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Semiconductor Measurement Technology:

Some Aspects of Dose Measurement for Accurate Ion Implantation

39

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Douglas M. Jamba

Hughes Research Laboratories
Malibu, California 90265

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PREFACE

This study was carried out at the Hughes Research Laboratories as a part of the Semiconductor Technology Program in the Electronic Technology Division at the National Bureau of Standards. The Semiconductor Technology Program serves to focus NBS efforts to enhance the performance, interchangeability, and reliability of discrete semiconductor devices and integrated circuits through improvements in measurement technology for use in specifying materials and devices in national and international commerce and for use by industry in controlling device fabrication processes. The work was supported by the Defense Advanced Research Projects Agency, ARPA Order 2397, Program Code 6D10, through the National Bureau of Standards Semiconductor Technology Program, Contract 5-35891.

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The author wishes to acknowledge the valuable assistance of Dr. Robert G. Wilson of the Hughes Research Laboratories in the preparation of this report.

SEMICONDUCTOR MEASUREMENT TECHNOLOGY: Some Aspects of Dose Measurement For Accurate Ion Implantation

by

Douglas M. Jamba

Abstract: An investigation of various phases of ion implantation dose measurement was carried out, covering in detail ion beam scanning, secondary particle suppression, and current measurement instruments. Problems are discussed and preferred techniques, electrode structures, and measurement circuitry are presented. Five current integrators were tested and are compared, especially in regard to pulsed current measurement.

Key Words: Accurate ion beam current measurement; current integrators; ion beam scanning; ion implantation; ion implantation dose measurement and control; secondary particle suppression.

1. INTRODUCTION AND SUMMARY

After less than ten years of development, ion implantation has reached a stage where it is routinely used by most semiconductor processing facilities. The growth of the technique has been so rapid that often little time has been available for the production and manufacturing personnel to become familiar with the sophisticated details developed in the research laboratories.

Measurement of the ion dose is one of the most important steps in a reproducible and well-characterized ion implantation process. In most applications of the semiconductor industry, the required dose is determined empirically based on the testing of the completed devices. For any particular system and target combination, reproducing a particular ion current and implantation time will usually produce the same ion dose, and the absolute value of that dose will not be a major concern. However, if more than one system and target material are involved or if it becomes desirable to transfer operations to another facility or the implant technology to another device processing line, there is a need for absolute dose calibration.

The accuracy of calibration required usually depends on how variations in dose affect the operation of devices. The use of ion implantation for threshold voltage control in CMOS devices may be cited as an example of a critical application [1]. Figure 1 taken from Ref. 1 shows a curve of the threshold shift obtained for boron doses implanted into the p-channel of a CMOS device. An implantation must be controlled to within 3×10^{10} /cm^2 in order to control the threshold shift to within 0.1 V of any desired value.

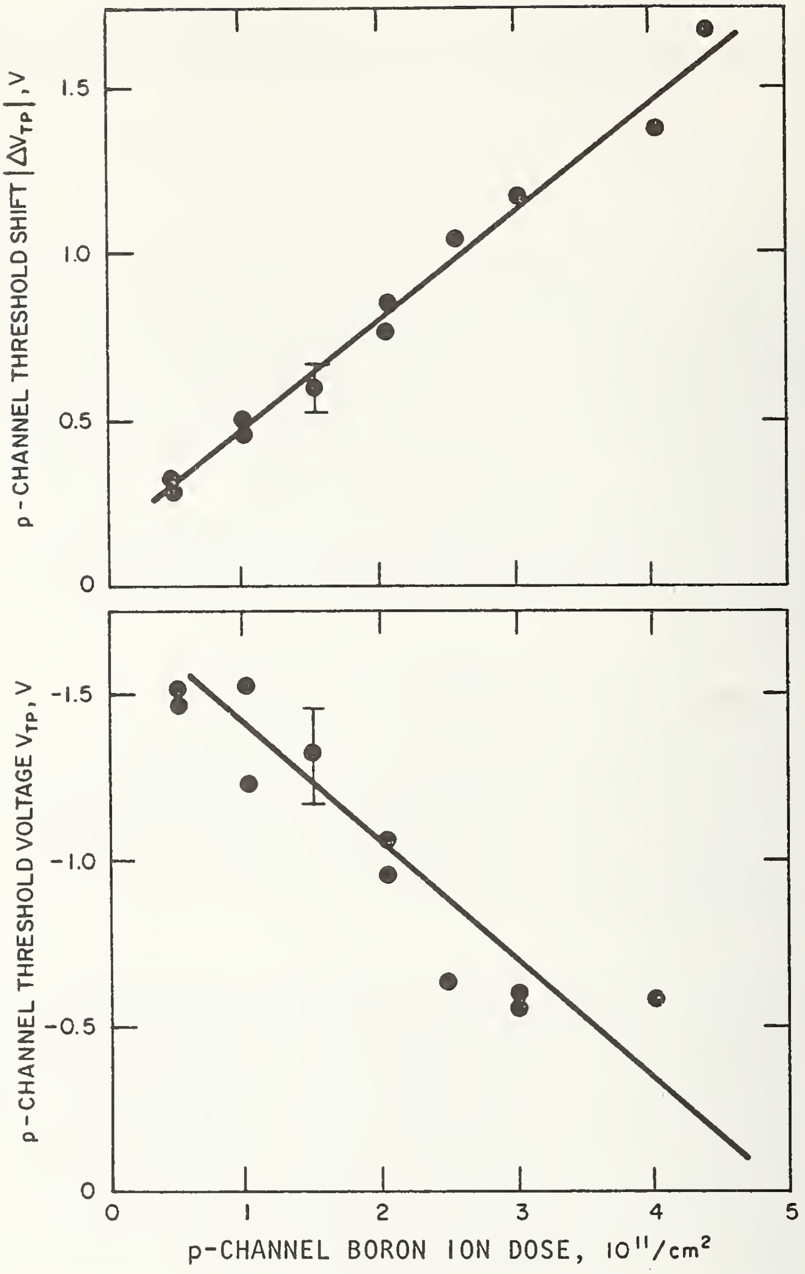

Figure 1. CMOS p-channel threshold shift versus implanted boron ion dose.

As another example, an accurately controlled dose has been shown to be required in the fabrication of ion implanted bipolar transistors [2]. The current gain of these all-implanted transistors can be set at desired values by controlling the doping density in the range of less than ±3% in both the emitter and the base regions of the devices.

The subject of ion implantation dose measurement was discussed briefly by Wilson and Brewer [3] who showed methods for electrostatic suppression of secondary charged particles at the target. Dearnaley [4], in reviewing the problem, emphasized the use of magnetic field suppression of secondary electrons to obtain accurate dose measurement. However, neither of these references treats the subject with enough detail to enable the operator of an ion implantation facility to be sure making accurate measurements.

This report presents the results of a detailed study of methods for making accurate current measurements and points out places where errors are likely to occur. It is hoped that the transfer of this information to the semiconductor device and integrated circuit industry will result in a more efficient and useful application of ion implantation techniques.

Three main aspects are covered in this investigation. The first deals with uniformly distributing the ions over the target and accurately calculating the implanted area and dose. Since the dose is a direct function of the target area, it is essential that the area covered by the beam be determined carefully.

The second section discusses the techniques for proper suppression of secondary charged particles. There are significant quantities of positive secondary ions as well as secondary electrons emitted from the target, and both cannot be suppressed at the same time. Biasing the suppressor electrode negatively prevents secondary electrons from leaving the target but collects all the positively charged particles emitted as a result of the primary beam hitting the target. Secondary positive ions can have energies in the range of several thousands of volts [5] resulting in the release of secondary electrons from the suppressor electrode which are collected by the target. These effects reduce the collected target current to less than the beam current. A grounded bias circuit can result in errors of 20% or more between the true and measured beam current in some cases when secondary positive ions are neglected. There is no assurance that these effects will be reproducible because secondary emission changes with system pressure, adsorbed gases, and surface conditions [3,5,6]. The recommendations offered in this report include measurement circuitry designed to determine the true incident ion beam current in the presence of all secondary particles.

The third section compares five different current integrators emphasizing the need to check carefully the specifications and the operating characteristics of each unit. Factors such as the capability of measuring scanned beams common to ion implantation, integrator scaling, and current indicator off-scale operation can be responsible for errors even when using sophisticated integrators if the operator is not aware of proper handling procedures. Parts of this report dealing with the measurement of high current levels are of particular relevance to the production industry where implant times must be kept to a minimum. Another section discusses problems arising from the effects of neutral atoms, ac interference, and insulator leakage.

2. ION BEAM SCANNING

2.1. Methods

In order to implant 2- or 3-in. diameter silicon wafers, typically either a focused ion beam is electrostatically scanned or the wafers are mechanically scanned. The ions must be distributed uniformly over the target surface and current measurements must confirm that a uniform current distribution exists before implantation proceeds. This section deals with the important aspect of setting up the ion beam at the target in preparation for an implantation.

A typical ion implantation system is shown in figure 2. All of the data reported were obtained in our laboratory in two implantation systems, one of which is shown in the figure. However, the conclusions and recommendations resulting from the study are general and can be applied to most other systems.

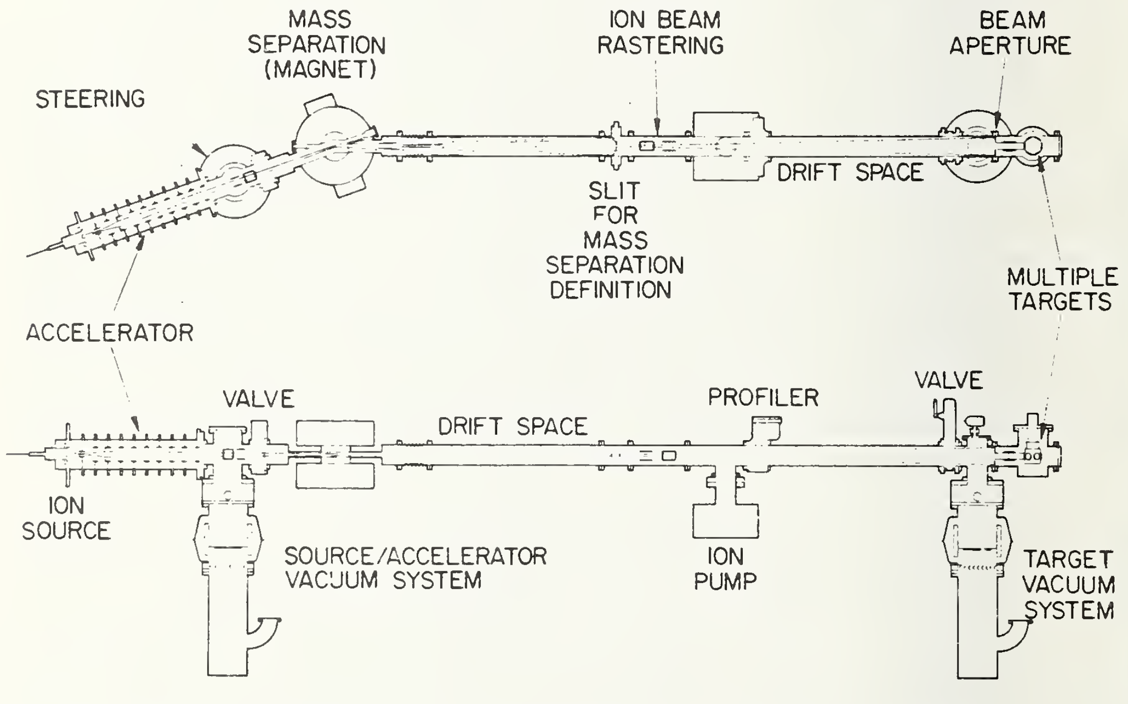

Figure 2. Schematic of a 150-kV ion implantation system.

One target configuration with a broad ion beam impinging on the target collector is shown in figure 3. Some target chambers employ a wafer holder that rotates in steps as this one does, exposing wafers one at a time to the ion beam. Some systems have wafer holders that continuously rotate the wafers past the ion beam (mechanical scanning). In both cases it should be noted that the ions impinge perpendicularly to the wafer surface only at the center of the wafer. In the case of electrostatic scanning, the impingement angle depends on the distance between the scanner and the target. In the case of some mechanical scanning the wafers are tipped as the target drum rotates past the ion beam causing the impingement angle to depend on the diameter of the drum.

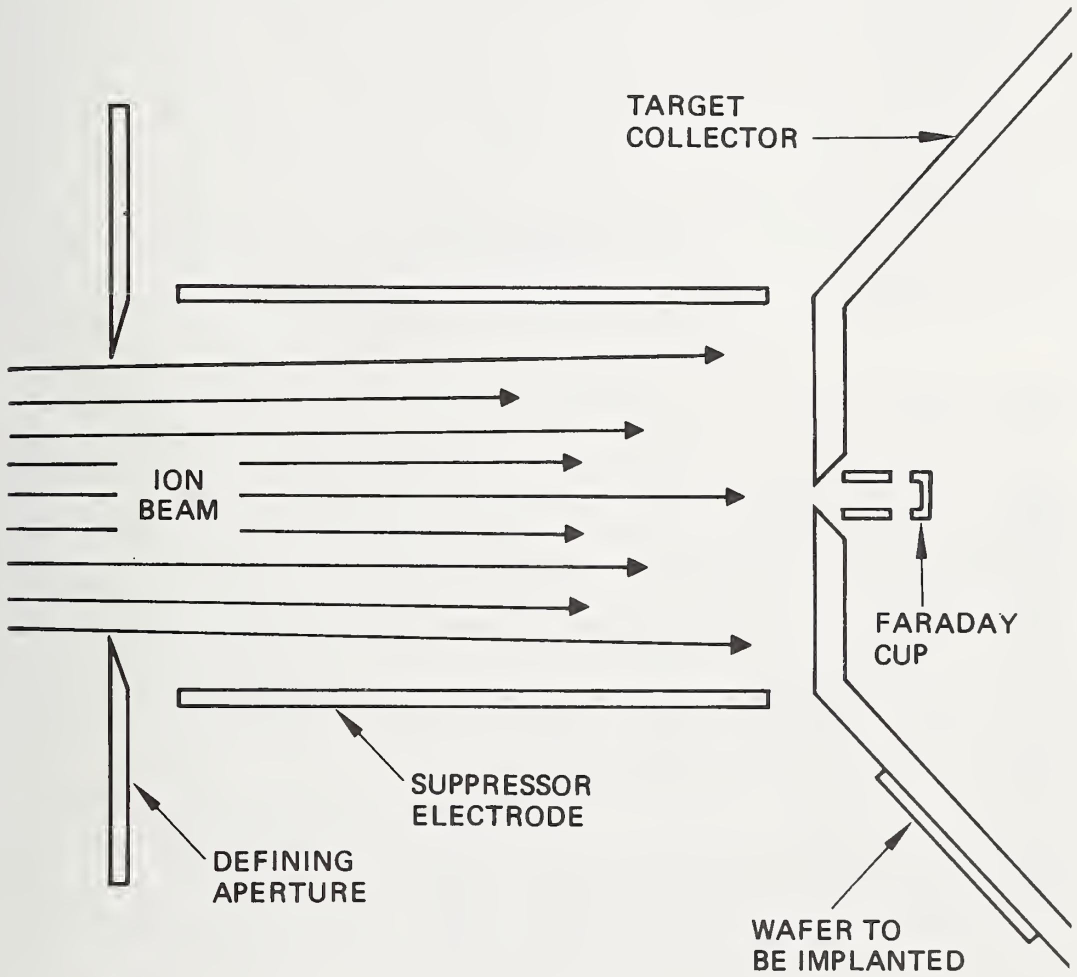

Figure 3. Typical target configuration.

The impingement angle does not have an effect on the measurement of the ion dose and will not be discussed further here. The effects of angular variation of the impinging ion beam on the implanted ion distributions in silicon wafers is dealt with in another report. [7]

2.2. Electrostatic Scanning

In order to obtain a uniform beam over a large area without continuous mechanical motion, the beam must be electrostatically scanned in both the vertical and horizontal directions, creating a raster similar to a television display. This type of scanning produces a square pattern over the defining aperture (usually circular), as shown in figure 4(a).

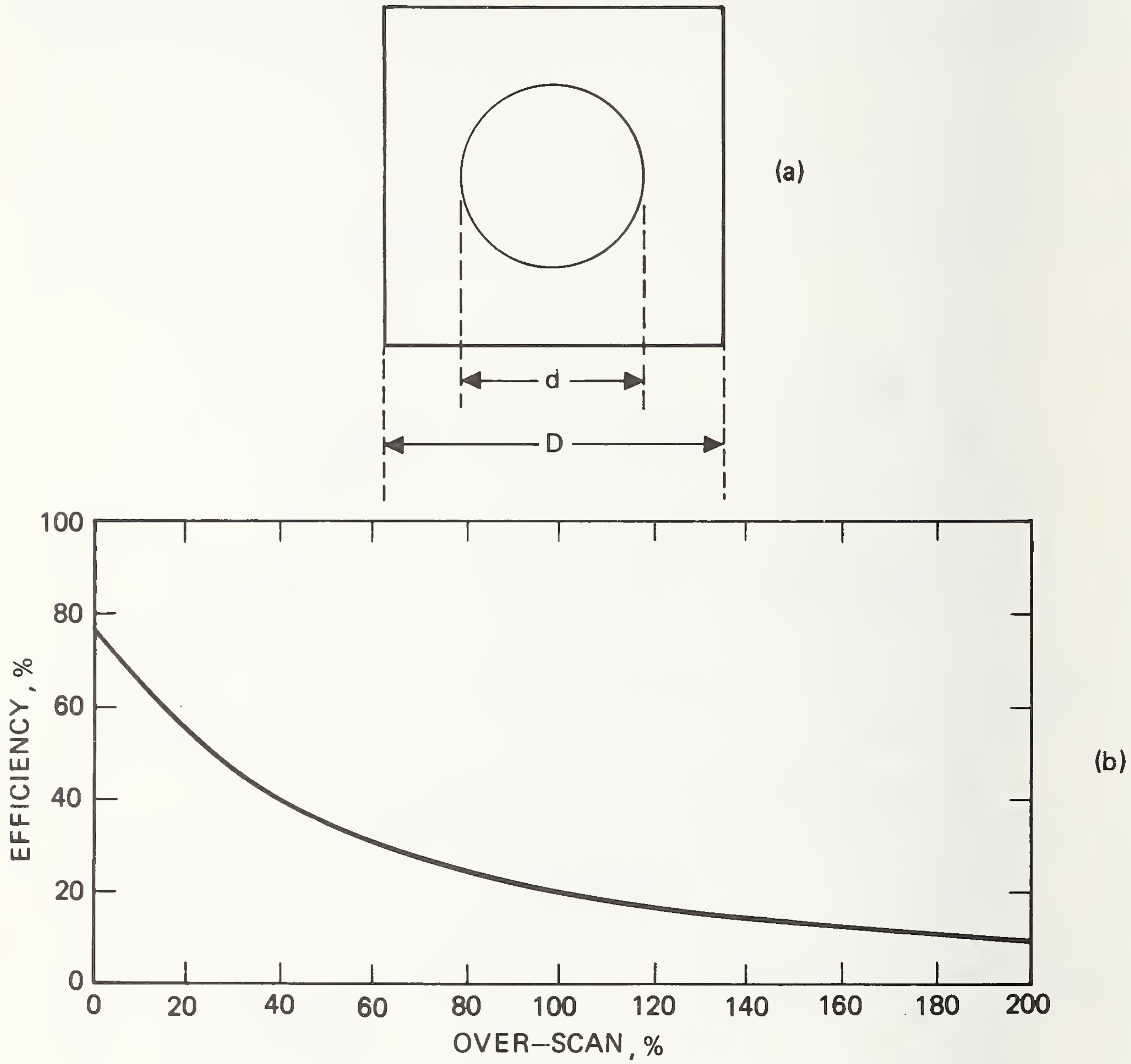

Figure 4. Theoretical effects of beam scanning.

The scan frequency in one direction must be significantly higher than in the other direction so that the traces of the ion beam overlap and cover the surface of the wafer uniformly. To accomplish this the line trace separation must be smaller than the beam diameter. Ion beam diameters can be as small as 1 mm, which then requires approximately 75 traces over a 3-in. diameter wafer. It is, therefore, recommended that the ratio of scanning frequencies be 100:1. Synchronizing of the scanning voltage signals causes the beam to retrace one particular pattern and is to be avoided. Both free-running scan voltage sweeps and high scan-frequency ratios enhance the achievement of uniformly implanted wafers.

a. Efficiency

If the ion beam shape is irregular, it is important to scan the beam sufficiently past the edges of the defining aperture to maintain uniformity. The more the beam is overscanned, the more of the beam that is lost. Therefore, it is important to have some guidelines to follow in setting up the scan voltage amplitudes. Figure 4(b) is a plot of the efficiency of utilization of the ion beam as a function of how far the beam is scanned past a circular defining aperture. For a small beam (beam diameter << defining aperture diameter) scanned to the edges of the aperture (overscan = 0) the maximum efficiency is 80%. This ideal beam shape is difficult to achieve and should not be expected in ordinary systems. A typical condition found to be satisfactory is to scan the beam such that the average current in each of the horizontal and vertical directions is reduced to one-half of the unscanned current, resulting in an average current one-fourth that of the unscanned beam current. This condition occurs when the beam deflection distance D shown in figure 4(a) is equal to 1.8 times the target diameter, or 80% overscanning.

b. Uniformity

A verification of beam uniformity at the target can be obtained by comparing the current measurements of the target collector and the Faraday cup as shown in figure 3. The current densities shown in figure 5 were measured using both the target collector and the Faraday cup collector as a function of the beam scanner voltage. With no scanning voltage applied, the steady state ion beam is centered on the target collector at the Faraday cup and shows a relatively high reading depending on how well the beam can be focused. The total beam current is the sum of the cup and target current values. When the scanner voltage is applied, the beam is deflected back and forth across the target producing a series of pulses collected by the cup current meter. With increasing scanner voltage these pulses get smaller in width and the cup current decreases. The target collector current increases in proportion to the decrease in cup current until the scanner voltage is high enough to deflect the beam past the aperture defining the target collector area. As the voltage increases beyond this point, the target current becomes a series of pulses and the fraction of the beam that is collected by the target collector decreases in proportion to the scanner voltage. When the beam is swept far enough to completely cover the defining aperture and average out any nonuniformities in the beam shape, the Faraday cup and target collector current densities become equal and a satisfactory beam uniformity is obtained over the entire target area. The appropriate scanning voltage for any particular system depends on the scanning electrode geometry and dimensions, the distance from the scanner to the target, the target area, and the beam accelerating voltage.

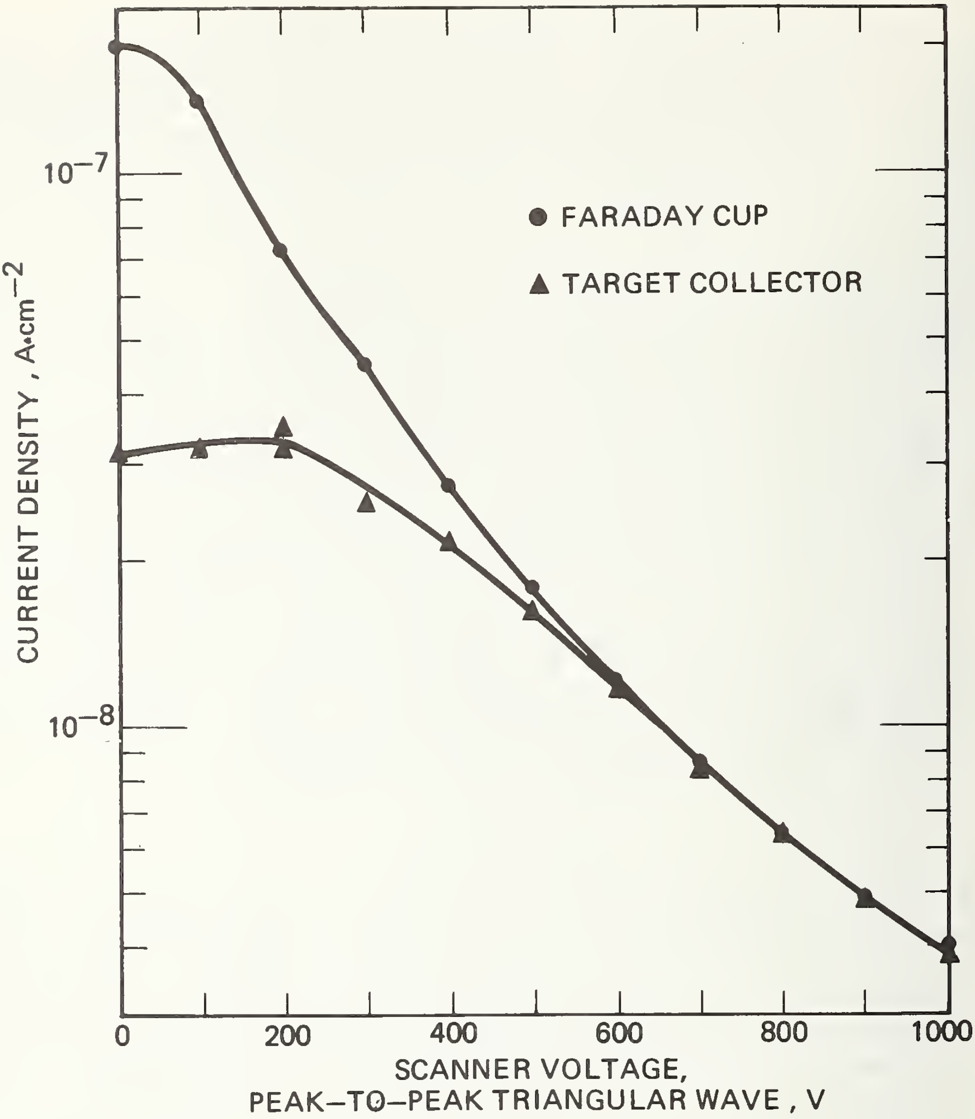

Figure 5. Target current density as a function of scanning voltage for 84-keV boron ions.

It is recommended that implantation systems have methods built in for double checking measurements in case of operator error or equipment failure such as a loss of bias voltage. The verification of proper current density as measured by both the target collector and the Faraday cup is an example of such a double check.

c. Ion Beam Control

The placement of current collector plates or Faraday cups near the edges of the defining aperture as shown in figure 6 provides another way to set up the scanning voltages and to monitor the beam position. The scanning voltage can be increased until a current is obtained in both collectors

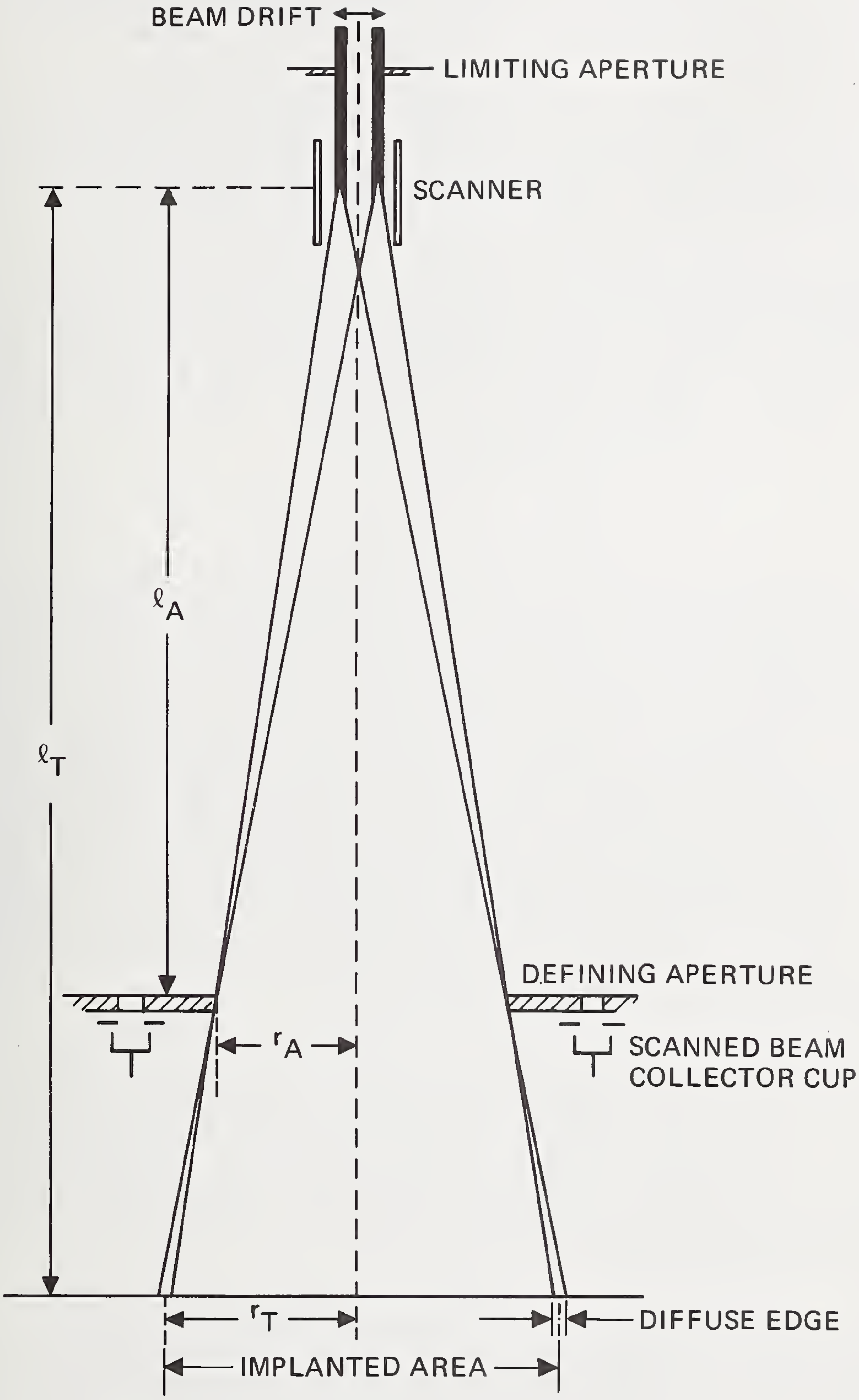

Figure 6. Schematic drawing showing the effect of a drifting ion beam at the scanner.

indicating that the beam is completely filling the defining aperture. Four collectors are necessary to monitor both scanning directions; and when properly uniform conditions are obtained, the current in all four collectors will be equal. Any one or all of these collectors can be used to monitor the target current density and therefore can be used as the input to an integrator for measurement of the ion dose. This technique is useful when it is impossible or impractical to measure the current on the target itself (for example, when the target cannot be isolated from ground or the samples have insulating surfaces).

Another important use of these peripheral collectors is to provide a means for feedback stabilization control of the ion beam position. When this technique is used the currents collected by an opposite pair of collectors are fed into a differential amplifier that is able to detect shifts of the beam toward one side or the other. This signal is processed to supply a correcting voltage applied to a beam steering electrode which returns the beam to the center of the target.

2.3. Target Area

In order to calculate the current density, the exact target area the ion beam strikes must be known. A straightforward method for this purpose is to implant a piece of sensitive (e.g., zinc oxide coated) paper placed in the target position until the paper shows the outline of the beam area. This technique is useful for checking beam location. However, it is difficult to measure the area accurately because a sharp edge is not always obtained as is illustrated in figure 6. When the defining aperture is placed away from the target and when the ion beam diameter is smaller than the limiting aperture at the scanner, there can be a shift of the implanted area caused by a drifting of the ion beam position at the scanner. Drifting of the ion beam is common in the horizontal direction and is caused by variations in the beam energy or in the electromagnetic separator current. Such shifts, while causing a diffuse edge, do not significantly affect the dose measurement because the area of the implanted region remains essentially the same.

A better method of calculating the area of the beam at the target is to use the dimensions of the system components. The implanted area is $\pi\ (r_A \ell_T/\ell_A)^2$, for the recommended circular aperture where the quantities are defined in figure 6. The use of this value is recommended for calculating the current density at the target because, with proper scanning of the beam past the edges of the defining aperture, its use will minimize errors in dose determination.

It was mentioned that continuous mechanical motion of the target can be employed to provide uniform ion beam exposure over the target. One way to accomplish this is to have a circular rotation coupled with a radial oscillation to provide complete coverage of wafers while the ion beam stays in a fixed position. Another method is to have a circular mechanical rotation combined with a one-dimensional electrostatically scanned ion beam. In both of these cases, the ion beam current must be measured on the moving target and the current density must be calculated from the total area of the rotating surface exposed to the beam.

3. SECONDARY SUPPRESSION

When the primary ions penetrate the target surface, secondary particles are emitted. These particles, many of which are charged, cannot be neglected because they can introduce losses or additions to the ion dose. Secondary electrons and negatively charged ions leaving the target cause the target current to increase. Positively charged particles leaving the target and secondary electrons from other sources hitting the target cause a decrease in target current. This section presents techniques of electrode and circuit design for accurate target current measurement in the presence of emitted secondary electrons and ions.

3.1. Electrode Design

The most common method used to prevent the loss of charged secondary particles is to place a suppression electrode in front of the target and to apply a voltage to repel the charges and keep them on the target surface. The suppression electrode can be either a cylinder or a flat plate containing a hole. A typical target with a cylindrical suppressor electrode and defining aperture is shown in figure 7(a). The ion beam must be prevented from touching the suppressor by the use of a collimator in front of the suppressor. If the beam were allowed to hit the suppressor, with the suppressor at a negative voltage, the secondary electrons generated would be collected by the target causing the measured beam current to be lower than the true value. The cylindrical suppression geometry is superior to the flat plate because it is more efficient for supplying a potential barrier along the beam axis and because it concentrates a stronger electric field near the outer edges of the implanted area and assures that no secondary electrons escape to the walls of the vacuum chamber to affect current measurements.

The suppression geometries shown in these figures and used in this study resulted from analytical (electrolytic tank) and experimental studies [3] of electrode geometries to determine suitable potential contours for secondary suppression across the beam aperture, especially on the beam axis. The function of the suppressor electrode is not only to establish a potential field to keep secondary electrons from leaving the target but also to keep other electrons from being collected by the target. For example, any secondary electrons generated from the ion beam striking the vacuum chamber walls upstream from the target or the defining aperture must be repelled by the supression voltage. This accounts for the long length between the defining aperture and the target. A general rule of thumb is to allow a space between each electrode equal to the maximum diameter of the aperture. Thus, it is recommended that the distance between the defining aperture and the target be two aperture diameters.

In some instances it is desirable to change the size of the defining aperture to implant smaller wafers. For example, if heavy ion doses are

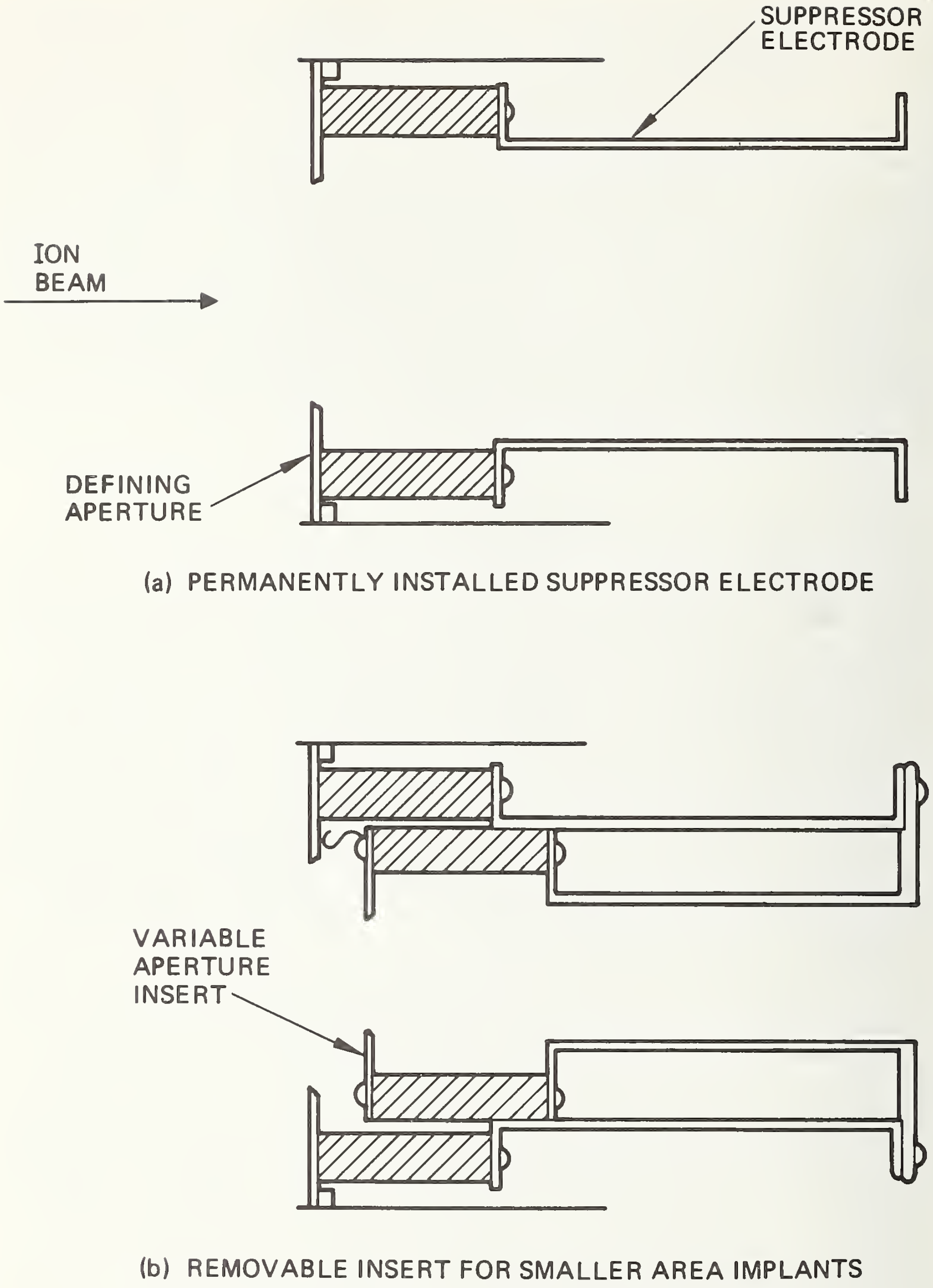

Figure 7. Secondary suppression geometries.

desired, reducing the size of the implanted area results in more efficient use of the total ion beam available and reduces the time required for implantation. One technique used at this laboratory is to insert a smaller diameter electrode unit as shown in figure 7(b). Other types of variable apertures have been used where the defining apertures are holes in a rotating disc controlled from outside the vacuum system.

3.2. Measurement of Currents

We began the investigation of secondary suppression electrodes by recording the currents collected by each electrode of the system as shown in figure 8(a). The voltage (V_S) on the suppressor electrode was continuously varied from positive values through zero to negative values of several hundreds of volts. When V_S is positive, the secondary electrons and negative ions are attracted to the suppressor and the suppressor current (I_S) has a high negative value. In this case, for an ideal suppressor, the secondary positive ions are repelled, back to the target. The secondary current depends mainly on the ion beam energy and can be anywhere from one to more than ten times the primary ion beam current. In this case the current (I_C) collected by the target is the sum of the incoming positive ion current plus the secondary negative particle current leaving. The true ion current is the algebraic sum of I_S and I_C. If there were no suppressor electrode, the secondaries would be lost to the chamber walls and I_C would be in error from the true beam current by the magnitude of the secondary current.

When V_S is negative, the current I_S has a positive value as a result of collecting the secondary positive ions. In this case, for an ideal suppressor, the secondary negative particles are repelled back to the target. The number of the positive ions also depends on the beam energy but is usually only a small fraction of the number of primary ions. This number typically has a maximum at a beam energy less than 50 keV. Positive ion emission occurs in conjunction with the emission of neutral atoms during sputtering. In this case, I_C is the difference between the incoming ions and the secondary ions leaving. The true ion current is again the sum of I_C and I_S.

3.3. Recommended Circuit

It is obvious that both negative and positive secondary particles cannot be suppressed at the same time. Therefore, methods must be employed to assure collection of all the currents and to present the true collected ion charges to the integrator. The method we have used to accomplish this is shown in figure 8(b). With the suppressor operating at either positive or negative voltage, the current I_S is cycled in a looped circuit floating on the total current I_T. The collected current I_C indicates both the secondary and true currents but I_T records the true incident ion beam current.

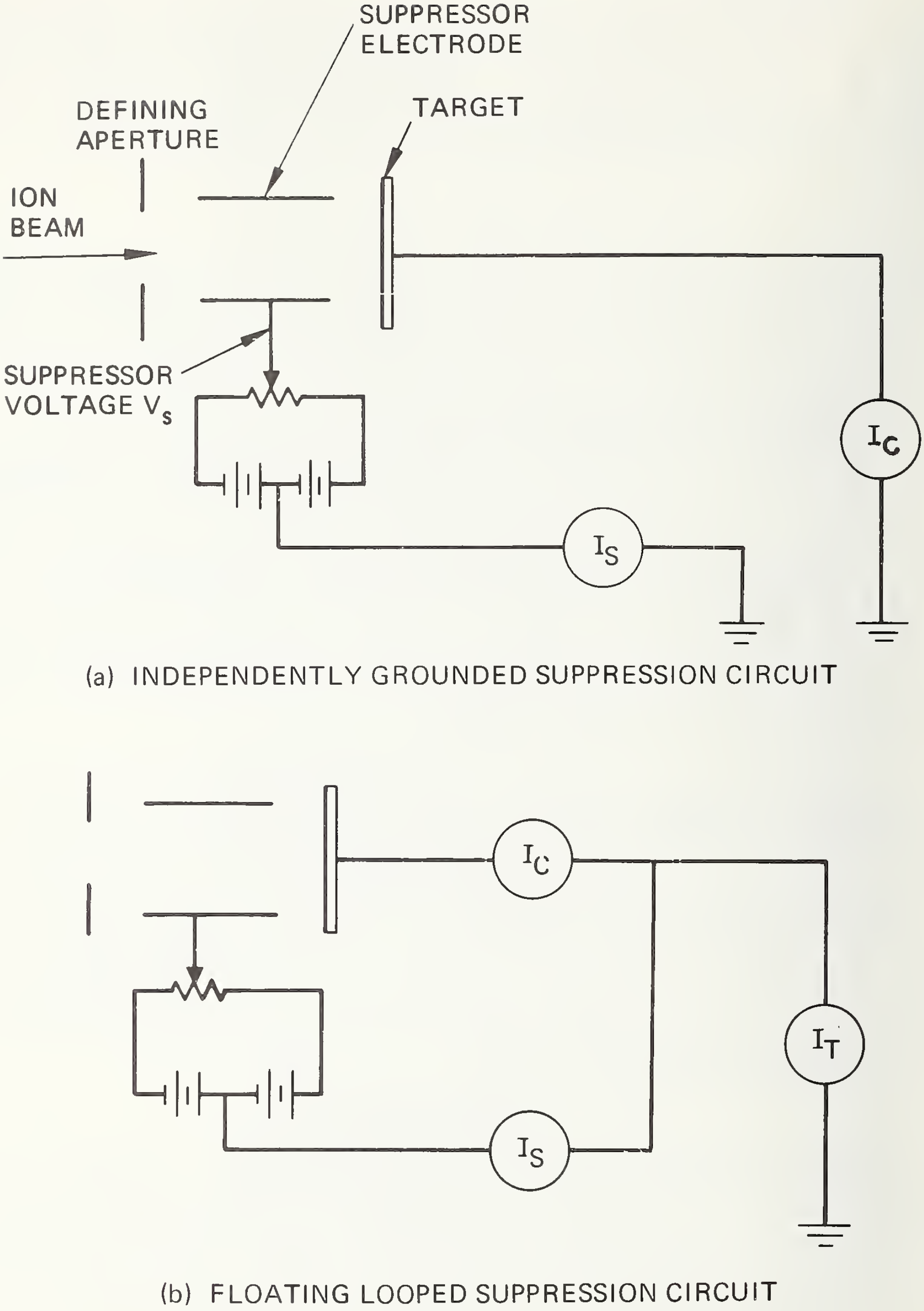

Figure 8. Implantation target current measuring circuitry.

We recorded data for the circuit of figure 8(b) in our 300-kV implantation system using N^+ and N_2^+ ion beams in the energy range from 50 to 300 keV. Curves typical of these data are shown in figure 9 for 50-keV N_2^+. With the suppressor bias looped to the target, the total current was approximately 1.3 μA throughout the measurements. The total current, I_T is the sum of the suppressor (I_S) and collector (I_C) currents for the high voltage biased conditions. When the bias voltage is near zero, a discrepancy appears which represents the secondaries lost to the surrounding environment (the target chamber walls) either directly back along the beam axis or out of the space between the suppressor electrode and the target. These curves indicate that for these conditions with typical negative V_S operation, any voltage larger than -30 V is sufficient to suppress the secondary electrons.

3.4. Negative Secondary Emission

A measure of the negative secondary emission (primarily electrons, but including negative ions) can be obtained by dividing the suppressor current obtained with the suppressor at high positive values by the total current (the incident ion current), 5.85 for this case of 50-keV N_2^+ ions (see figure 9).

A set of data was taken with an N^+ ion beam for a series of energies from 10 to 300 keV to show the variation in secondary emission with ion energy. The resulting increase in suppressor current with ion energy is shown in figure 10. The inset in the figure plots the changes in the calculated negative secondary coefficient as a function of the ion beam energy. The coefficient increases sharply at the lower ion energies. Above 100 keV it continues to increase, but more slowly. A value of 10 is reached at about 300 keV.

It is obvious from these curves that the suppressor is repelling the secondary electrons effectively for negative voltage exceeding -30 V. However, it is possible for some secondaries to be lost from the target current reading under such limited bias voltage conditions. For example, secondaries from the target with enough energy can pass directly through the center of the suppressor back toward the ion beam source and cause the total current reading to be larger than the true beam current. In such a case the suppressor current may be constant above -30 V because no more electrons are being collected. However, examination of the collector current may show that the target is still losing some electrons. This effect is shown more clearly in figure 11 which is an expanded scale plot of the collector current as a function of suppressor bias voltage for the same set of N^+ ion beam measurements of figure 10. Here we can indeed see that the current does not level off until the bias voltage is around 100 V for the 300-keV N^+ ion beam.

It should be emphasized here that these data were taken with what we consider to be a good suppression configuration (that of figures 7 and 8(b)). Other systems should be checked to verify that complete suppression is being achieved. This can be done most easily by increasing the suppressor voltage until there is no change in the target current.

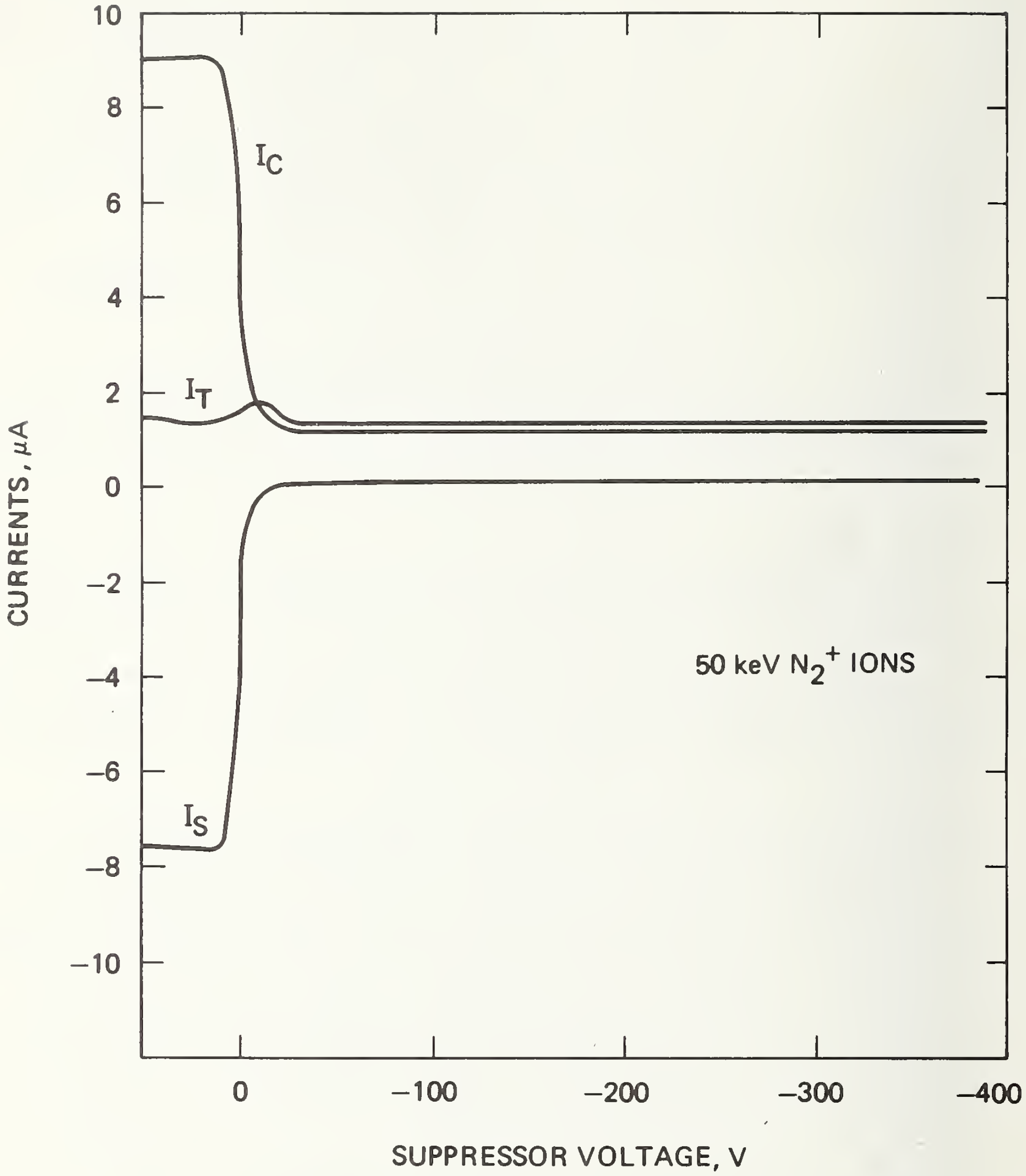

Figure 9. Implantation target currents versus suppressor voltage using the circuitry and geometry of figure 8(b) with 3-cm^2 target beam area.

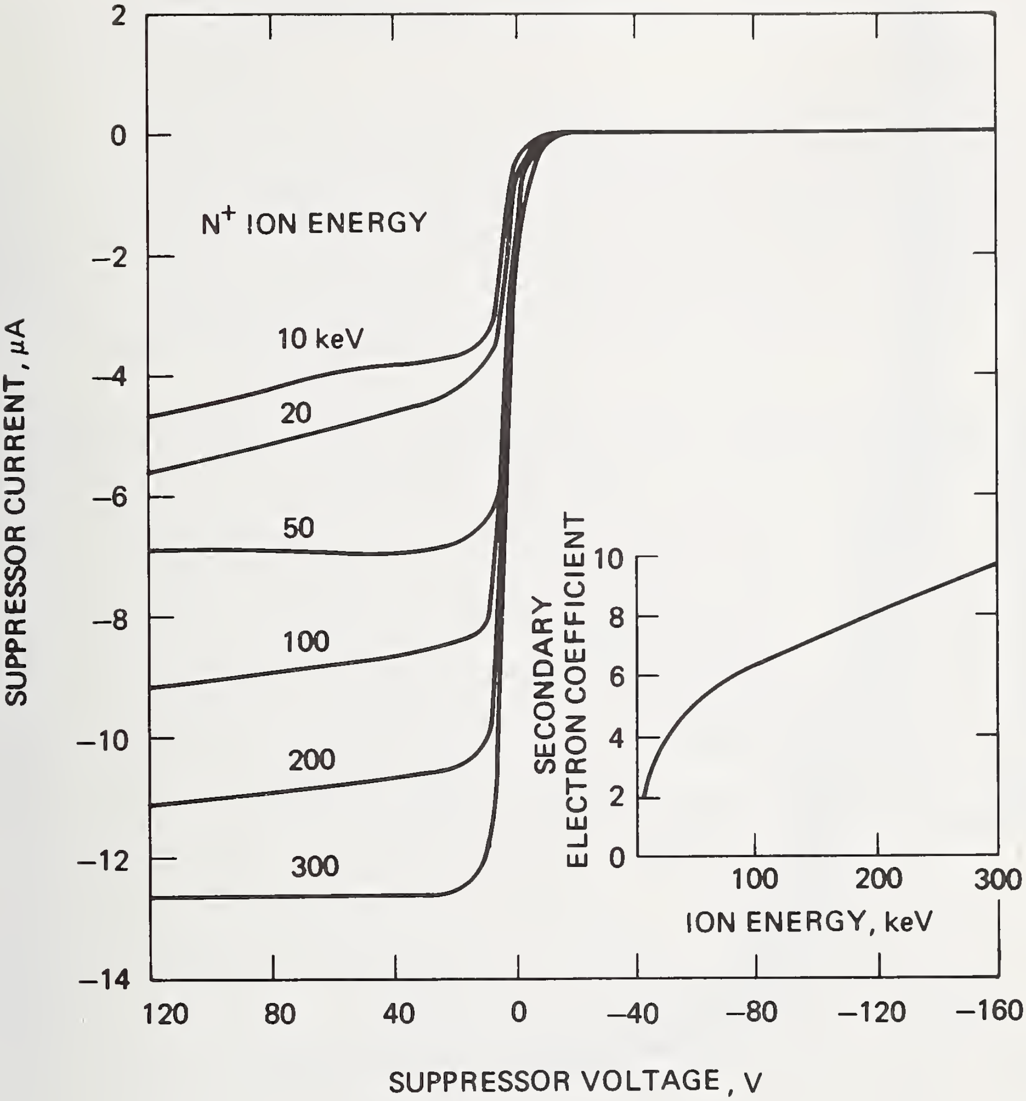

Figure 10. Suppressor current versus suppressor voltage for N^+ ion energies from 10 to 300 keV. Circuitry and geometry are shown in figure 8(b) with 3-cm^2 target beam area (5-cm^2 area for 10-and 20-keV data). Inset shows secondary coefficient versus ion energy. Total ion current was 1.3 μA.

There are two other methods used to suppress secondary electrons. The first is to operate the target at a positive voltage, thus preventing the secondary electrons from leaving the target. The second is to utilize a magnetic field at the target surface to return the secondary electrons to the surface. Magnetic field suppression has the advantage of not requiring any elements of the system (either target or suppressor electrodes) to operate with a bias voltage across insulating supports which might lead to leakage current losses. However, neither of these methods is effective in preventing positively charged particles from escaping, and they are not recommended for this reason.

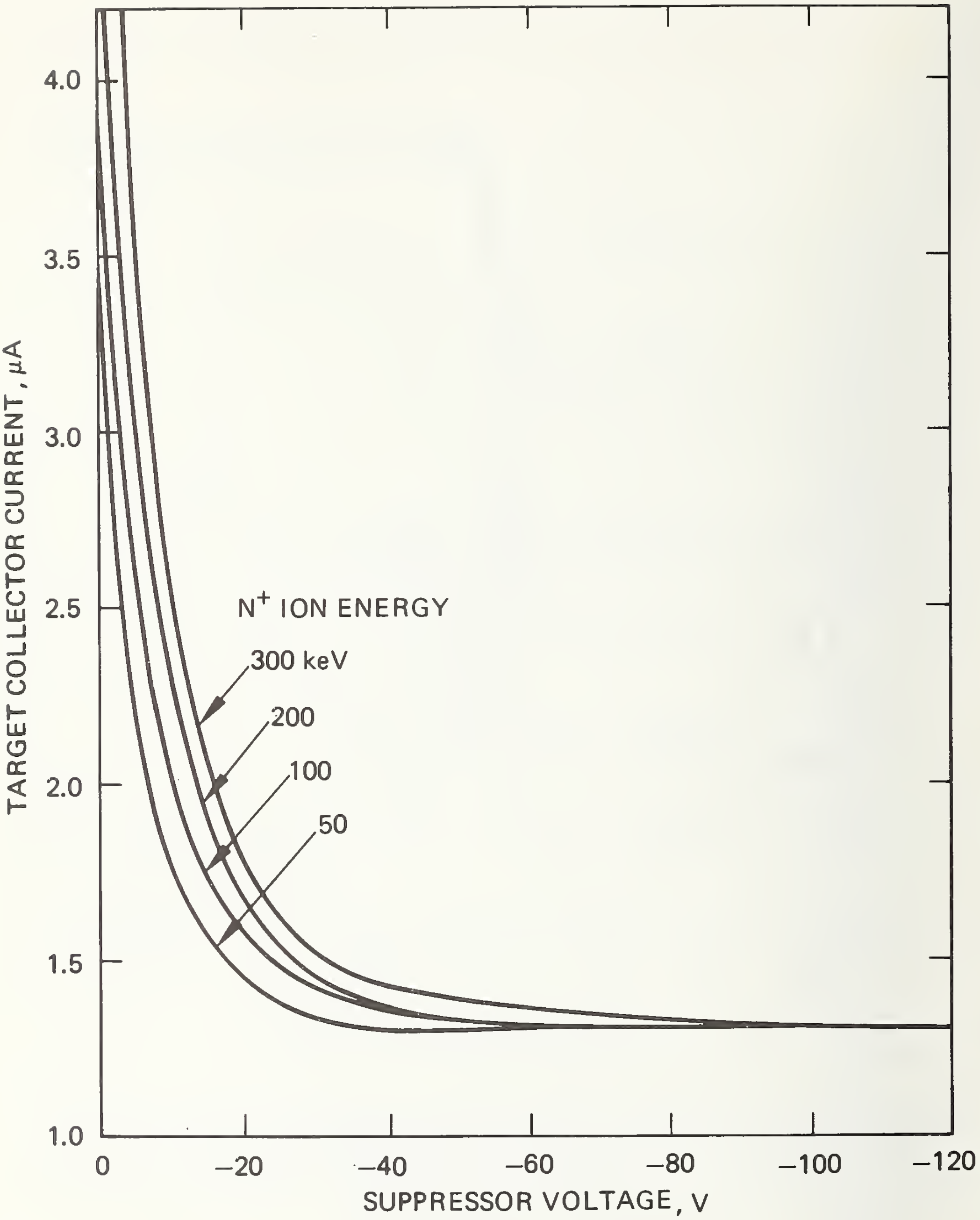

Figure 11. Collector current versus suppressor voltage for N^+ ion energies from 50 to 300 keV. Total ion current was 1.3 μA.

3.5. Positive Secondary Emission

The secondary positive ion emission coefficient can be obtained by dividing the positive secondary ion current measured in the suppressor circuit under negative bias by the true total incident ion current. In the specific case of figure 9, the value is 0.12 μA/1.3 μA = 0.09.

Operation in the grounded suppressor mode under these conditions and interpreting I_C as the beam current would result in an error in implantation dose 9% too large.

The variation of positive secondary emission current for both monatomic and diatomic ions as a function of ion beam energy is shown in figure 12. These curves show an emission maximum at 50 keV for N^+ and 100 keV for N_2^+ or a value of 50 keV per incident atom. The nitrogen secondary emission coefficients calculated from these curves are seen to be essentially coincident because the values of positive ion current are twice as large at twice the energy for N_2^+ as for N^+, leading to identical coefficients for one atom at a given energy.

The magnitude of positive secondary ion emission changes with other ions and targets as well as with beam energy. Some additional data are included in tables 1 and 2 to provide a rough idea of the variations that might be expected for different ion beams and different target surfaces. Even for the same surfaces, the secondary emission can change with vacuum conditions, adsorbed gases, method of surface preparation, type of cleaning process used, orientation of crystal lattice, etc. No attempts were made to control or reproduce these conditions exactly from run to run. Therefore, the data should only be taken as a relative comparison with no absolute significance given to the percentages. General trends are obvious, showing that higher atomic mass elements produce higher secondary emission at the same energy, and that higher secondary emission is obtained with semiconductor samples compared with aluminum foil targets. It was previously shown in connection with the discussion of figure 12 that the beam energy is also a factor in secondary emission.

It is important to be aware that the number of secondary positive ions may be in the range of 15 to 20% of the true ion beam current. This magnitude of emission is capable of causing significant errors in dose measurement when using an independently grounded suppressor circuit. In a system using the floating loop circuit shown in figure 8(b), the positive secondary ions are collected by the suppressor electrode and the current circulates only through the floating loop such that the integrator reading (I_T) is not affected.

3.6. Effect of Current Density

Our investigation also revealed a variation in secondary emission as a result of the ion beam current density. Measurements were taken at eight different levels of current from 1.5×10^{-9} to 5×10^{-5} A/cm^2. Figure 13 shows the percentage of the true ion beam current being emitted as secondary positive ions plotted as a function of the current density of a 50-keV argon ion beam. The reduction in emission at higher current density may be attributed to a surface change caused by the higher target temperature or to an increase in positive beam potential, caused by the higher ion space charge, which suppresses the secondary positive ions more effectively.

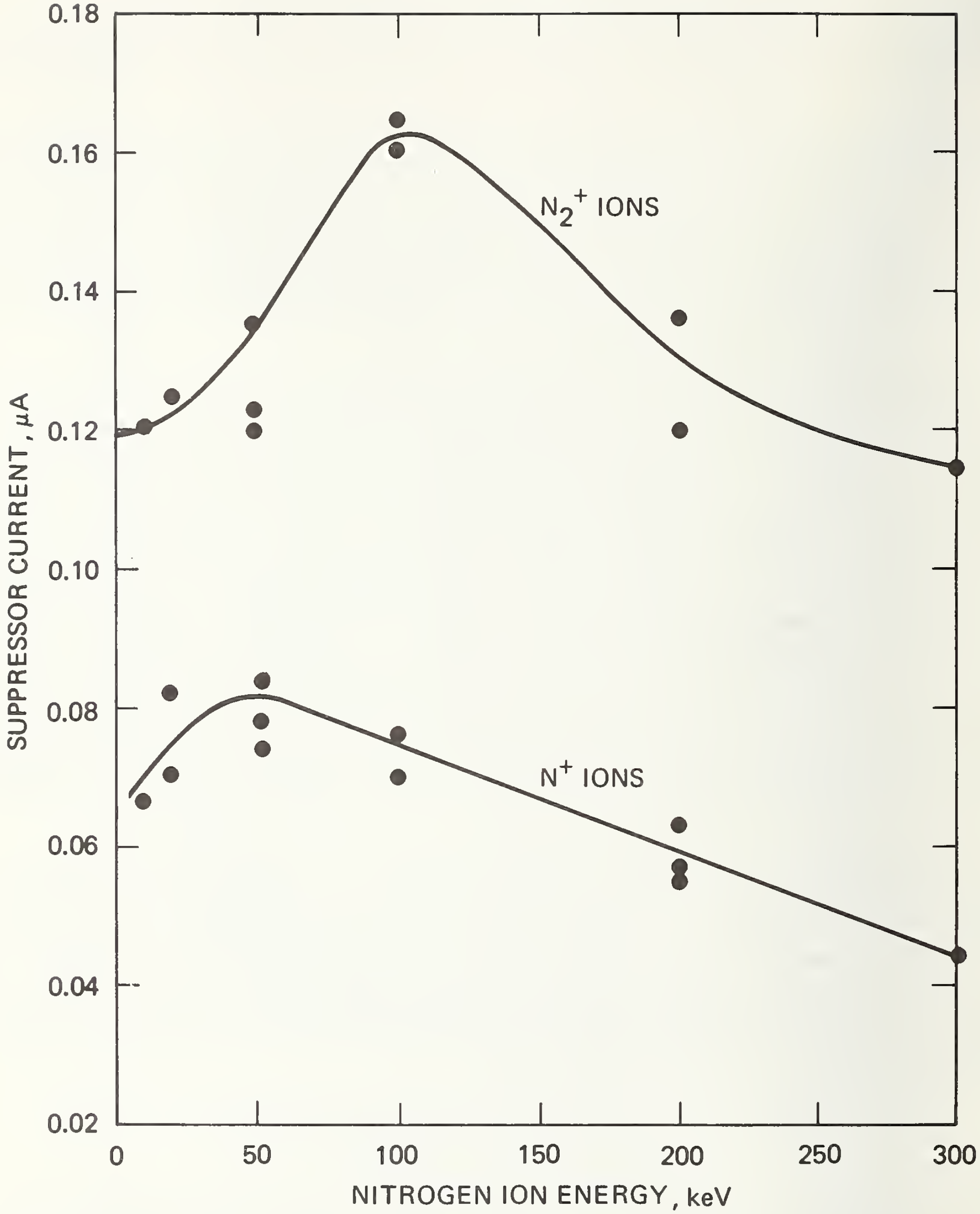

Figure 12. Positive secondary ion current as a function of N^+ ion energy. Circuitry and geometry are shown in figure 8(b) with 3-cm^2 target beam area (5-cm^2 area for 10- and 20-keV data). Total ion current was 1.3 μA.

Table 1. Secondary Positive Ion Emission Measured For Some Ions On Stainless Steel. (Surface Conditions Not Controlled).

Primary Ion	Energy, keV	Total Current, μA	Percent Secondary Ions
Be	100	1.05	2.6
B	20	1.5	3.0
N	50	1.3	6.2
N_2	50	1.3	9.2
Ar	50	2.5	15.6
Ga	40	5.0	17.7
As	50	1.3	18.9

Table 2. Secondary Positive Ion Emission Measured For Different Targets. (Surface Conditions Not Controlled).

Primary Ion	Energy, keV	Target	Percent Secondary Ions
Be	100	aluminum foil	2.6
Be	50	gallium arsenide	7.4
Ar	50	aluminum foil	8.4
Ar	50	silicon	15.6

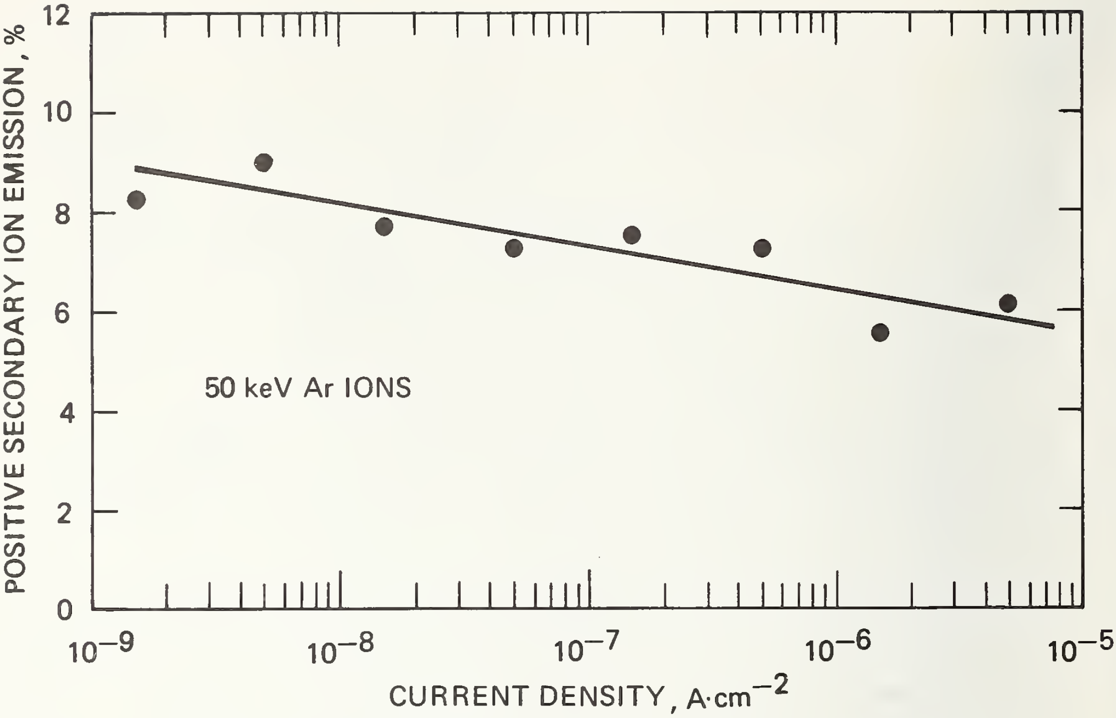

Figure 13. Positive secondary ion emission as a function of primary 50-keV argon ion beam current density.

4. CURRENT MEASUREMENT

Measurement of the ion beam current density and integration of the beam current for dose measurement are important parts of the implantation process and must be done before and during implantation. The section of this report on beam scanning has suggested ways to set up proper conditions before the implant. Assuming proper suppression and collection of secondary ions and electrons, the remaining possibility for error is the current collecting instrument or integrator itself.

4.1. Current Integrators

We studied the characteristics of five models of current integrators from three manufacturers. These instruments will be referred to as integrators A through E. Additional data, referred to as F, were taken using integrator E equipped with an input circuit designed to increase its frequency response. The manufacturers' specifications of these instruments are listed in table 3. Many of the specifications for these integrators do not describe how the units respond to pulsed current conditions, especially pulse rates. The absolute accuracy of any of these integrators is not considered a major issue as far as this work is concerned. What is important here is the reaction of the integrators to the test conditions and the different results that would be obtained using each integrator measuring the same test signal.

Table 3. Comparison of Some Specifications of Selected Current Integrators

Integrator Designation	A	A[a]	B	B[b]	C	D, E, F	D[c]	X[d]
Input Voltage for Full Scale Indication, V	10^{-7}	10^{-7}	10^{-3}	10^{-3}	10^{-3}	10^{-5}	10^{-5}	5×10^{-3}
Input Connection	Isolated from case	Isolated from case	Shield grounded	Shield grounded	Shield grounded	Shield grounded	Shield grounded	Shield grounded
Current Indicator Accuracy, % of Full Scale	2.0	2.0	N.A.[e]	N.A.	N.A.	0.5	0.5	2.0
Full Scale Current Minimum, A	2×10^{-9}	2×10^{-9}	3×10^{-9}	3×10^{-8}	3×10^{-10}	1×10^{-10}	1×10^{-8}	1×10^{-9}
Full Scale Current Maximum, A	2×10^{-2}	2×10^{-2}	1×10^{-3}	1×10^{-3}	1×10^{-4}	1×10^{-2}	1×10^{-2}	1×10^{-2}
Internal Calibration	None Required	None Required	Required	Required	Required	None Required	None Required	N.A.
Off-Set Adjustment, % of Full Scale	±10	±10	N.A.	N.A.	N.A.	None	None	None
Absolute Integrating Accuracy, % of Full Scale	0.02	0.02	2.0	2.0	2.0	0.01	0.1	0.1
Charge Counting Reproducibility, %	N.A.	N.A.	0.3	0.3	0.3	0.001	0.1	0.01
Integration Linearity, %	No Non-Linearity Measured	No Non-Linearity Measured	N.A.	N.A.	N.A.	0.01	0.1	N.A.
Temperature Stability, ppm/h	±30	±30	N.A.	N.A.	N.A.	N.A.	N.A.	0.05
Maximum Drift, %/h	N.A.	N.A.	0.04	0.2	0.04	N.A.	N.A.	N.A.
Digitizing Rate, pps	1000	100	100	100	100	100	1000	$0\text{-}10^{4}$
Peak Pulse Input, mA	20	20	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Maximum Frequency of Input Pulses	Unlimited	Unlimited	N.A.	N.A.	N.A.	Pulses Not Recommended	No limit given	No limit given

a. A model similar to A but not studied in this work.
b. A model similar to B and C but not studied in this work.
c. A model similar to D and E but not studied in this work.
d. A model from another manufacturer not studied in this work.
e. N.A. indicates not available in the specifications.

One of the integrators (A) was chosen to be a basis of comparison because of its demonstrated satisfactory performance during many years of use in our laboratory. Signals from either an ion beam or a current source were measured by each of the units separately and each reading was compared with the reading obtained by integrator A. These ratios are plotted in the subsequent graphs.

4.2. Measurement of dc Current

The integrators were first compared measuring steady dc currents typical of unscanned beams over the range from 5 x 10^{-8} to 5 x 10^{-4} A. The units were not especially calibrated for this comparison but were removed from their regular operations and tested as they would normally be used. In general, they were all found to compare very favorably, as seen in figure 14. Integrator E was within 1% of the reference. Integrators B and C varied less than 1% over the range but were off-set in absolute value to 0.99 and 0.98 respectively. Integrator D varied as much as 2% low at low current levels. Integrator F was the unit equipped with the input circuit to improve the frequency response when measuring pulsed currents; the use of such a circuit is undesirable for dc current measurements above 10^{-5} A.

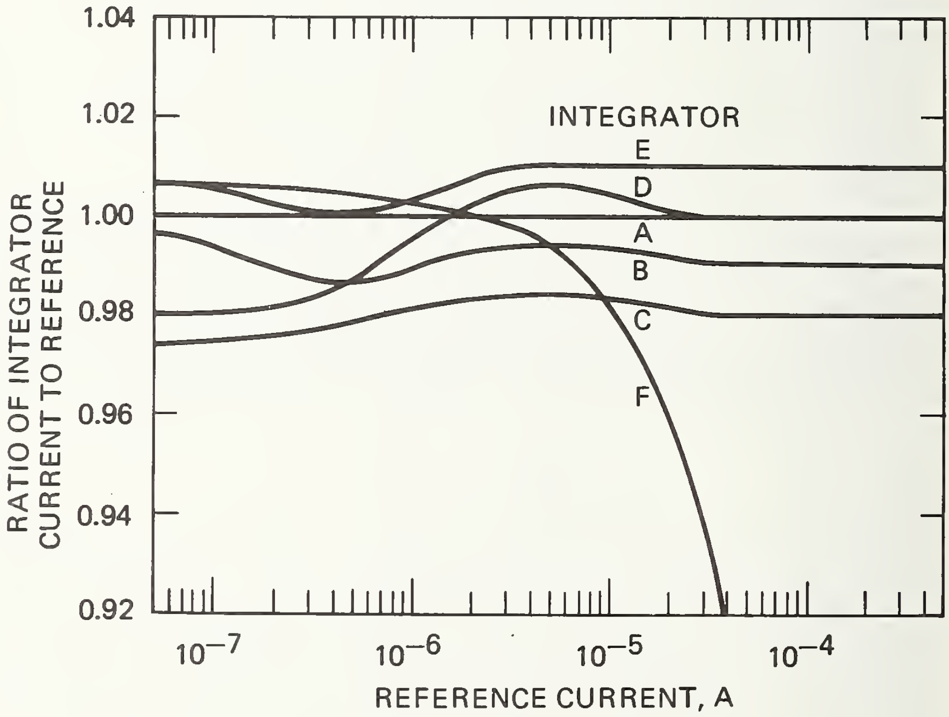

Figure 14. Comparison of integrator dc current readings. (Integrator A used as a reference).

4.3. Off-Scale Current

Two of the integrators were compared in regard to their accuracy when the indicator of the current went past full scale. These tests were conducted using steady dc currents monitored by another reference current meter. Even though the current meters on both integrators indicated full scale, charge counting continued and was recorded as a function of time to determine integrator accuracy. Integrator A was found to give a charge collection count equivalent to the full scale reading no matter how high the current was increased beyond this level. The result, as shown in figure 15, was a sharp increase in error when attempting to measure currents above full scale. Integrator D was found to continue counting the collected charge with a much slower increase in error. Even when the current was increased to 1.2 times full scale, the integrator still recorded this collected charge with an error of less than 1%.

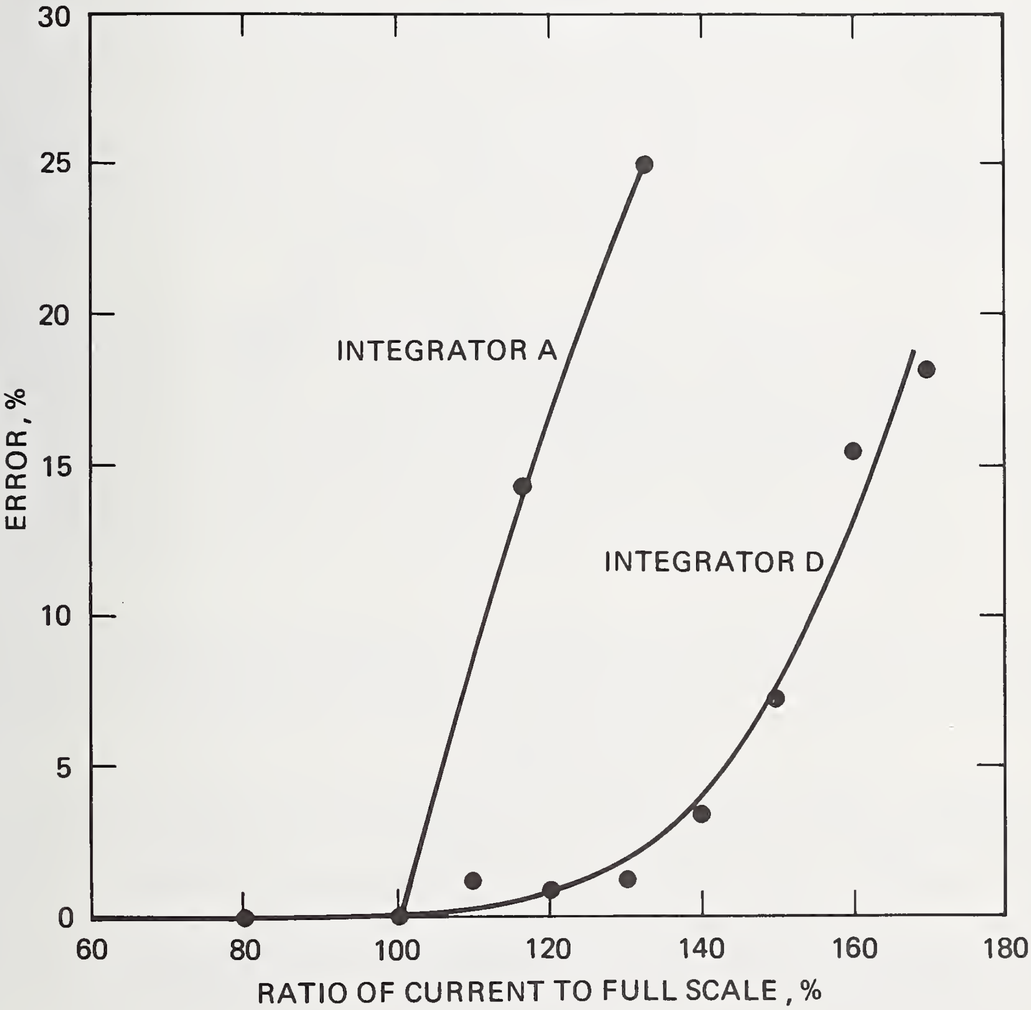

Figure 15. Off-scale current reading errors.

This potential cause of error must be considered if the current being monitored is drifting or jumping to levels exceeding full scale. It is recommended that a high enough integrator scale setting be chosen so that the indicated current is less than mid scale with no chance of exceeding full scale.

4.4. Measurement of Pulsed Current

Referring back to figure 4, as the beam passes over the center of the target in the typical 80% overscan case, the integrator measures a square wave type pulse. For this case the width of each pulse at a scan rate of 2000 pulses per second (pps) is about 250 μs. The pulse width gradually decreases with distance from the center, becoming zero during the maximum levels of the slower sweep voltage. The integrator must be capable of measuring this wide variety of pulse widths.

In order to investigate the accuracy of the current measurements under these pseudo-pulsed conditions, two sources of current were used: 1) actual ion beam currents obtained from an implantation system and 2) simulated beam current pulses obtained from a pulse generator. The currents in both instances were measured and compared using the five different integrators as well as other current measuring instruments. The readings were taken from dc conditions to 10,000 pps. The ion beam scanner unit was variable over a range from 20 to 2000 pps; the remaining frequencies were covered with the pulse generator.

Lower pulse rates (from 2.5 to about 30 pps) usually produced a fluctuation in the indicator meter needle making it impossible to record the current indicated by the indicator. For example, at 2.5 pps and with a 50% duty cycle, the pulse was on for 0.4 s and off for 0.4 s. For these low pulse rates the integrator count was measured as a function of timed intervals. At the higher pulse rates it was found that the indicated current accurately matched the integrated charge divided by the time interval and could be used for the comparison of the test integrator with the reference unit.

Average current readings were compared over the range from 5×10^{-8} to 5×10^{-4} A, maintaining a 50% duty cycle. The results are plotted in figures 16 through 20, each figure presenting the data for one integrator with the parameter being the five current levels that were measured.

Integrator C (figure 17) was found to record nearly the same currents as the reference. The average values were around 0.98 of the reference, being very close to the dc current comparison. The variation in pulsed current readings around the average was less than 1.5% showing that this integrator was reproducing the reference very closely over the complete range of pulse rates tested. The maximum current scale on this unit was 10^{-4} A. Therefore, the highest average current tested was 5×10^{-5} A.

Integrators B and D (figure 16 and 18) were found to have significant variations (in the range of 10%) but at different ends of the pulse rate spectrum. Both integrators were satisfactory (±1.5%) over the central range of 50 to 1000 pulses per second for all current levels tested.

Integrators E and F (figures 19 and 20) were found to be unsatisfactory for use in measuring pulsed current. Use between 100 and 10,000 pps should be possible if limited to low current levels (less than 5×10^{-7} A for E and less than 5×10^{-6} A for F). The curves for 5×10^{-4} A in figure 19 and 5×10^{-4} and 5×10^{-5} A in figure 20 are not shown because they were mostly outside the range of the graphs.

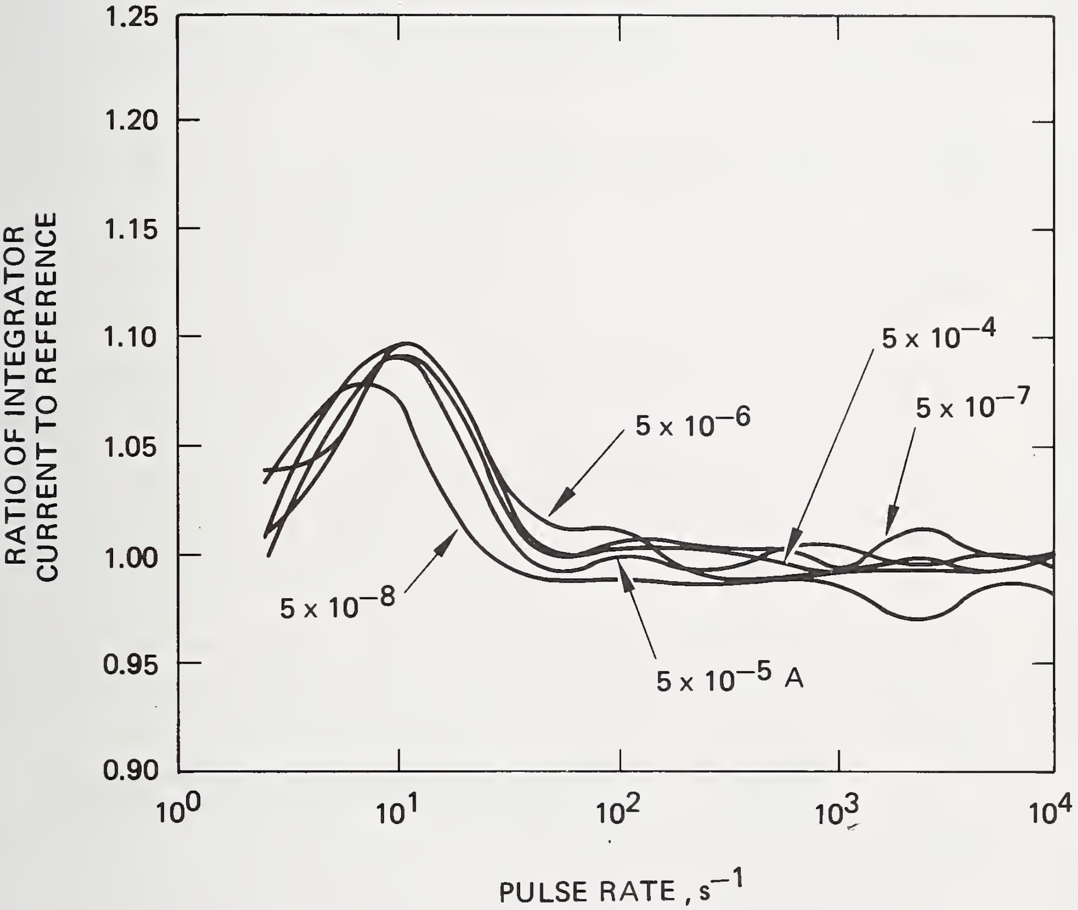

Figure 16. Pulsed current comparison of Integrator B to reference.

4.5. Effect of Pulse Width

An operating property of integrators that must receive separate attention can be referred to as scaling. Scaling means switching scales on the integrator to record the charge at the most convenient current indicating level. In some instances errors can be introduced when the ratio of the pulse peak height to the average current reading is high. For example, when a high current beam is scanned excessively to reduce the average current to a low value for a light dose implant, the pulses become very narrow. This type of test should not be confused with the off-scale tests where the current indicator exceeded full scale. In this case, even though the individual pulse heights may exceed full scale, the averaged current reading remains on scale.

A set of data was taken with all the integrators recording the current readings as the width of the pulse from the pulse generator was reduced. A pulse repetition rate of 2500 pps was used in this test. The integrators were set to read the average current at the most convenient scale setting. This means that in most cases the peak of the pulse was higher than the full scale setting of the current meter. For example, a current pulse with a peak value of 100 μA could be scanned to 25 μA average and

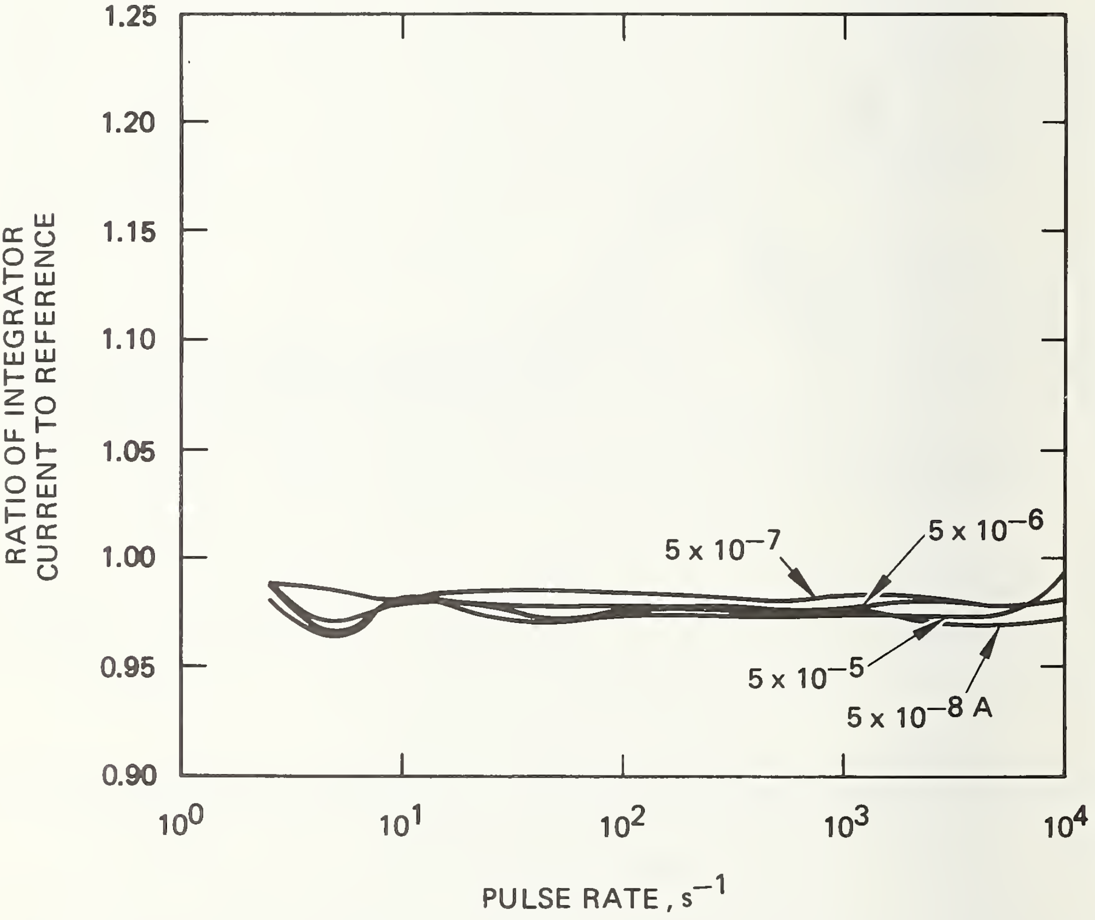

Figure 17. Pulsed current comparison of Integrator C to reference.

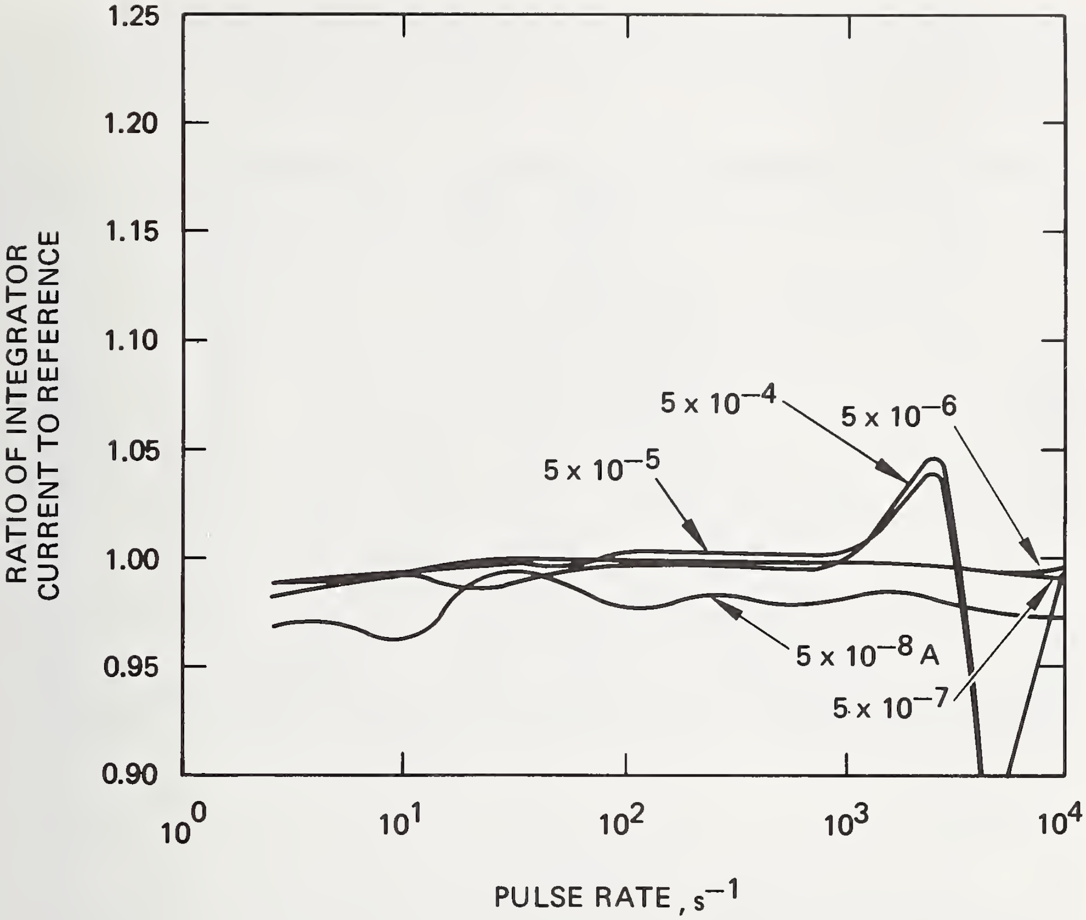

Figure 18. Pulsed current comparison of Integrator D to reference.

measured on the 10^{-4} A full scale setting (reading 1/4 of f.s.). Higher scanning voltage might reduce the same pulse to an average value of 5 μA, allowing a measurement to be made on the 10^{-5} A f.s. setting (reading 1/2 of f.s.). The object of these tests was to compare the readings obtained at such different scale settings. The data obtained were compared and normalized to integrator A. The specifications of the manufacturer state that this integrator can correctly measure pulses having peak amplitudes as high as 20 mA on any scale as long as the average value of the indicator current is on the scale being used. The same kind of errors result with pulsed currents as with dc currents (see figure 15) if the average value is allowed to exceed the full scale of the indicator meter. Curves for these tests are shown in figures 21 through 25. The parameters are marked showing the peak steady state values of the current before generating the pulses. For example, the lowest level tested was a steady dc current of 1×10^{-7} A. At a 50% pulse duty cycle the current represented the average value of a square wave pulse with the current indicating approximately 5×10^{-8} A. The pulse width was continually reduced by one-half for each step, resulting in current readings of 2.5×10^{-8},

1.25×10^{-8} and 6.25×10^{-9} A. The integrator scale setting for the lowest reading was typically 10^{-9} A full scale, two orders of magnitude lower than the original pulse height.

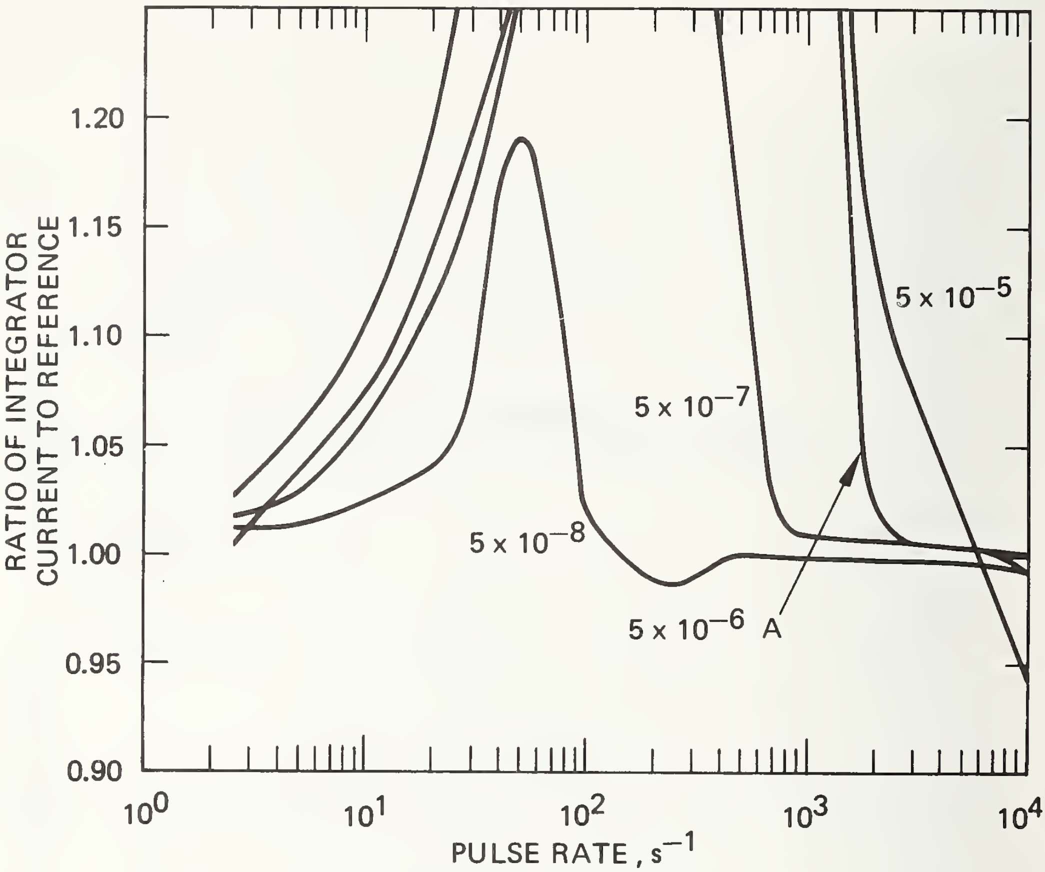

Figure 19. Pulsed current comparison of Integrator E to reference.

All of the integrators were able to give correct readings within a few percent for such low level currents. Even the next two curves (10^{-6} and 10^{-5} A) were satisfactory. However, 10^{-4} A and higher were not measured correctly by three of the units, giving errors greater than 10%. This means that steady beam current levels between 10 and 100 μA might be causing measurement errors when scanned across the target. The best way to check for such discrepancies is to compare readings on different scales. If at all reasonable, always record implantation doses using the higher full scale settings.

These errors are usually caused by frequency response limitations of the input amplifiers of the integrators, some of which are not able to handle the high current, high frequency components of the pulses. Integrators specified to be used for the measurement of pulses will most likely cause no problem. It is recommended that a second integrator or other electrometers be available for periodically double checking accuracy or for replacement use during calibration.

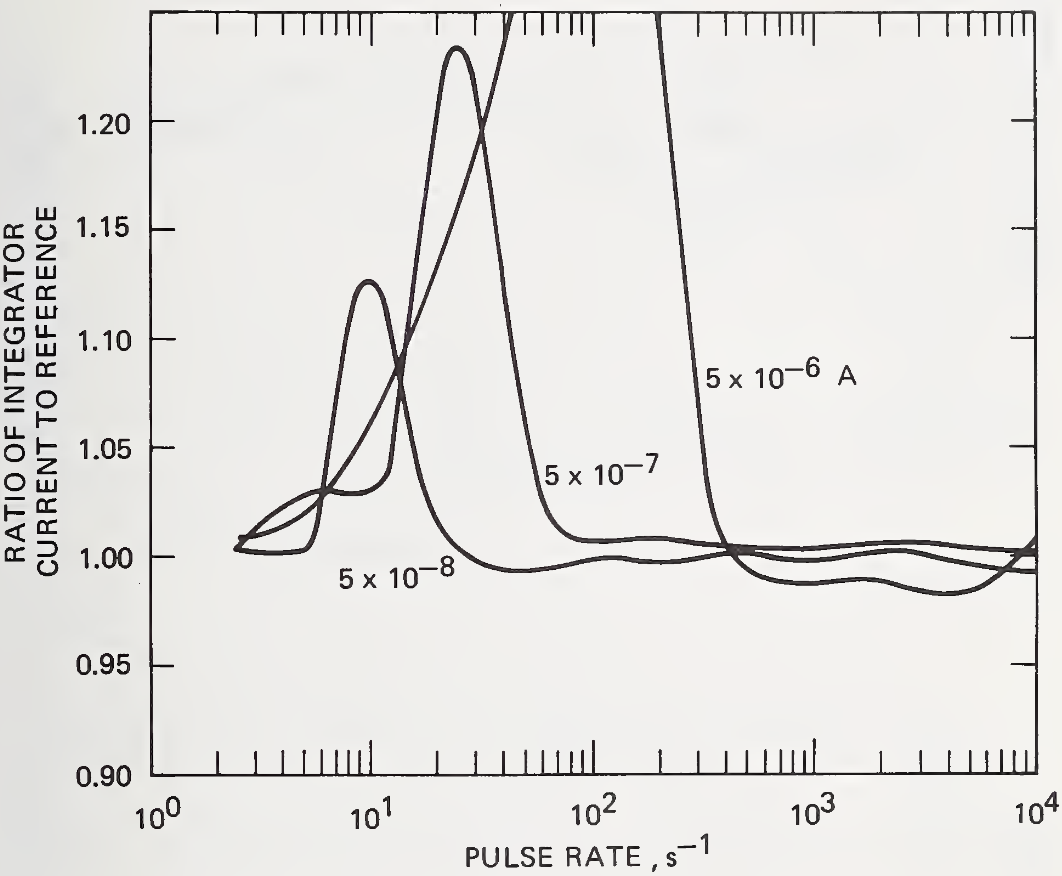

Figure 20. Pulsed current comparison of Integrator F to reference.

5. OTHER FACTORS AFFECTING DOSE MEASUREMENT

There can be other conditions that interfere with the accurate measurement of ion dose. A few of these will be discussed briefly in this section.

5.1. Neutrals

Energetic neutral atoms or molecules can originate in the ion source or anywhere along the ion beam path as a result of charge-exchange collisions. If these neutrals are allowed to penetrate the wafers at the target, they will contribute to the doping density in the wafer but will not be measured by the integrator, thus leading to errors in the implanted dose. Since they are not affected by electrostatic scanning or magnetic fields they can also be present at the target in a nonuniform pattern leading to nonreproducible devices.

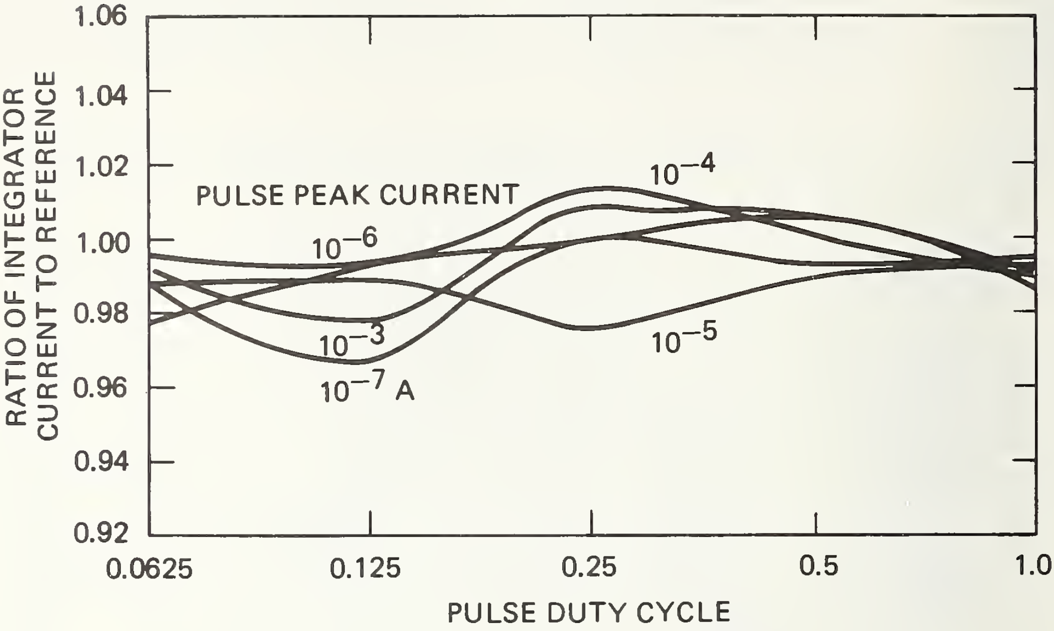

Figure 21. Pulsed current comparison of Integrator B to reference using 2500 pps.

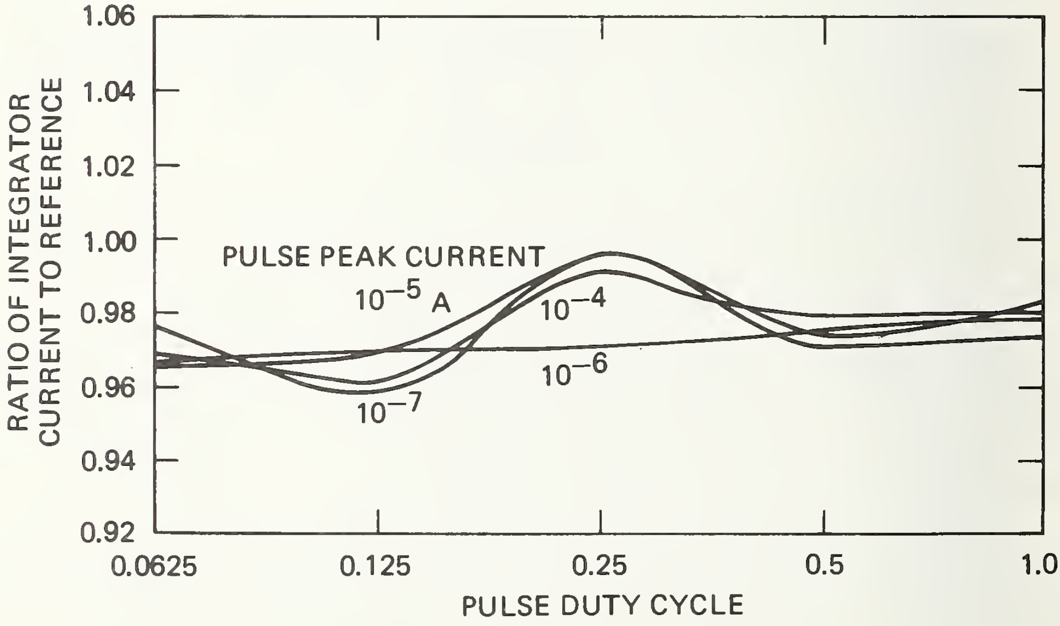

Figure 22. Pulsed current comparison of Integrator C to reference using 2500 pps.

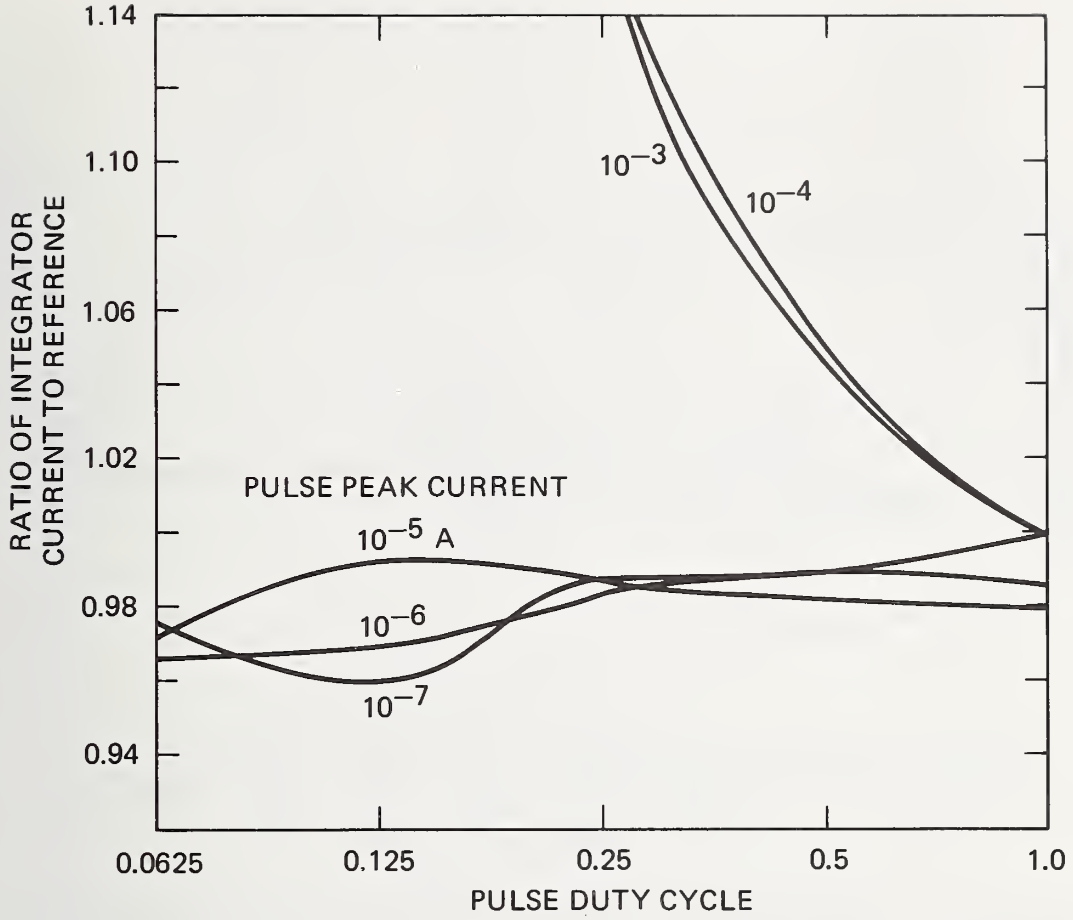

Figure 23. Pulsed current comparison of Integrator D to reference using 2500 pps.

Neutrals from the ion source directed along the beam line do not reach the target if the ion beam is bent in a magnetic field for mass separation. If a combination electrostatic and magnetic separator (EXB) is used where the desired ion component is passed straight through, the use of a separate beam deflector should be employed to bend the beam slightly displacing the target from the path of the neutrals. In addition to deflecting the beam, charge-exchange in the target end of the system can be minimized by improving the vacuum pumping to keep the pressure as low as possible.

5.2. ac Interference

Another problem arises when ac operated equipment is used for any function in the target. Some examples are target heaters, bias power supplies, or thermocouple meters. These units can be isolated from the system ground with isolation transformers, but there is usually some leakage current depending on the quality of the transformer and the operating level of the ac voltage. If the leakage is low enough on the particular

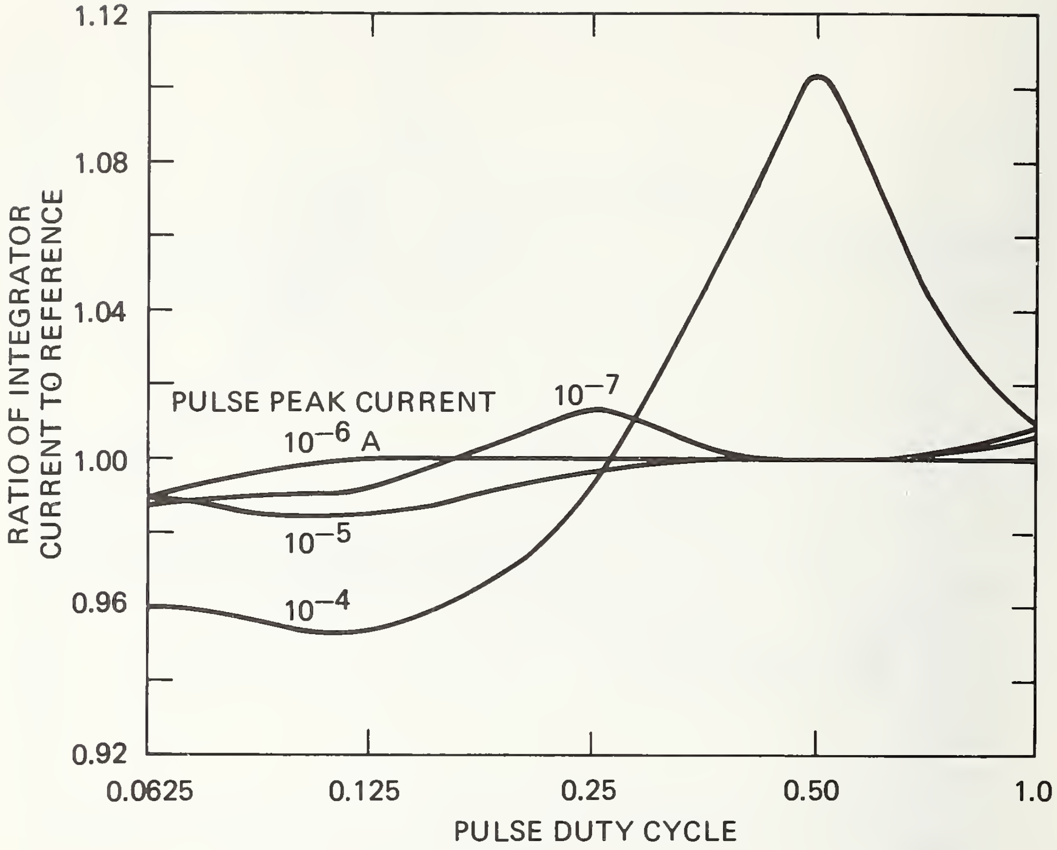

Figure 24. Pulsed current comparison of Integrator E to reference using 2500 pps.

current scale being used, the effect can be neglected. If not, some current integrators are equipped with zero off-set adjustments that allow the operator to eliminate the effect of such leakage. When making implantations, especially at low dose, in the presence of ac operated equipment, care should be taken to check the leakage current on lower scale settings of the integrator before proceeding with the implantation.

5.3. Insulator Leakage

There can be leakage currents across insulators that are used to support the suppressor electrodes or target holders. These leakages are proportional to the voltage across the insulators and the condition of the insulator surfaces. It is important to shield insulators from any sputtered particles to keep the surfaces clean. Physical placement of the insulators can also be an important factor. For example, if the suppressor electrode, as seen in figure 8(b), is mounted on the target holder with insulators, leakage across these insulators will never cause an error in I_T because the leakage currents will be collected in the same loop as the secondary particles. Again, a check of the leakage current on a lower scale setting of the integrator will determine if a problem exists.

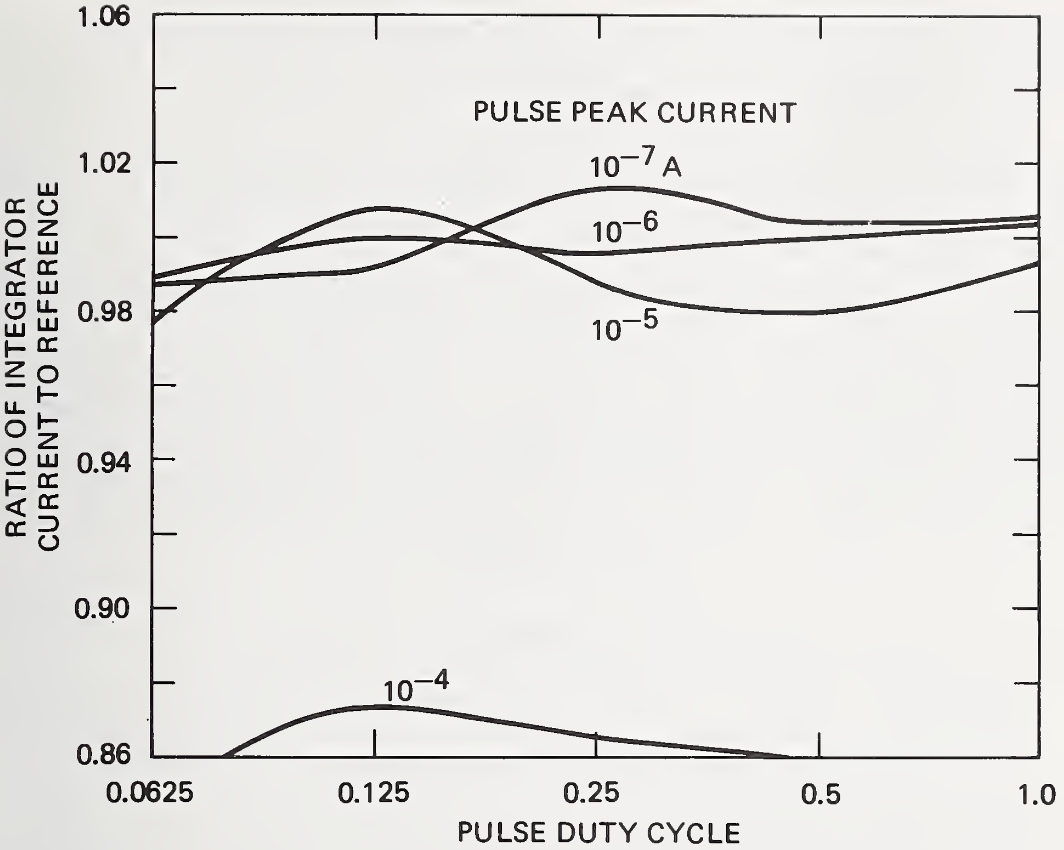

Figure 25. Pulsed current comparison of Integrator F to reference using 2500 pps.

5.4. Dose Calculation

The ion dose or fluence is the number of ions implanted per unit area of the target. The number of ions is determined by dividing the collected charge by the charge per ion (1.602×10^{-19} C times the charged state of the ion). Integrators usually display a value for the current being collected but they are primarily instruments designed to measure the total charge collected. Therefore, the dose is calculated by using the following formula:

$$\text{Dose (ions/cm}^2\text{)} = \frac{\text{integrated charge}}{1.602 \times 10^{-19} \times \text{target area (cm}^2\text{)}} \qquad (1)$$

If an integrator is not available, the dose may be obtained by implanting for a measured time at a uniform current level. In this case the product of the current and time is substituted for the integrator charge in equation (1). The accuracy of this measurement technique depends on maintaining the ion current at a uniform level over the entire time period of the implantation. Experience at our laboratory has shown that it is difficult to maintain ion beams at constant levels for an extended length of time because of fluctuations in power supplies controlling the beam, changes in ion source fuel feeding rates, etc. Therefore, this method of measuring dose is not recommended.

There are occasions when it is appropriate to utilize ion species other than the normal singly ionized atoms. Multiply ionized single atoms are used to obtain higher ion energies. For example, accelerated doubly charged atoms gain twice as much energy as the same atoms singly charged and their use is equivalent to operating at twice the accelerator voltage. However, it must be remembered that when implanting with multiply ionized particles, there is only one implanted atom for every two charges (or more depending on the charge state of the atom) and the total charge required to be collected by the integrator must be increased accordingly. Where lower energies are desired (and not obtainable, perhaps because of limitations in system operation) diatomic or multiatomic ions can be used. In this case, there are two or more atoms implanted for each electron charge and the integrator setting must be reduced accordingly.

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

An investigation of various phases of ion implantation dose measurement was carried out, covering in detail ion beam scanning, secondary particle suppression, and current measurement instruments. Problems are discussed and preferred techniques, electrode structures, and measurement circuitry are presented. Five current integrators were tested and are compared, especially in regard to pulsed current measurement.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Accurate ion beam current measurement; current integrators; ion beam scanning; ion implantation; ion implantation dose measurement and control; secondary particle suppression.

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