform basic experiments on a limited budget to show the feasibility of doing more sophisticated experiments with more elaborate equipment. This experimentation may be grouped under the following headings:

1) Vacuum system
2) Electron beam microalloying
3) Generation of boron ions using electron beam bombardment

Vacuum System:

The construction of the vacuum system involved the design and manufacture of a suitable working chamber and of fittings to couple together the complete system. It was decided that the system would be built around a National Research Corporation four inch diffusion pump and a Balzers type DUO 5 rotary pump.

A diagram of the vacuum system is shown in figure 8. A liquid nitrogen cold trap was used to minimize back streaming in the system. The vacuum chamber which was designed is shown in figure 9.

The vacuum gauge used was a National Research Corporation ionization gauge type 724 and the ionization head type 524 was placed at the extremity of the vacuum system as shown in the diagram so that the pressure indicated would be the highest pressure in the whole system.

Roughing System:

The roughing technique used in the system is unusual because there is no separate roughing line to the vacuum chamber but rather the system is roughed through the diffusion pump. This roughing sytem worked well and was also economical since it saved the expense of the roughing line with all its necessary fittings and valves.

Performance:

The pump down time of the system to 10^{-6} millimeters of mercury from a cold start varied from approximately one half hour to one hour depending upon the system cleanliness. The ultimate vacuum of the system could not be measured because the limit on the National Research Corporation vacuum gauge is 10^{-7} millimeters of mercury.

Vacuum System

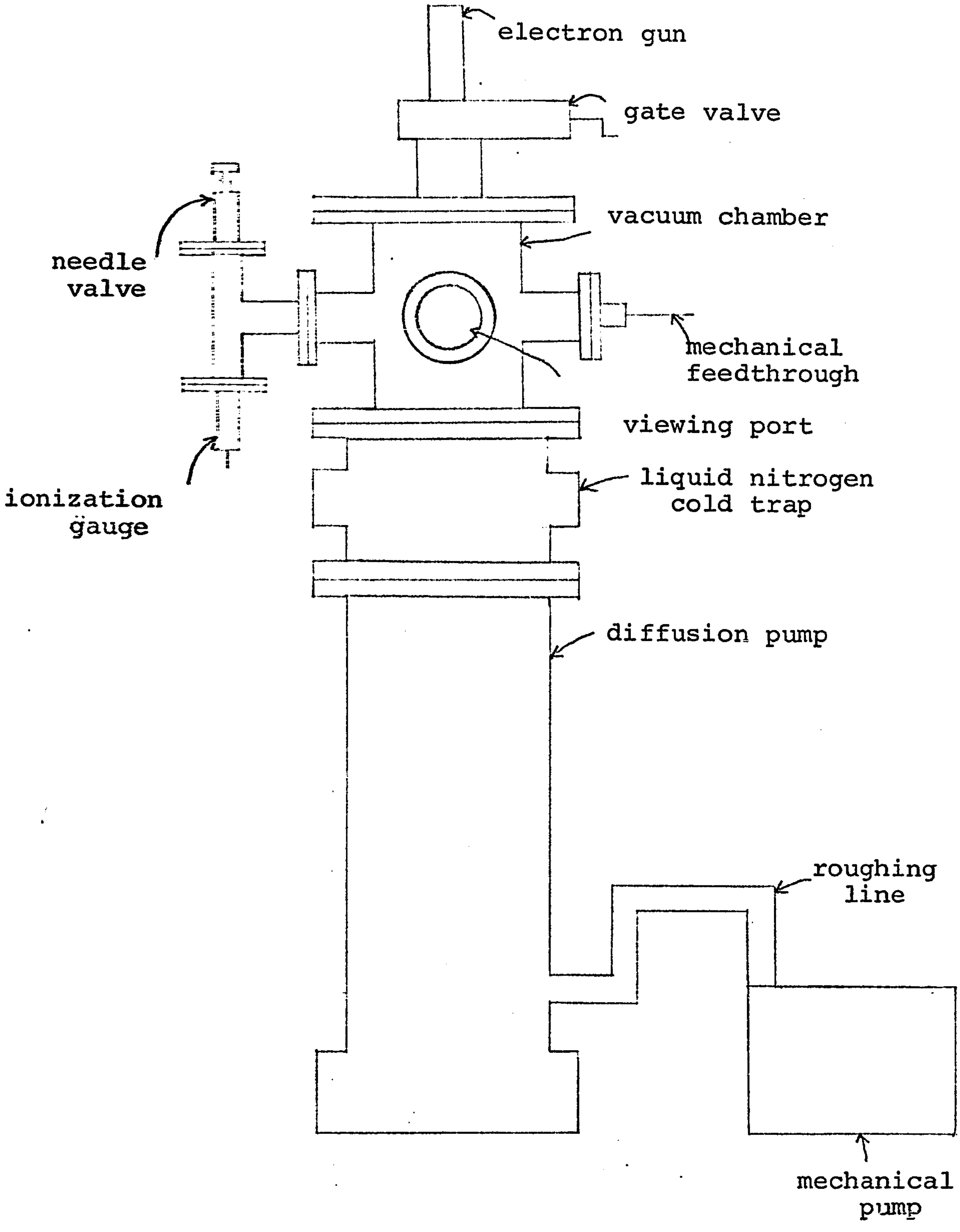


Figure 8

Vacuum Chamber

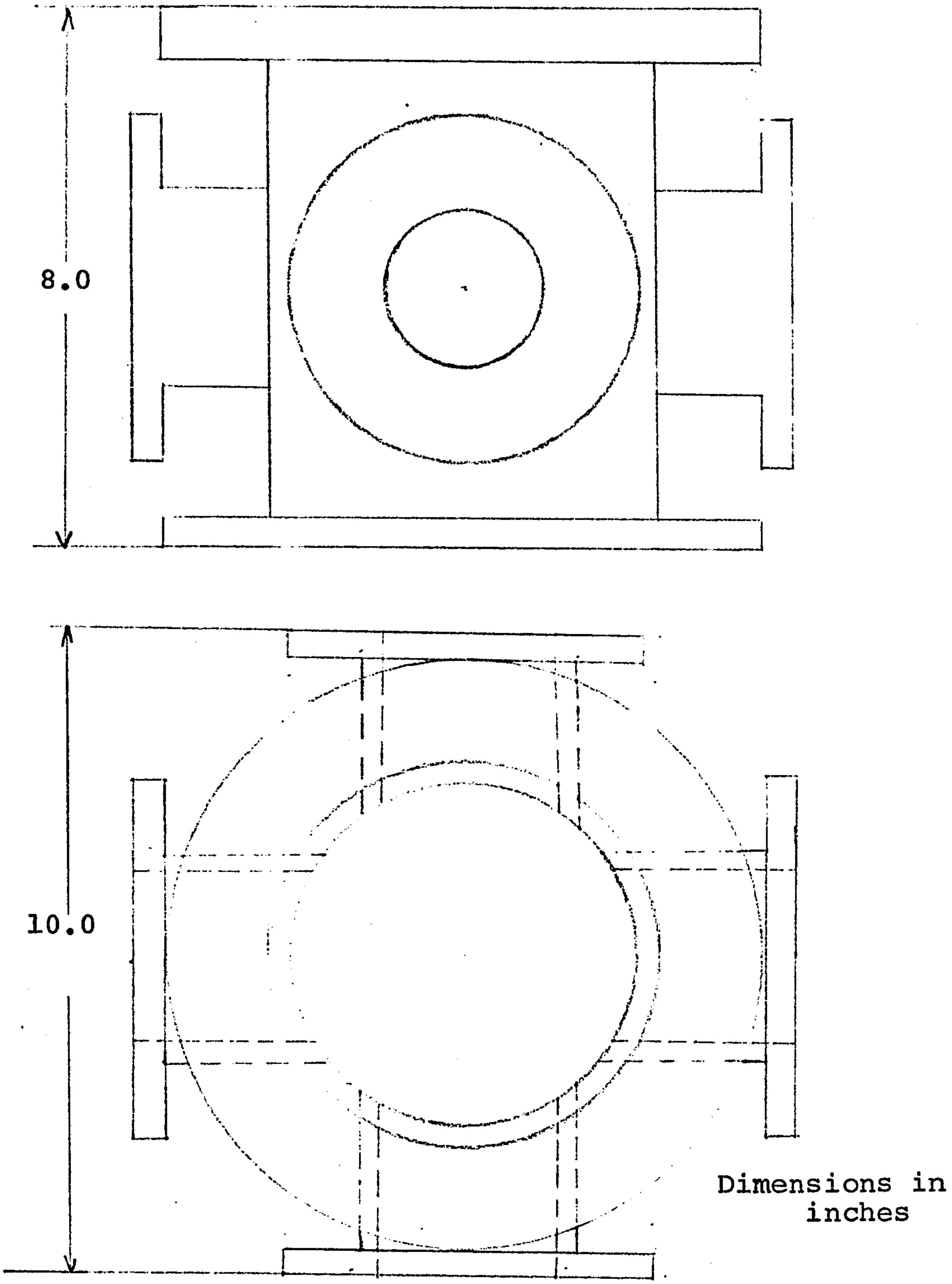


Figure 9

Electron Beam Experiments:

Rebuilt television picture tube electron guns were donated for these experiments Ref. 15 . These electron guns were sealed into the vacuum system using a substance called Pyseal, a type of high vacuum sealing wax. A fifteen kilovolt power supply was built to accelerate the electron beam. For both practical and theoretical reasons it is necessary to use a negative acceleration voltage applied to the electron gun and maintain the anode, chamber and target at zero potential. To do this the power supply shown in figure 10 was constructed. Since the anode is a part of the electron gun which is external to the chamber there is no electrostatic field inside the chamber.

Activation of Electron Guns:

The exposure of a coated cathode electron emitter to the atmosphere results in oxygen contamination of the coating and this oxygen must be removed before any acceleration voltages are applied to the electron gun. If this is not done the coating will be stripped off the cathode when the acceleration voltages are applied. The decontamination procedure for a 6.3 volt filament electron gun is: Ref. 16

Heater voltage	Time in minutes
6.5	5
7.0	2
9.0	5
12.5	1.5
6.5	10.0

The gun may now be used without fear of stripping the cathode. In order to avoid this procedure whenever the vacuum system was lowered to atmosphere a gate valve was placed below the electron gun to real it off when required. If the electron emission is still low it is caused by pump oil contamination of the cathode. This may be removed by applying the recommended voltages to the triode section of the electron gun fig. 10 and observing the first anode current while increasing the heater voltage. As the heater voltage is increased the anode current will increase but when the oil contamination is removed there will be a sudden increase in anode current. Once this has occured the gun should work properly.

Electron Beam Machining:

It has been demonstrated by others (Ref.17)that electron beam microalloying is feasible at beam diameters of approximately 10 micrometers or less. Electron beam microalloying is a process where an impurity is placed on the surface of a semiconductor material such as silicon and locally heated with an electron beam. A small pool of silicon is melted and the impurity diffuses into the molten pool which recrystalizes to form a junction.

At larger diameters the theory referenced above demonstrates that the beam current required to melt the substrate becomes excessive. The theory also shows that the required

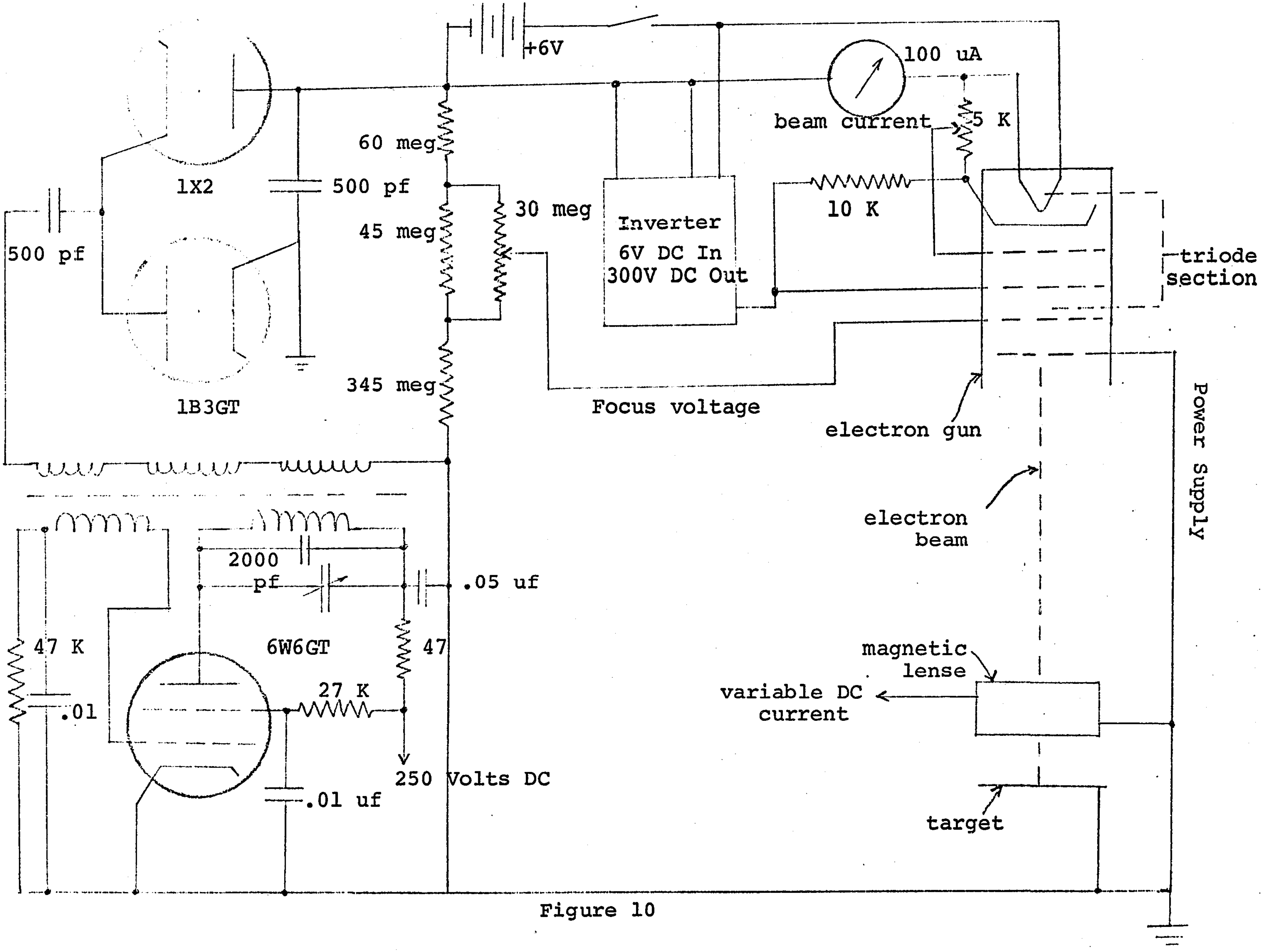

+6V
100 uA
beam current
5 K
1X2
500 pf
60 meg
45 meg
30 meg
Inverter
6V DC In
300V DC Out
10 K
triode
section
500 pf
1B3GT
345 meg
Focus voltage
electron gun
Power Supply
electron
beam
2000
pf
.05 uf
47 K
6W6GT
47
27 K
.01
250 Volts DC
.01 uf
magnetic
lense
variable DC
current
target

Figure 10

beam current is dependent upon the thermal properties of the material ie lower thermal conductivity and lower thermal diffusivity results in lower beam current required.

The diameter of the spot produced by the system used by the author was approximately 100 micrometers. From this it was obvious that microalloying could not be done but rather electron beam machining of quartz was done. Quartz was used because of its thermal properties and because it is easily coated with a flourescent material making it easier to observe the electrom beam. The quartz was also tilted at 45 degrees to make observation easier. The diagram of the experiment is shown in figure 11 . The electron beam strikes the quartz from above and gouges a hole in it. The machining started at a beam current of 85 microamperes and once initiated the beam current could be reduced to approximately 50 microamperes before the machining stopped. While the machining was taking place a bright yellow "burning" was observed.

Experiment II:

Figure 6 is a diagram of this experiment. The beam of electrons is bent at 90 degrees by a magnetic field before it strikes the boron. This was done because in order to separate the boron ion beam from the electron beam a magnetic field would be required, and the electromagnet used would simulate this field.

Because there was no electrostatic field inside the chamber the positive boron ions which were produced would not

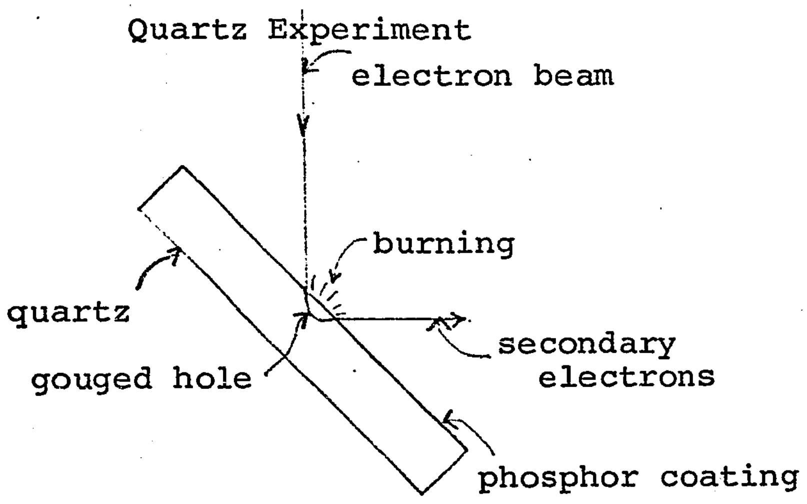


Figure 11

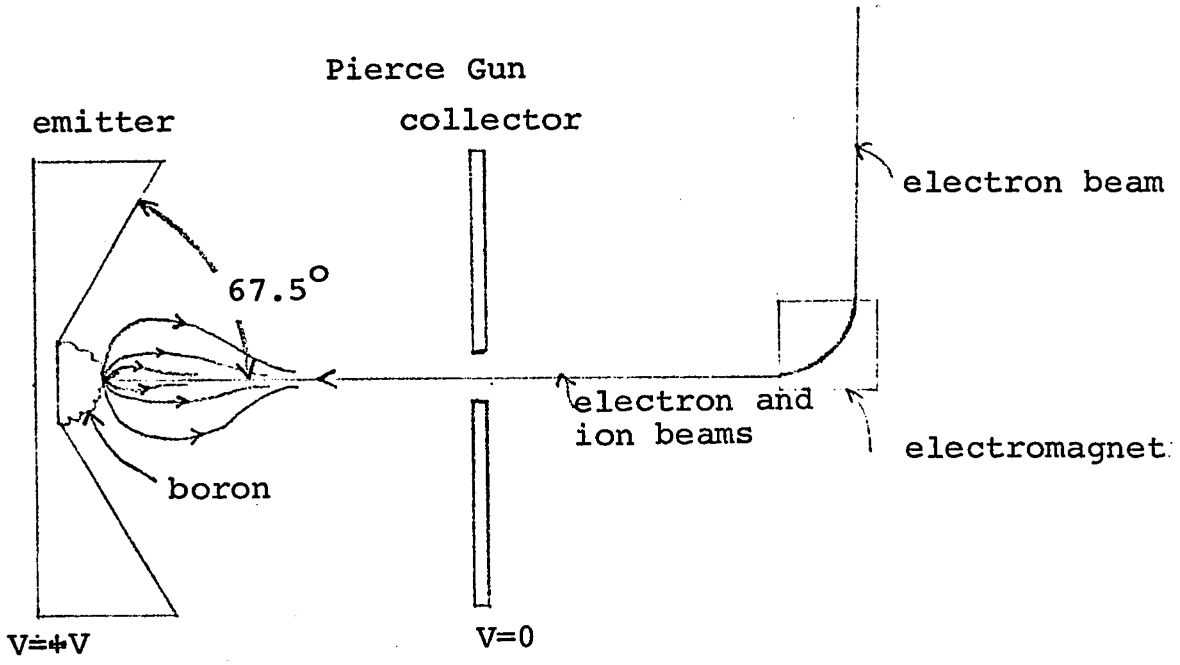


Figure 12

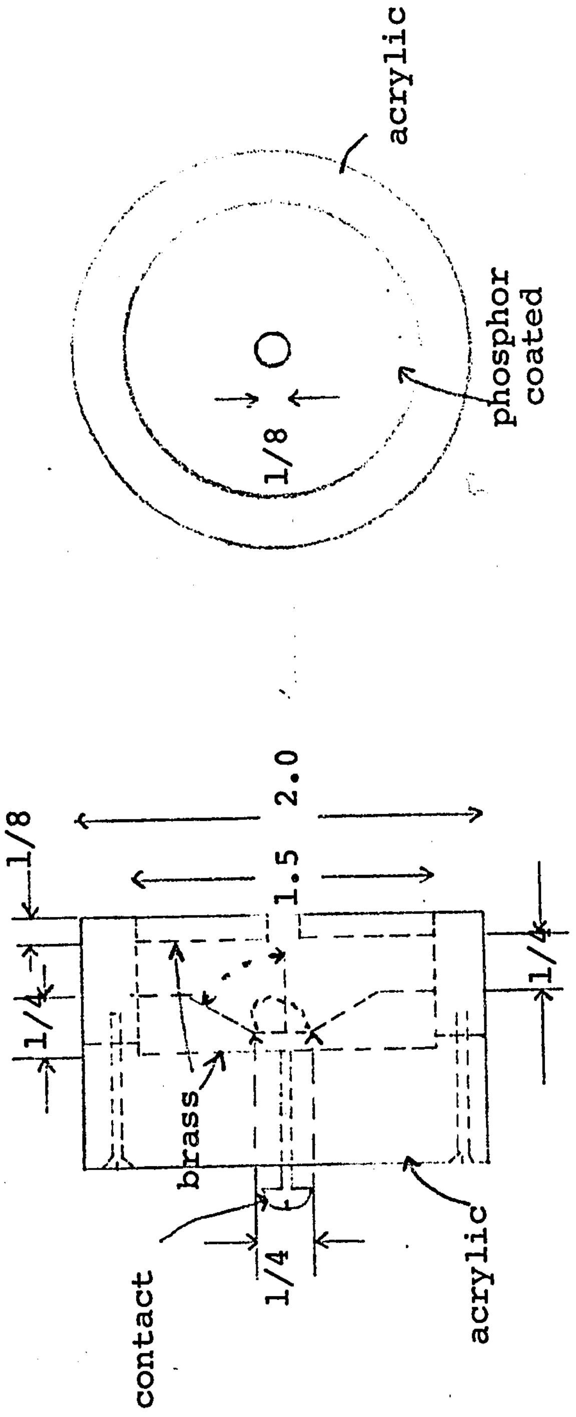
accelerate back along the electron beam and no beam of ions would result. This experiment was designed to see if the energy density of the electron beam was high enough to produce boron ions.

At approximately 70 microamperes of electron beam current the boron began to burn. Once initiated this burning continued with beam currents as low as 25 microamperes. The color of the burning was a yellowish orange, the characteristic color of boron ions recombining Ref.18. The electron gun did therefore have sufficient power density to produce boron ions.

The Pierce Gun:

The last step in the experimentation was to design an extractor which would produce the desired ion beam. At first a simple type of extractor was considred, but it was decided that if it were possible to make the extractor focus the ions about the electron beam this would be advisable. The simplest way to do this was to use the Pierce gun configuration shown in fig.12. The potential field in the extractor is in such a direction as to add energy to the incoming electrons. The divergent effect of the Pierce gun on the incoming electron beam is negligible because of the high velocity of the electrons. The potential levels indicated on the diagram were chosen because whether the ion emitter was at zero potential and the collector at positive potential or vice versa made no difference to the ions. If however, the ion collector was set at a high negative potential, and the emitter grounded the

Drawing of Pierce Gun



Dimensions in inches

Figure 13

collector would retard the electrons approaching it, and then accelerate them after passing through the hole, but with the collector grounded it has no retarding effect on the electrons while the emitter acceleration is still present giving the electron beam a high energy. Also in order to fulfill the conditions for a neutralized beam the external field in the drift space must be zero and this is not the case if the collector is at a negative potential.

The dimensions of the Pierce gun are shown in figure 13. The angle of 67.5 degrees is the Pierce angle calculated by Lomax in 1959. The theory of the Pierce gun may be found in Ref. 19.

Results:

The Pierce extractor was built and installed in the system as shown in figure 14. The electron beam is emitted by the electron gun at the top of the system. It is bent through 90 degrees in the magnetic field and passes through the hole in the Pierce extractor. The 500 volt field applied across the extractor accelerates the electrons until they strike the boron. The boron ions generated are accelerated and focused by the extractor field and return back along the electron beam until they reach the magnetic field where they leave the electron beam and continue as a pure ion beam. A fluorescent screen with a negative 400 volt potential is placed in its path to detect it.

When the experiment was run fluorescent screen showed no sign of any ion beam. The system was dismantled and the extractor examined. This revealed the following as shown in figure. 15

Extraction Experiment

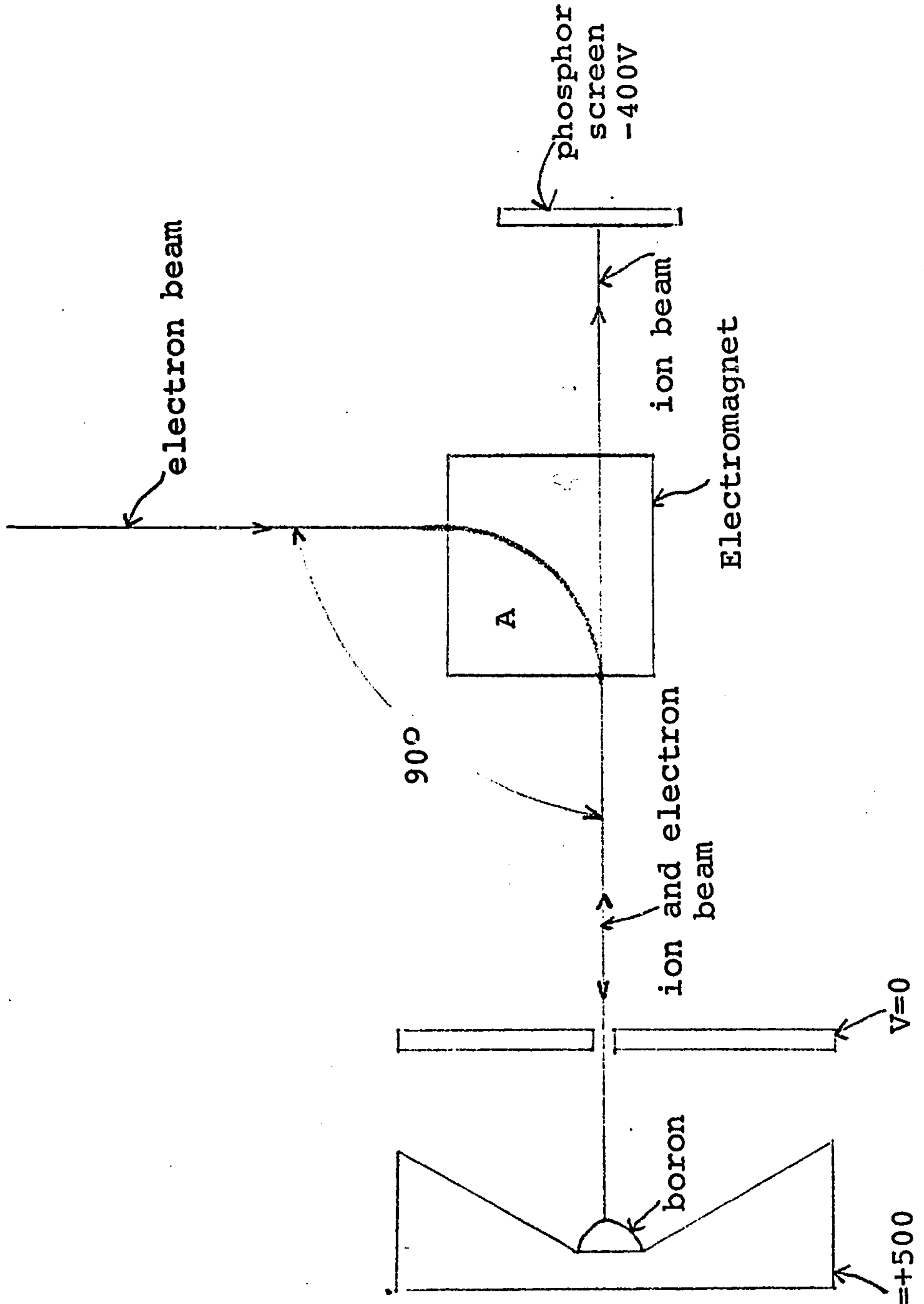


Figure 14

1) Two scorch marks; one on one side of the piece of boron and the other on the emitter of the Pierce gun.
2) A black spot on the inside of the collector.

The black spot was undoubtedly caused by a boron ion beam missing the collector hole. This was probably not an ion beam burn because of the high thermal conductivity of brass; but rather since boron itself is black in color it was probably a deposit of boron. The probable reason why the ion beam missed the hole is misalignment of the magnetic field at A in figure 14 with the extractor center line. This resulted in the boron being struck on the side rather than in the center and subsequently the ion beam missed the hole in the collector. Another theory may explain the fact that the ion beam missed the hole; the irregularly shaped pierce of boron distorted the electrostatic field within the Pierce gun with the result that when the ion beam was formed on the side of the piece of boron it missed the hole.

At this point the experimentation ended because in order to extract the ion beam the electromagnet and the Pierce gun both have to have some precise means of mechanical adjustment which would involve expensive machining and the budget did not allow for this.

Extractor Marks

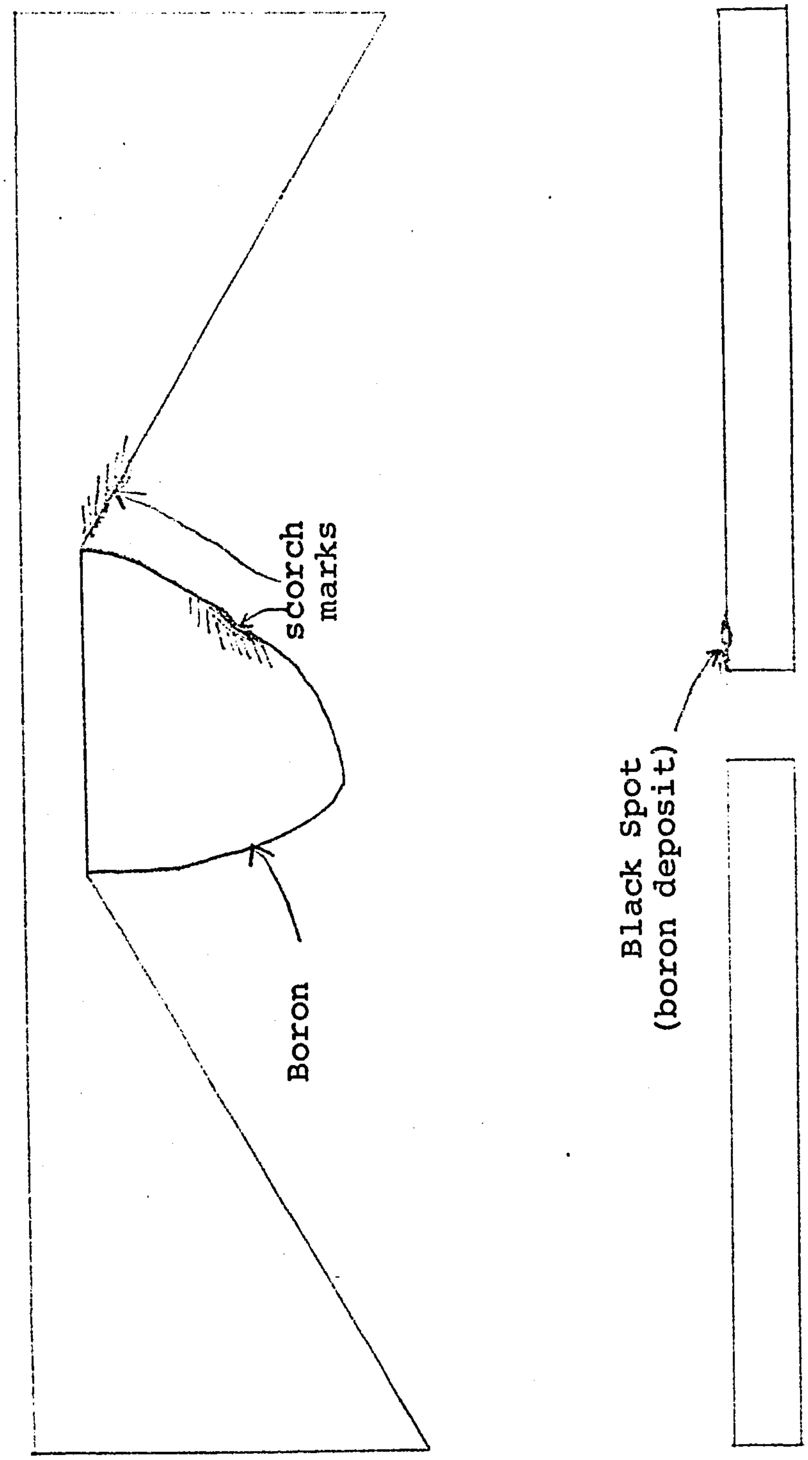


Figure 15

CHAPTER FOUR

CONCLUSIONS

Electron Beam:

The electron beam is a very flexible tool and could be made extremely useful in the production of microcircuits as a machining tool relatively complex operations are possible. For example:

1) Drilling of holes for foreign materials such as tantalum deposits in silicon.
2) Isolation of devices on a common substrate.
3) Machining interconnection patterns.
4) Electron beam trimming of components.

Electron beam microalloying was first reported by Schockley in 1957 (Ref. 20)and the author understands that research at Cambridge University is currently being carried out on melting and recrystalization of 1 micrometer pools of silicon.

Any of the above mentioned operations can be done with high resolution.

If the electron beam, used to perform the above operations, is then reduced to a lower power density, the same beam can be used as an electron microscope and in this mode can check the operations just completed. Some of this checking using a scanning electron microscope is being done today.

Ion Beam:

The experimentation proves that the technique of electron beam bombardment for producing a boron ion beam does work and further work should lead to a practical way of producing a small diameter ion beam. The ion beam can then be used without neutralization to form deep junctions where the acceleration potential is of the order of 50 kilovolts. For shallower junctions, however where the acceleration voltage may be approximately 5 kilovolts the beam spreading becomes excessive and neutralization of the ion beam becomes necessary. A complete proposed system for generating a neutralized ion beam is shown in figure 16. The electron beam A is bent in the magnetic field M and generates the ion beam B by electron bombardment. The ion beam B returns back along the electron beam A as far as the magnetic field M. A second electron beam C is injected into the ion beam at M and travels in the same direction as the ion beam. The current of the electron beam C is adjusted to equal the ion beam current hence neutralizing it. A system such as this would have approximately 300 times better resolution than present day photolithographic techniques.

A low energy neutralized ion beam could be used for other purposes as well. It may be used in conjunction with electron beam microalloying to deposit the desired impurity on the surface of the silicon and then by turning off the ionization electron

Complete Neutralized System

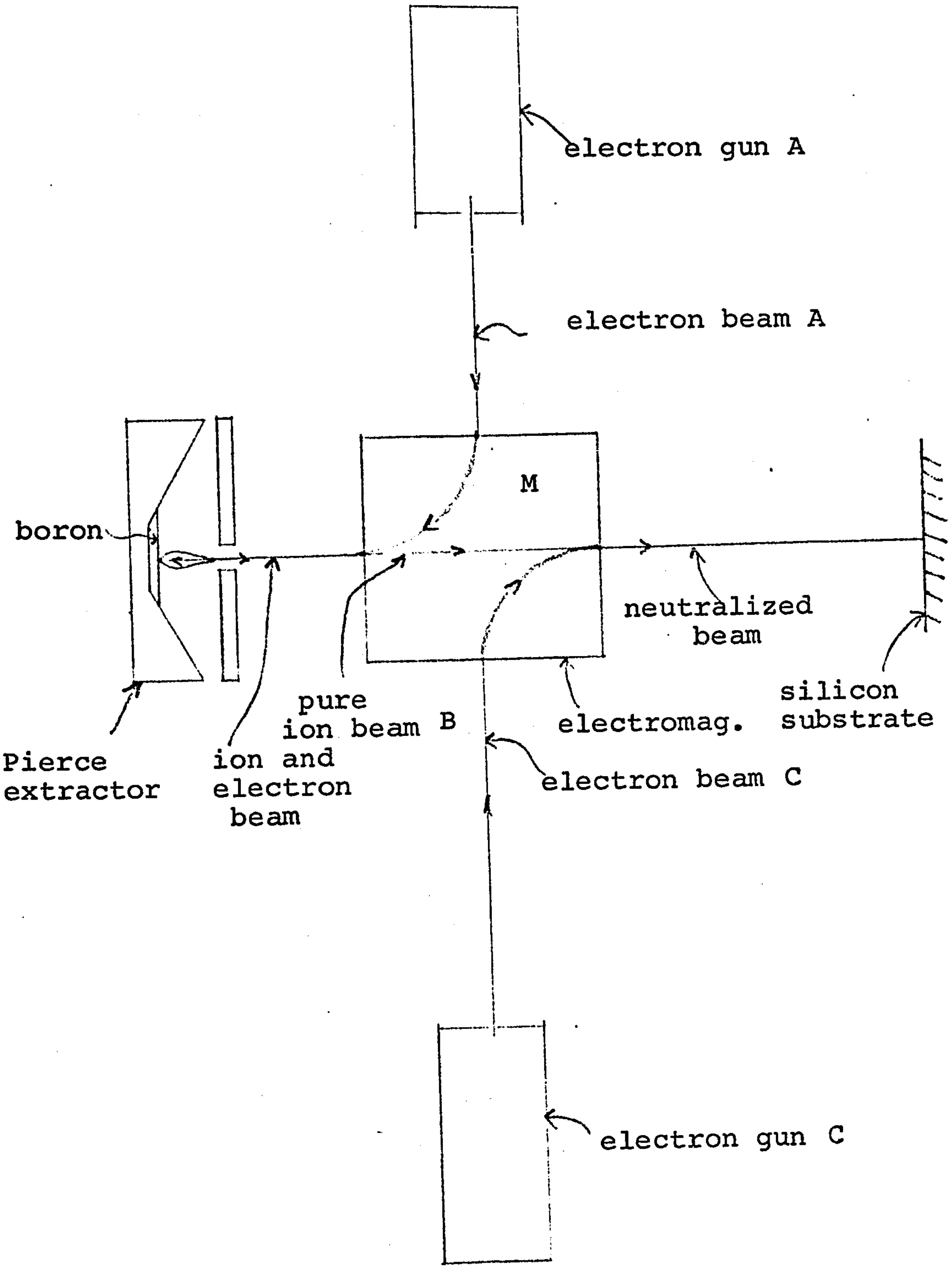


Figure 16

beam A in figure 16 and increasing the power density in the neutralization beam C the junction could be alloyed. By then reducing the current in beam C, this beam could be used to check the junction. A low energy neutralized ion beam could also be used to "draw" a pattern of an element, or an interconnection pattern directly on the surface of a device eliminating the need for photolithography.

Computer Control:

A big advantage in using ion and electron beams in the manufacture of microcircuits is that of being able to control the entire process with a computer. The computer could conceivably work from the circuit data and decide on the layout of the circuit, make the elements, check the elements, remake defective elements and discard the defective circuits immediately. Computer control of the system would mean that mass production would not be necessary for microcircuits to be economical and therfore circuits could be custom made.

Finally the study indicates that it will be feasible to fabricate junction devices in Silicon, using the University of Ottawa Multipurpose Microelectronic Processor, with a resolution 300 times better than is possible with presently available photolithographic techniques.

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