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LOW-ENERGY PROTON DAMAGE EFFECTS IN SILICON SURFACE-BARRIER DETECTORS

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J. A. Coleman,* D. P. Love,† J. H. Trainor, and D. J. Williams

SUMMARY

In order to predict the useful lifetime of semiconductor detectors which operate in the Earth's trapped radiation belts, the effects of damage by 50 keV, 200 keV, 600 keV and 1 MeV protons on silicon, surface-barrier, transmission detectors have been studied for fluences from 10^{10} to 10^{14} protons/cm^2. Detector current, noise and capacitance increased with fluence, with significant increases occurring after 10^{13} protons/cm^2. Bias-voltage-dependent multiple peaking was observed with Am-241 alpha particles. The effects of damage by protons with these low energies are significantly reduced in transmission detectors if the protons enter the rear, aluminum contact rather than the front, gold contact.

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LOW-ENERGY PROTON DAMAGE EFFECTS IN SILICON SURFACE-BARRIER DETECTORS

INTRODUCTION

The silicon solid state detector has proved itself to be a most useful nuclear particle detector in space research, as well as in the ground laboratory. This is especially true in investigations of the energetic electrons and protons trapped in the Earth's magnetic field and in investigations of the large proton fluxes sometimes associated with solar flares. The convenient size of these detectors, their low bias voltage requirements, extremely good energy resolution and small dead time effects have often led to their choice over competitive detector systems.

A characteristic of the energy spectrum of both solar-emitted particles and the trapped radiation is that the flux rises sharply at low energies. Thin metal foils or aluminized mylar windows which are placed over a detector to provide a light and/or thermal shield have also provided a shield against the large numbers of low energy electrons and/or protons. In the case of protons, this has ordinarily limited the measurements to energies greater than 0.5 to 1 MeV. Even with this shielding, the radiation damage effects of the penetrating particles have often been the limiting factor in the lifetime of the experiment, and hence, a major factor in the design of the experiment itself.

In the past several years it has become apparent that it is most important to extend the useful energy threshold of these experiments to much lower energies, perhaps as low as 30 or 40 keV. Available detectors and flight electronics will permit such thresholds and still allow an appreciable margin above the noise in the systems. Some newer spacecraft designs are such that the experiment need not have a sun or thermal shield directly over the aperture. The major problem which then arises is concerned with the radiation damage effects of these lower-energy particles, since their flux levels may well be several orders of magnitude larger than our previous constraining fluxes.

Whereas there has been available limited information on the radiation damage effects on solid state detectors for protons and electrons with energies above 1 MeV, there is essentially no information for the energy region of interest here. Thus our primary motivation for carrying out this study was to determine the performance parameters of our detectors as a function of particle species, energy and fluence,[1] in order to properly design the experiments for an adequate, useful lifetime in space. Additionally, it was apparent that the orderly progress of such a study could result in a much better understanding of the radiation damage mechanisms and the devices themselves.

The effects of damage in silicon surface-barrier detectors by 50 keV, 200 keV, 600 keV and 1.00 MeV protons are reported here for fluences of 10^{10} to 10^{14} protons/cm^2. The detector performance parameters measured at each fluence value as a function of reverse bias applied to the detector were current, noise, capacitance and counting response to Am-241 alpha particles.

EXPERIMENT

Detectors

Silicon, surface-barrier, transmission detectors, which were capable of total depletion, were used in this study.[2] These detectors were fabricated from 100 μm thick wafers cut from the same n-type (phosphorus-doped) ingot of silicon which had a resistivity range of 1700 ohm-cm to 2200 ohm-cm and a nominal photoconductive decay lifetime value of 2500 μsec. The silicon wafers were mounted in ceramic rings with epoxy cement and the front (gold) rectifying contact (which formed the surface-barrier) was about 200 Å thick and the rear (aluminum) ohmic contact was about 1500 Å thick. The nominal detection area was 50 mm^2, but capacitance measurements indicated an effective diode area of 70-80 mm^2. The bias voltage for total depletion of the 100 μm detectors was between 25 V and 30 V and the operating voltage (maximum) was 50 V.

Irradiation

Two detectors at each energy were independently irradiated for proton energies of 50 keV, 200 keV, 600 keV and 1.00 MeV using the analyzed beam of a 1 MeV Van de Graaff accelerator. The range in silicon of protons with these energies is given in Table I.[3] At the center of the irradiation chamber, the proton beam had a smooth variation in intensity of 30 percent across a 2 cm diameter circular area. The beam incident on the center of the detector's sensitive area was collimated to a spot 5 mm in diameter, so that the edges of the detectors' sensitive areas were not irradiated. A 6 mm thick aluminum beam collimator was placed 2.2 cm from the detector surface. The beam intensity on the detectors was measured by inserting a small Faraday cup between the beam collimator and the detector and measuring the Faraday cup current and the collimator current for a stable beam situation prior to the irradiation. The experimental setup is shown in Figure 1. During the irradiation the Faraday cup was removed, and the beam stability was monitored by noting the collimator

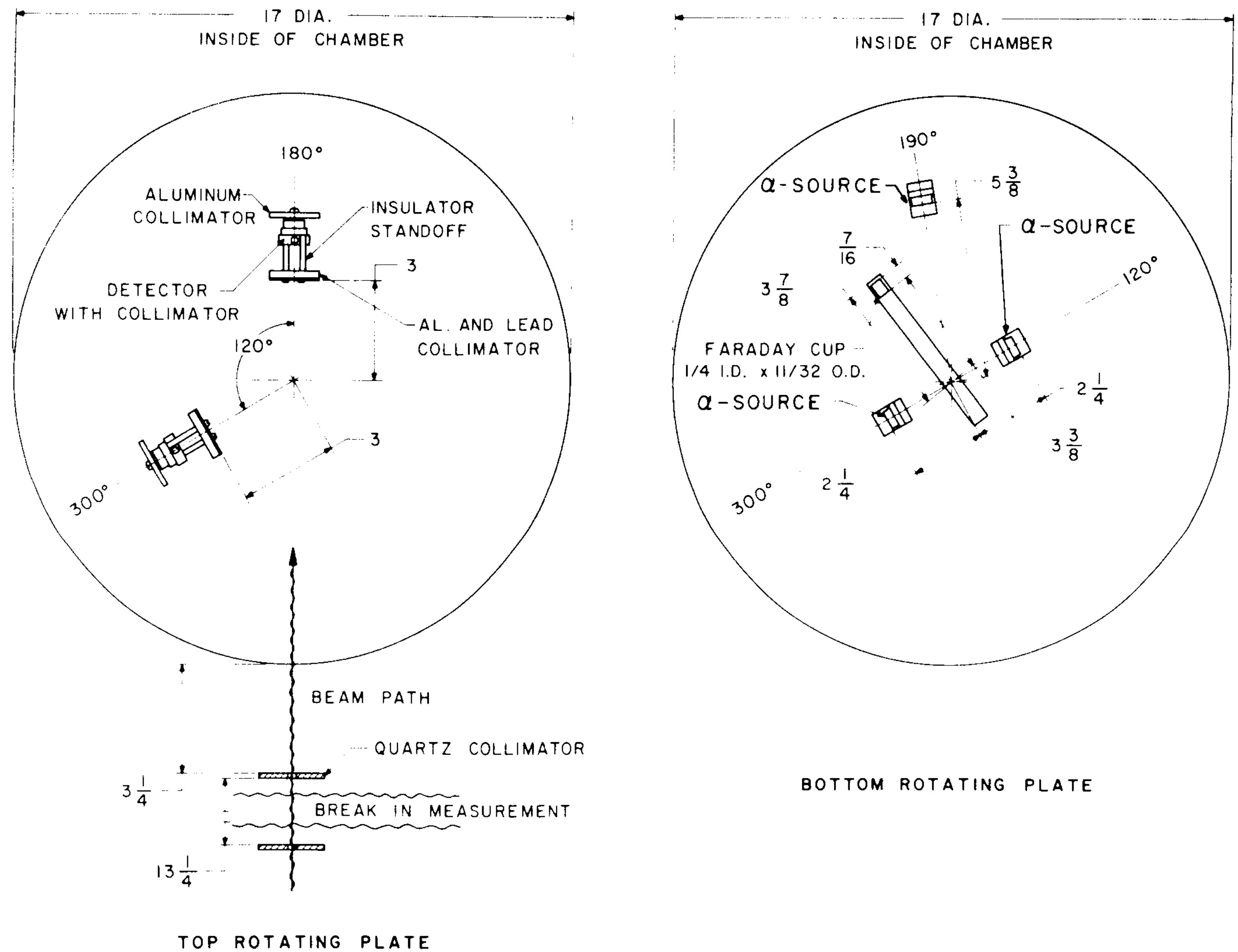

Figure 1—Arrangement of detector mounts, Faraday cup, and alpha particle sources for irradiation and subsequent testing. (a) top rotating plate, (b) bottom rotating plate.

current. The detectors were irradiated for 5 minutes for each increment of damage at appropriate beam currents ranging from 5×10^{-12} amp/cm^2 to 8×10^{-8} amp/cm^2. The resulting fluence values, integrated flux in units of protons/cm^2, are given in the figures and were in the range 10^{10} to 10^{14} protons/cm^2. The detectors were kept in the irradiation chamber at a temperature of approximately 25°C and in a vacuum of approximately 10^{-5} torr throughout the entire time for all irradiations and testing at a given proton energy. In order to further simulate spacecraft operation, the detectors were reverse-biased at their maximum voltage rating during the irradiation, and the leakage currents were monitored. The stability of the current during the irradiations indicated that no serious heating effects occurred for fluences up to 10^{14} protons/cm^2.

Irradiations also were performed with 200 keV and 800 keV protons incident on the rear, aluminum contact of two additional detectors. All other parameters were maintained as they were in the irradiations of the front, gold contacts. The detector performance measurements after these two rear-entry irradiations were also the same as described above.

Measurements

After each irradiation, the current, noise, capacitance and counting response to Am-241 alpha particles were measured as a function of reverse bias for each detector. Currents were measured with a picoammeter. The system noise was obtained by measuring the amplified noise signal with an rms meter and calculating the noise referred to the preamplifier input in keV for the full-width-at-half-maximum (FWHM) referenced to a Gaussian distribution, and also by pulser line-width measurements. The capacitance was measured on a bridge using a 30 mV peak-to-peak signal with a frequency of 100 kHz. The amplification system for the counting measurements had a field-effect transistor input stage with a noise slope of 0.16 keV FWHM/pF. The pulse shaping network had double differentiation and double integration with equal time constants of 0.8 μsec. The counting response of the detectors after each irradiation was accomplished using Am-241 alpha particle sources which were placed directly in front of the aluminum and lead collimators. With this geometry, the source irradiated an area slightly larger than the area damaged by the beam.

For fluences less than 10^{14} protons/cm^2, the detector characteristics were measured directly after the irradiations. At higher fluences, measurements were not made until the current and noise characteristics had stablized several hours or days depending on the fluence. This partial recovery of detectors after extensive damage may be due to fast annealing effects as the density of defects and the probability for defect-defect interactions becomes very high.

RESULTS

Front Entry

Detector current-voltage characteristics for various proton fluence values which are typical of the irradiations of the detector front, gold contact are shown in Figure 2 for the 50 keV and 1.00 MeV irradiations. The current plateaus are more level for the lower energy irradiations. A summary of the current increase as a function of proton fluence for the four proton energies used is given in Figure 3. In general, above 10^{11} protons/cm^2 the increase in leakage current due to proton damage appears to be directly proportional to the fluence and, perhaps, the number of defects produced. Departures from this relationship occur at fluences above 10^{14} protons/cm^2 when microplasma formation was observed for the higher bias voltages.

Representative noise-voltage characteristics for various proton fluence values are shown in Figure 4 for the 50 keV and 1.00 MeV proton irradiations. The noise values given are for the total system noise including the effect of high detector capacitance on the preamplifier input. This effect is evident in Figure 4a for the noise-voltage characteristics below 10 volts at a fluence of 5.5×10^{13} protons/cm^2. Detector noise as a function of fluence for the four proton energies studied is shown in Figure 5. In general, the noise increases very rapidly above 10^{13} protons/cm^2. As the current data might suggest, the noise was larger for the higher proton energies for a given fluence except for the 1.00 MeV irradiation. In this latter case, it may be that the type and density of defects formed by the 1.00 MeV protons which are located in the depletion region are different than those in the lower energy irradiations. Defects which are formed at the end of the proton range may occur in the available depletion region at the proton energies below 1.00 MeV.

Above 10^{14} protons/cm^2, microplasma-type noise bursts were observed. The values shown at the highest fluences, therefore, are only approximate, and errors of 50 percent to 100 percent may be present. However, this data is presented only to show the very rapid increase in noise above 10^{14} protons/cm^2. In general, the noise increases with fluence at a slower rate than the current. This trend is consistent with the model of Goulding and Hansen[4] which shows that, if the noise is dominated by generation current fluctuations, the mean square noise is proportional to the generation current. In the present case, it is assumed that the number of current generating sites is proportional to the number of incident protons.

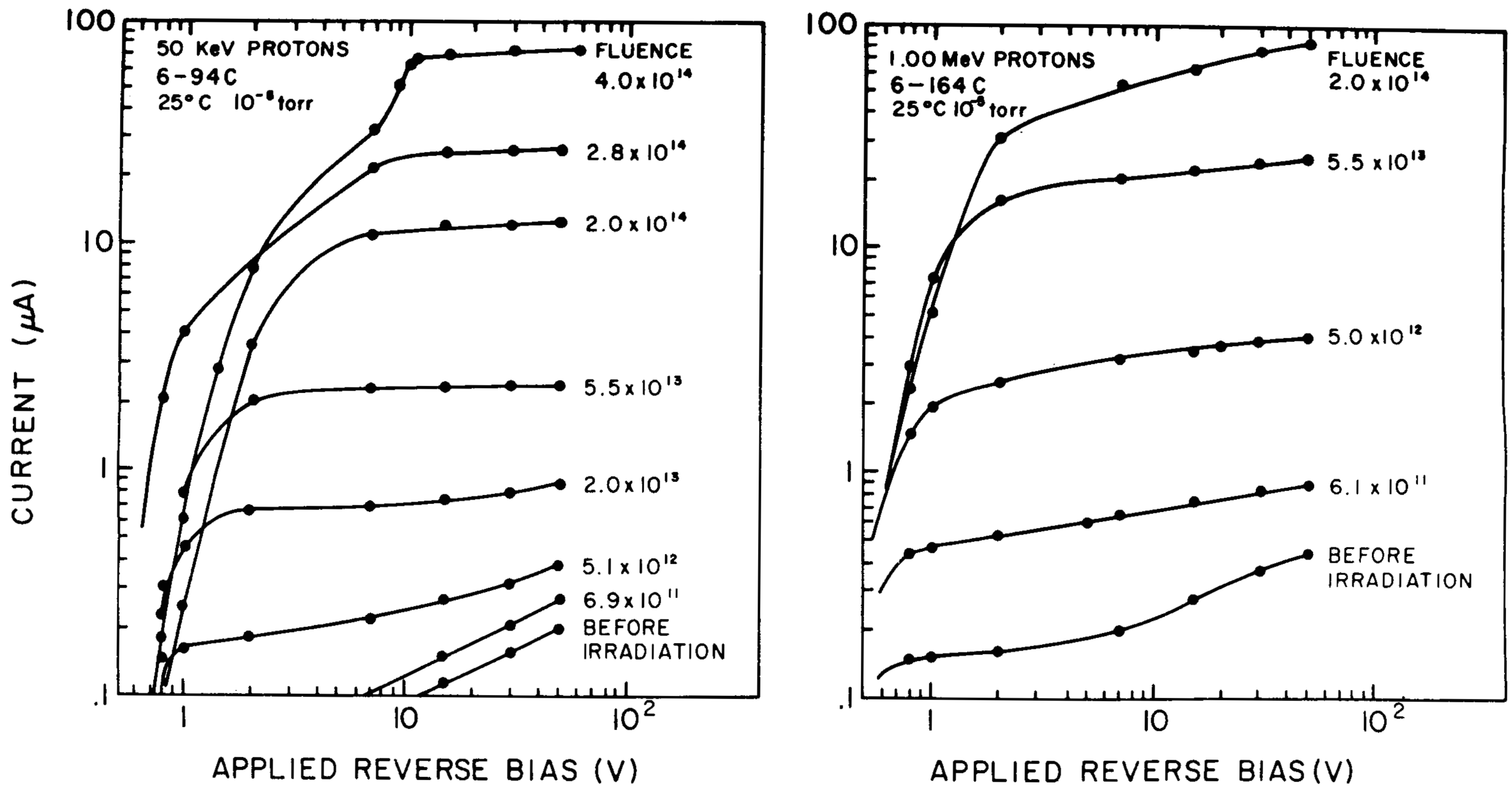

Figure 2–Current-voltage characteristics after various proton fluences (protons/cm^2) for (a) 50 keV and (b) 1.00 MeV irradiations. The applied reverse bias is the voltage measured directly across the detector.

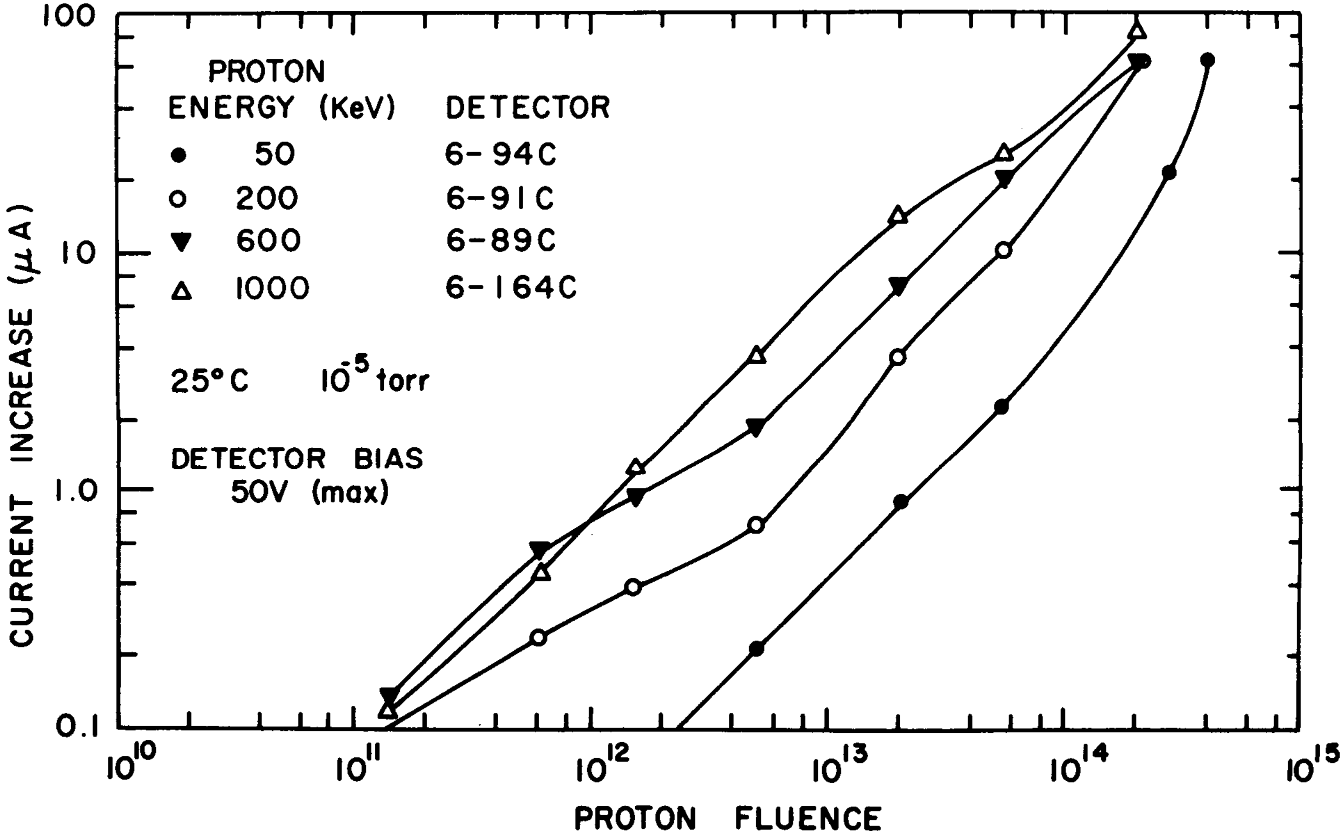

Figure 3–The increase in reverse-biased detector current as a function of fluence after 50 keV, 200 keV, 600 keV and 1.00 MeV proton irradiations.

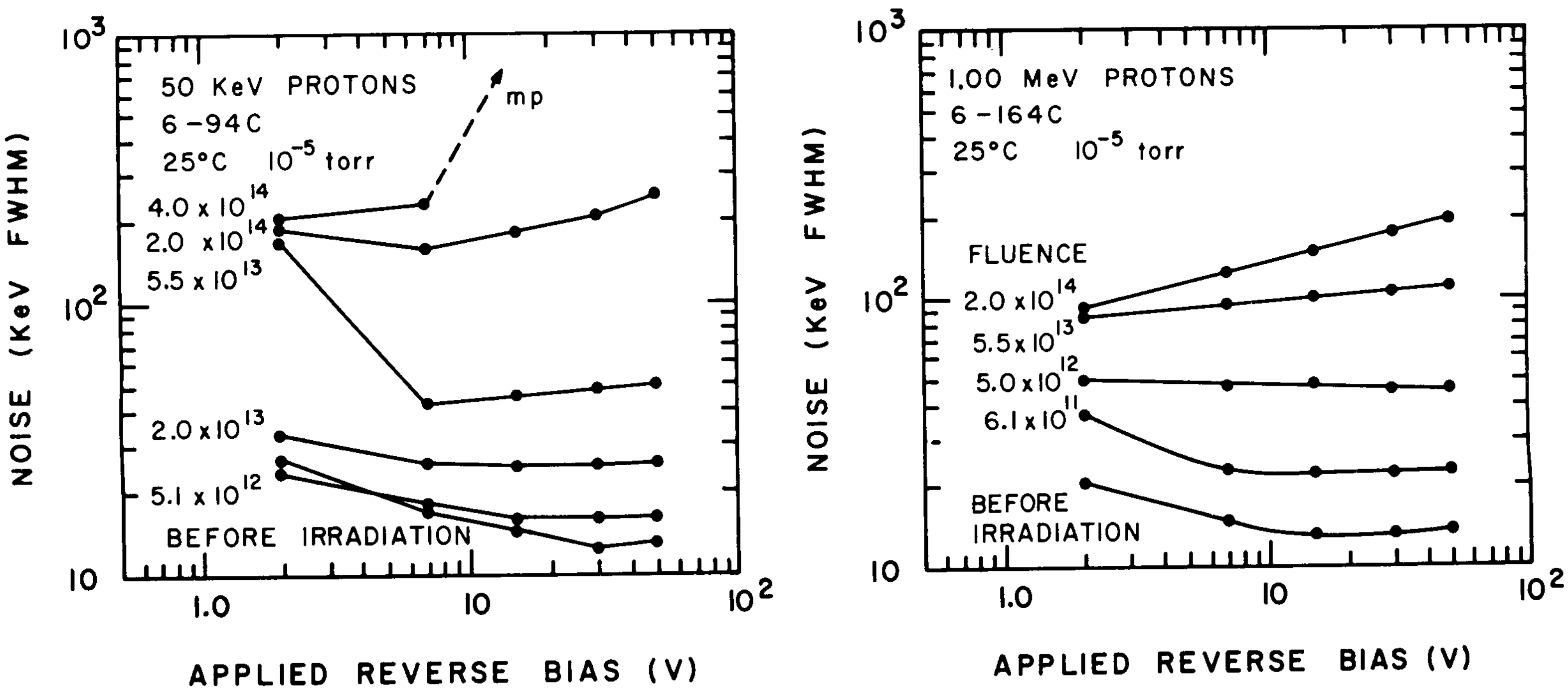

Figure 4—Noise-voltage characteristics measured after irradiation with (a) 50 keV and (b) 1.00 MeV protons at various proton fluences.

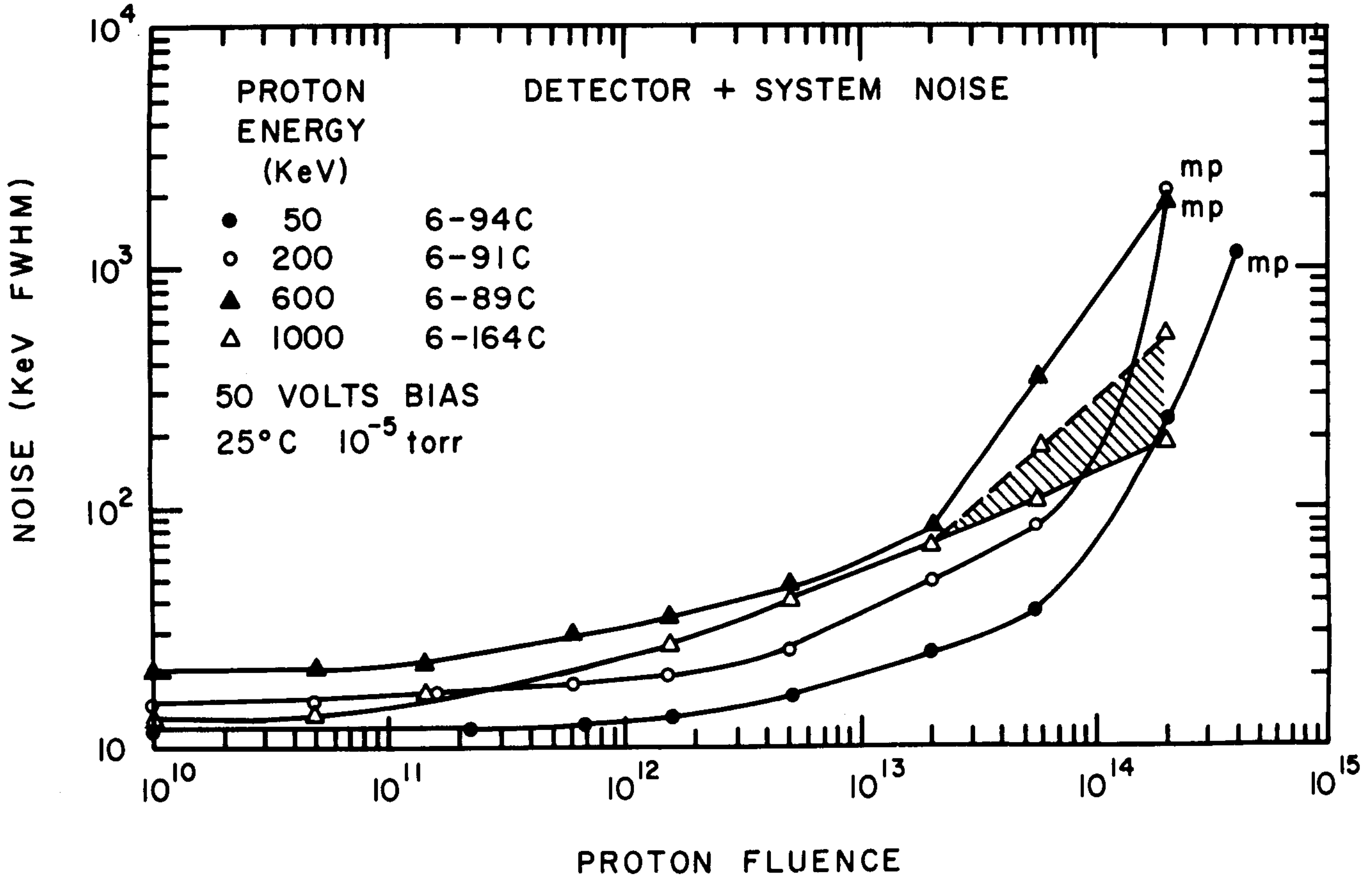

Figure 5—Total system noise as a function of fluence after 50 keV, 200 keV, 600 keV and 1.00 MeV proton irradiations. The observation of microplasma effects during a measurement is indicated by mp.

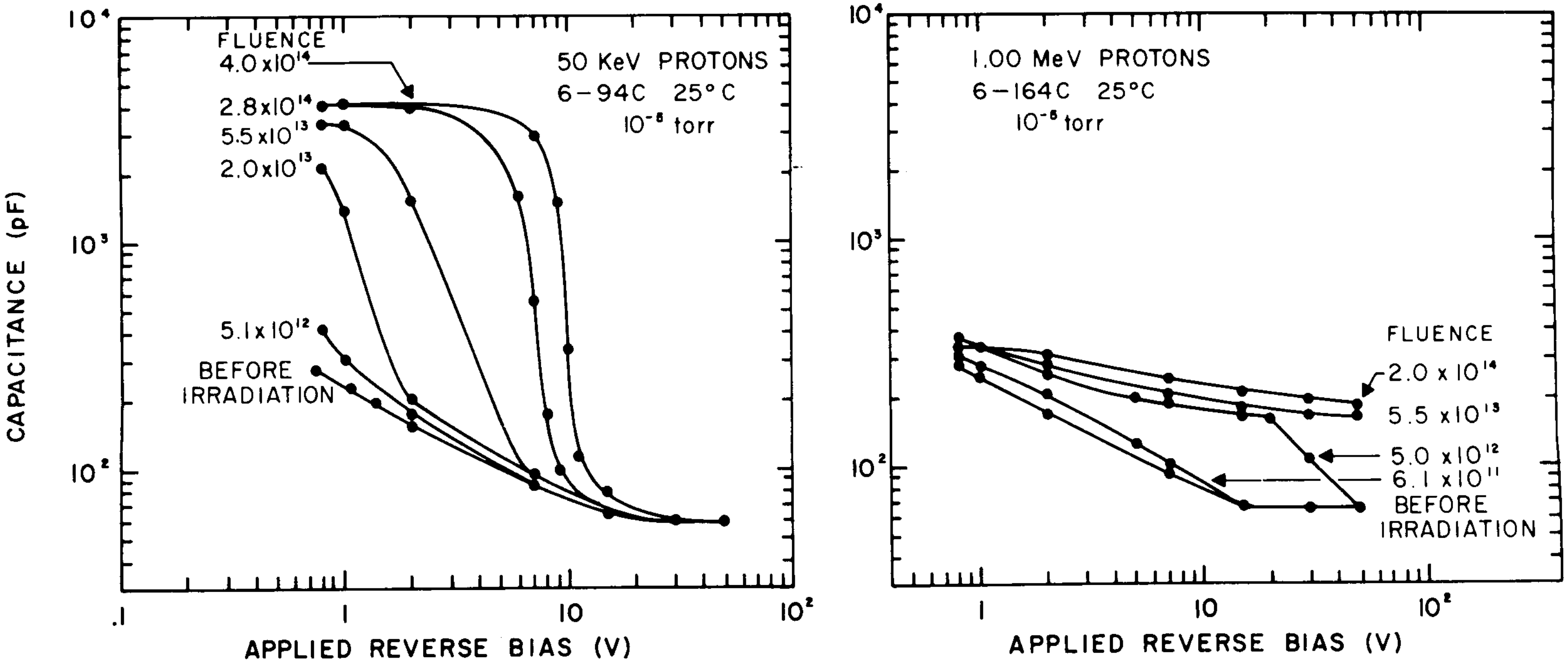

Figure 6–Capacitance- voltage characteristics measured after irradiation with (a) 50 keV and (b) 1.00 MeV protons at various fluences.

Capacitance-voltage characteristics for various proton fluences are shown in Figure 6 for 50 keV and 1.00 MeV protons, which show the irradiations in which the largest and the smallest capacitance changes were observed. A summary of these characteristics for the final irradiation at each energy studied is given in Figure 7. In all irradiations, the capacitance at a given voltage was observed to increase with fluence. If the damage is assumed to be the bulk silicon predominantly and not to the surface, the capacitance measurements indicate that mostly donor-type defect states are being formed by these low-energy protons.

The bias voltage necessary to totally deplete the detectors increased with fluence and was always larger for the higher energy proton irradiations. Thus, it was observed that at fluences of 2×10^{14} protons/cm^2, the damaged layer

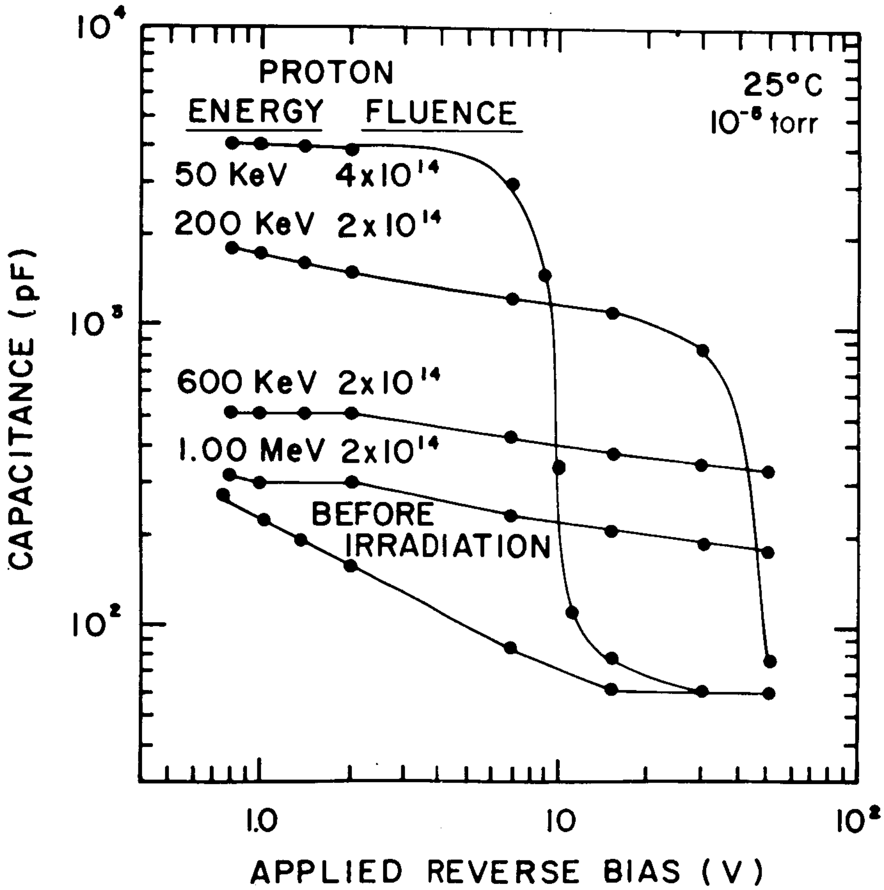

Figure 7—Capacitance-voltage characteristics measured after irradiation with the 50 keV, 200 keV, 600 keV and 1.00 MeV protons at the highest fluence values studied.

could be depleted at the maximum detector bias only for the 50 keV and 200 keV irradiations. Above a fluence of about 5×10^{13} protons/cm^2, too many charged effect centers were produced by the two higher energy proton irradiations for total depletion.

The relative values of capacitance below 10 volts bias for the energies shown in Figure 7 generally reflect the relative ranges of the protons if it is assumed that the capacitance is inversely proportional to the depletion depth. Thus, the highest concentration of damage appears to be at the end of the proton range where the atomic displacement probability becomes very large.[5]

The counting response of a detector to Am-241 alpha particles incident on the irradiated front, gold contact after fluences of 1.6×10^{12} and 2.0×10^{14} 1.00 MeV protons/cm^2 is shown in Figures 8 and 9, respectively. Alpha particles which entered the undamaged peripheral region just outside the damaged area at the center of the detector yielded the full-energy, bias-independent peak. The bias-dependent peak came from alpha particles entering the damaged region. A scan of the damaged detector with a collimated alpha particle beam confirmed these conclusions.

At a given detector bias, the collection efficiency for alpha particles entering the damaged region decreased with fluence. This loss of charge is caused principally by two effects: a depletion depth which is less than the range of the alpha particles and radiation-produced trapping sites which remove charge carriers before collection. For example, the small decrease in energy of the peak at 50 volts bias in Figure 8 is caused principally by the trapping of charge produced in the damaged layer. Capacitance measurements indicate that the detector is fully depleted at this voltage and fluence. As the bias is reduced on the detector, the trapping probability is increased by the lower field strength and the narrowing depletion depth which eventually becomes less than the alpha particle range. The decrease of the collection efficiency as a function of 1.00 MeV proton fluence for three bias voltages is shown in Figure 10.

Rear Entry

The noise produced by damage effects of 200 keV and 800 keV protons incident on the rear, aluminum contact of these detectors was lower, by a factor of 10^3 to 10^4, than when protons of the same energies were incident on the front, gold contact. This vast difference is shown in Figure 11. The data was recorded with each detector biased at 50 volts, its maximum bias rating. Capacitance measurements indicated that nearly total depletion of the detectors occured at the maximum fluences studied for each detector exposed to rear entry.

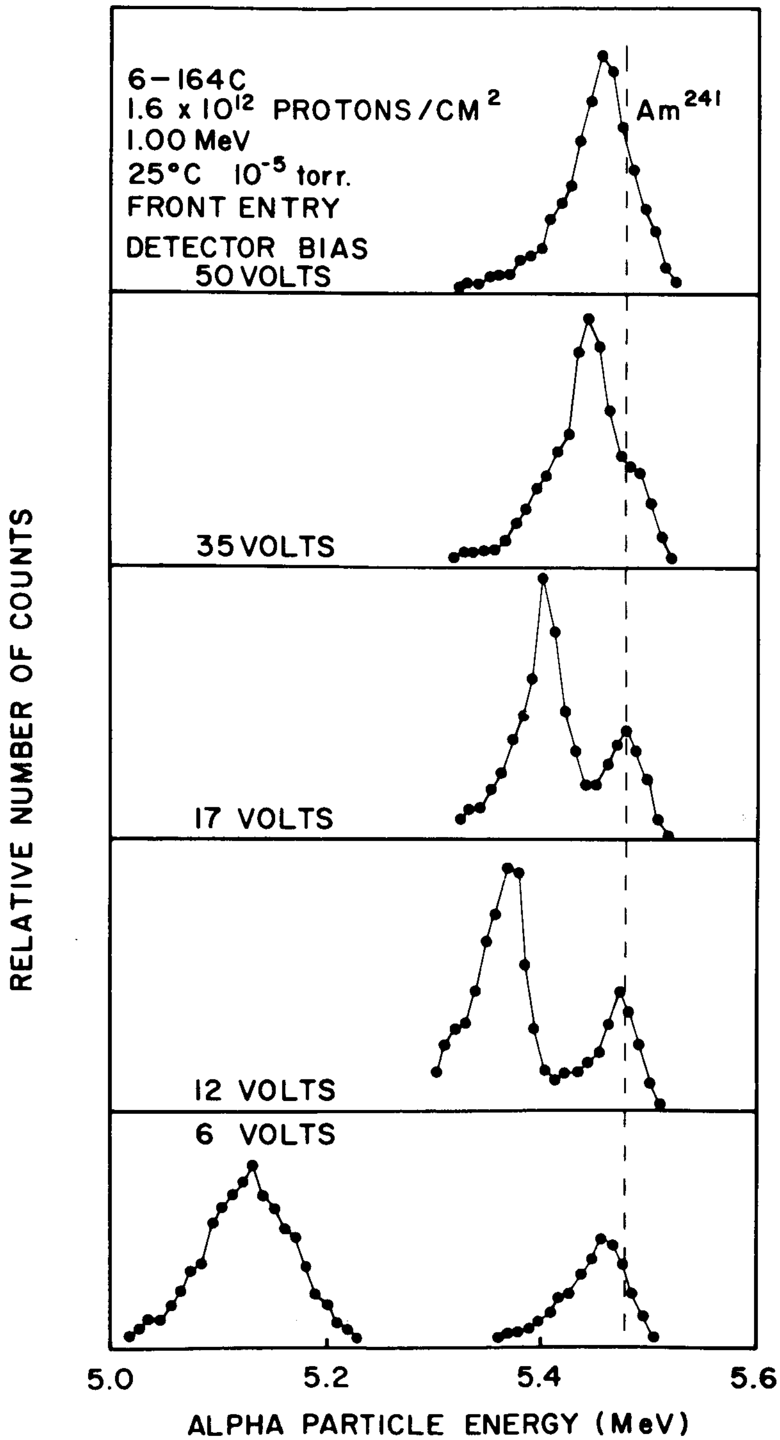

Figure 8—Am-241 alpha particle spectrum at several detector biases measured after irradiation with 1.6×10^{12} 1.00 MeV protons/cm^2.

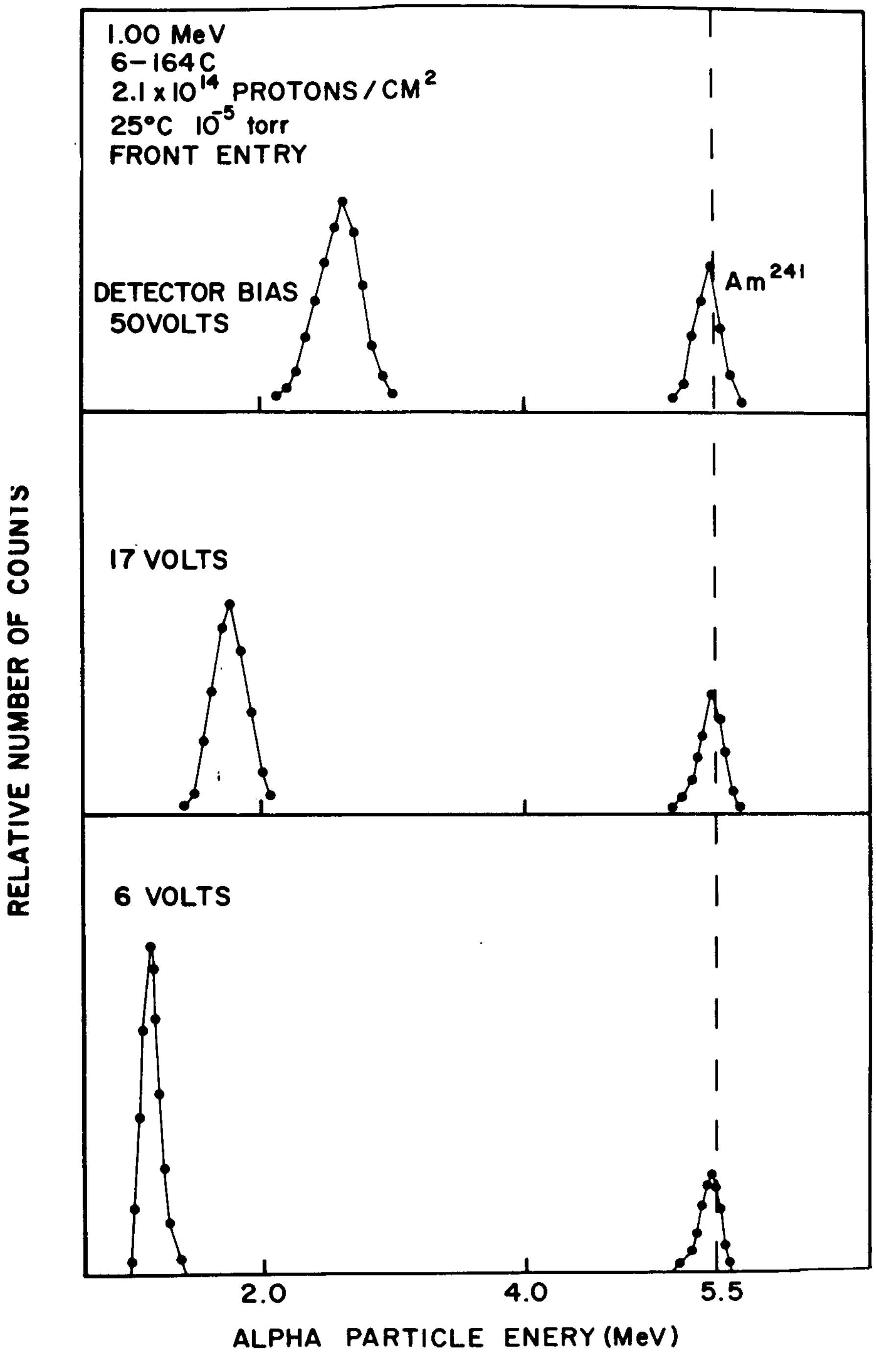

Figure 9—Am-241 alpha particle spectrum at several detector biases measured after irradiation with 2.0×10^{14} 1.0 MeV protons/cm^2.

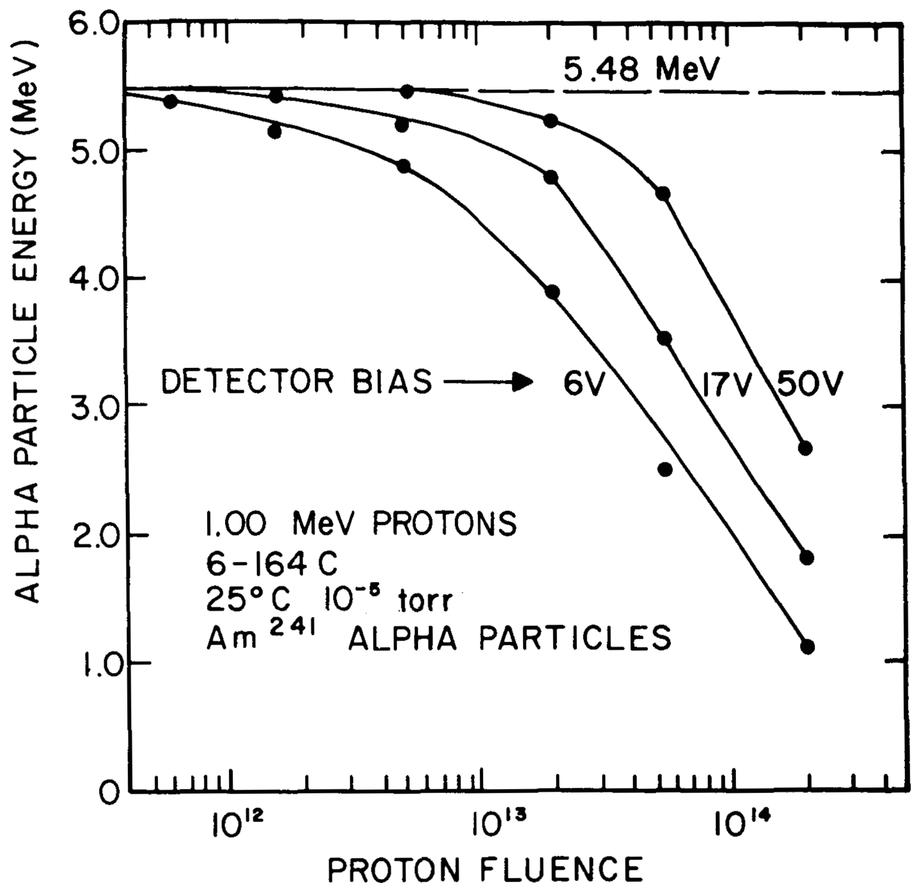

Figure 10—Observed energy (collection efficiency) for Am-241 alpha particles as a function of proton fluence measured at three different detector bias voltages after irradiation with 1.00 MeV protons.

These results are understandable, in part, if the assumption made earlier is valid, that protons with these energies create predominantly defect sites which act as donors. Protons with energies of 200 keV and 800 keV have ranges which are less than 10 percent of the thickness of the 100 μm detectors. The damage which they produce is very close to the contact through which they entered. Damage sites created near the gold, surface-barrier contact are immediately "exposed" and are located in the high-field region of the junction when any bias is applied. However, this is not the case for damage sites near the rear, aluminum contact. If the damage sites behave as donor-type states, then the thin damaged layer under the aluminum contact acts simply as an ohmic contact. As the bias voltage is applied to the detector, the undamaged silicon is depleted from the gold surface-barrier contact through the wafer to the thin damaged layer at the rear, aluminum contact. It appears that even at 50 volts bias, more than 50 percent above the bias necessary for total depletion of the detectors, very few of the

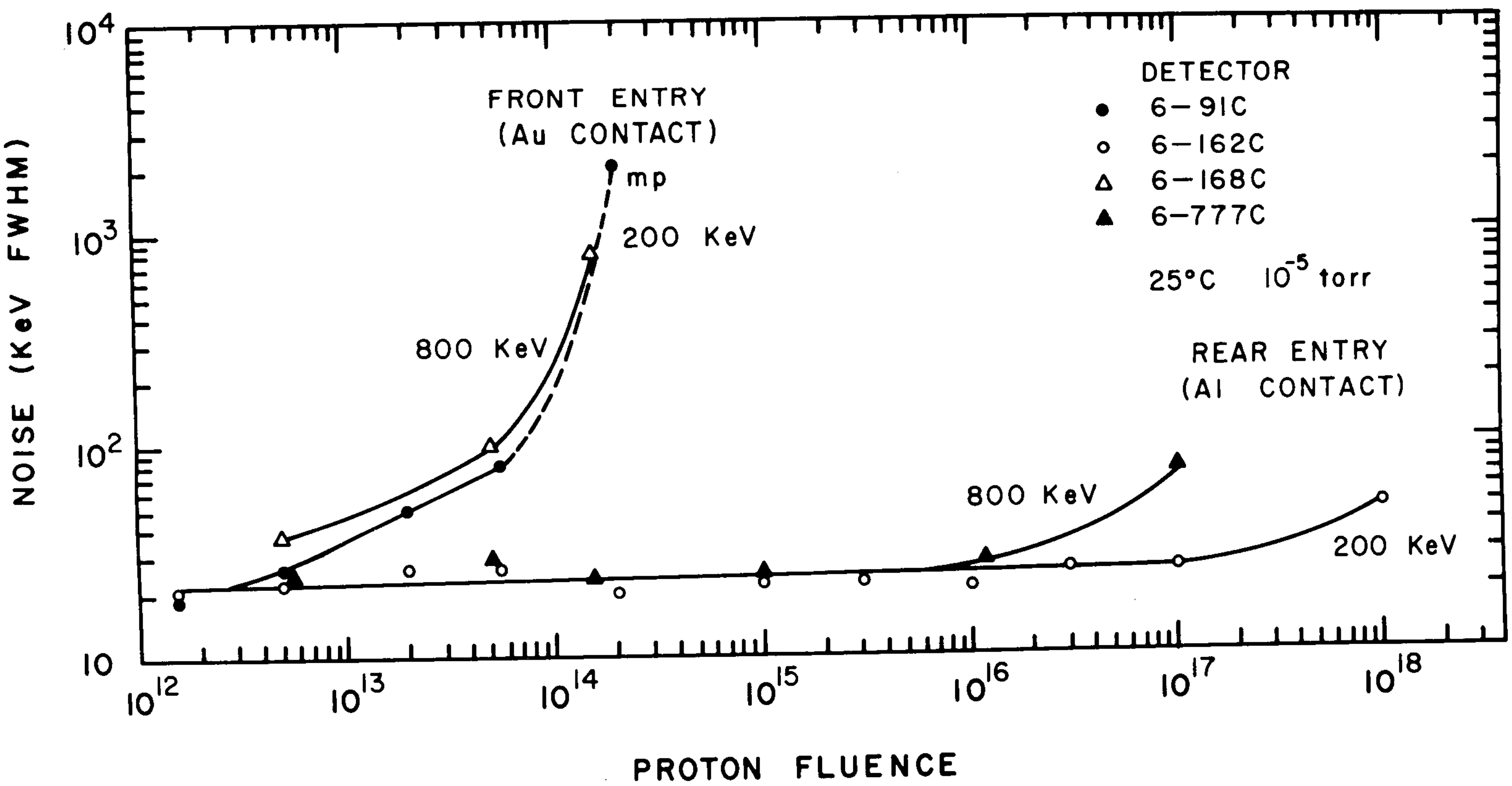

Figure 11–A comparison of the total system noise as a function of fluence for the front (gold) entry and rear (aluminum) entry measured after irradiation with 200 keV and 800 keV protons.

damaged sites are "uncovered" and exist in the depletion region. Therefore, the only detrimental effect of damage by short range protons to the rear, aluminum contact of surface-barrier transmission detectors is the production of a thin dead-layer with a thickness which is approximately the same as the range of the protons.

DISCUSSION

Previous Studies

Damage effects by heavy, charged particles in semiconductor materials has not been a popular field for study in the last twenty years. However, an abundance of data exists on the effects of damage in silicon and germanium by more penetrating radiations such as electrons, gamma rays and neutrons. Damage effects by these penetrating radiations tends to be more uniform throughout the bulk of the samples, and the interpretation of the measurements in terms of a model is simplified in contrast to the damage by heavy, charged particles in which the distribution of the defects is highly dependent on the particle type, mass, and energy. Characteristic of charged particle damage is the relatively low density of defects produced at the beginning of the particle range with respect to the defect density at the end of the range. Also of importance is the charge state of the defect which is eventually formed at various points along the particle track. Because of the gross end-of-range damage, the interaction of adjacent defects and the type and charge state of the defect complexes are important considerations. The production of defects in silicon by alpha particles and protons has been considered by Dearnaley[6] in terms of the defect density as a function of particle energy using certain simplifying assumptions.

With surface-barrier detectors similar to the ones used in these experiments (1000 ohm-cm n-type silicon), Dearnaley[6] studied the effects of damage on the detector performance using 5.48 MeV Am-241 alpha particles. After irradiations of 10^8 to 10^9 alpha particles/cm^2, the leakage current and alpha particle energy resolution began to increase significantly. Between 10^9 and 10^{10} alpha particles/cm^2, multiple peaks were observed. The equivalent energy of the peak positions and the peak energy resolutions were improved with higher detector bias voltages. In another experiment using similar detectors and a flux of protons, deuterons and alpha particles with energies extending up to 20 MeV, the detector depletion depth was found to increase significantly and reasonably good charge collection was maintained. Presumably the net positive space charge in the depletion region of the n-type silicon was decreased by neutral defects trapping conduction band electrons or by charge compensation.

The effects of 8.2 MeV, 11 MeV and 31 MeV protons on silicon n^+-p diffused-junction detectors have been studied by Scott.[7] The p-type silicon which Scott used had a resistivity range of 5000-12000 ohm-cm. In his case, the damaging protons passed through the depletion regions of the detectors, and the intense end-of-range damage was not located in the depletion, or high field region. Only defects caused by higher energy protons were observed in Scott's investigation.

After damage by 10^{12} protons/cm^2, Scott observed an increase in detector reverse current and noise, a decrease in the charge collection efficiency, especially at lower voltages, and a decrease in the diode capacitance. The capacitance decrease was largest for the 8.2 MeV protons. This latter result agrees with the work of others which shows that the damage rate for protons in silicon is inversely proportional to the proton energy.[8] Scott interpreted his observations in terms of the introduction of donor-type defects as a result of proton damage in the depletion region. It seems reasonable also to interpret the decrease in net negative space charge with damage as the trapping of holes by neutral defects.

Many studies of proton damage to silicon solar cells have been carried out because of the intense proton fluxes in the earth radiation belts through which the solar panels of many satellites must pass.[9] The chief goal of most of these studies has been to obtain an empirical relationship for the loss of power output by the cells as a function of proton flux. The relevance of solar cell work to this study is difficult to assess, chiefly because the silicon used in solar cells is usually much less pure than that used for particle detectors (1-10 ohm-cm versus 10^3-10^4 ohm-cm assuming minor impurity compensation). In addition, most solar cells studied are now made from p-type silicon whereas the detectors studied here were made from n-type silicon. The type of electrically active defects formed often depends on the type and concentration of impurities with which the damaged sites can interact.

Current Study

The current, noise, and collection efficiency results herein reported agree in general with the observations of Dearnaley and Scott. However, there is some disagreement in the capacitance and depletion depth measurements. The results of Dearnaley indicate a decrease in the net space charge density of high resistivity n-type silicon as a result of damage by protons with energies greater than several MeV. This study suggests that the net space charge density increases in high resistivity n-type silicon as a result of damage by low energy protons.

The effects of damage to the surface of the detectors by these low energy protons has not been considered because the changes in current, noise, capacitance and counting response after damage appear to be dominated by defect production in bulk silicon along the particle track. However, surface damage may play a larger role for the damage by lower energy protons which stop within a few microns of the detector surface. Small deviations in the data do exist for the lower energy irradiations, but the analysis has not been carried out.

Implications for Experimenters

Low energy protons which produce defects in the depletion, or high field, region of biased surface-barrier detectors cause the rapid degradation of detector performance beginning at fluences of 10^{12} - 10^{13} protons/cm^2. In general, at fluences larger than 10^{12}, the current and noise increase in proportion to the fluence and the square root of the fluence, respectively; the diode capacitance increases with fluence and the relative value depends on the proton energy and the detector reverse bias, with the capacitance being largest for the lower energies at small detector biases. In addition to increasing the noise level, an increase in the detector current for a fixed bias-supply voltage reduces the voltage applied to the detector as more of the bias voltage is dropped across the load resistor. This means that the field in the detector is lowered and, perhaps, the depletion depth is reduced and the capacitance is increased. These effects can cause a lower collection efficiency and a degradation in energy resolution. The gain of the amplifier system can also be reduced by a large increase in the detector capacitance.

In consideration of these effects of radiation damage, it is most desirable to operate semiconductor particle detectors which may experience radiation damage at sufficiently high bias voltages to insure that, for the particles of interest, the detectors have adequate depletion depths with high enough fields for the efficient stopping and subsequent collection of charge throughout the required lifetime of the experiment. Thus, the use of transmission detectors is often desirable in many space applications since the required depletion depth can be the physical thickness of the detector and over-biasing the detector can insure some latitude in terms of high field strength and full depletion depth in the face of eventual radiation damage effects. However, high bias voltage may be detrimental at the higher fluences. In the detectors studied, microplasma formation was usually observed for detector biases above 30 - 50 volts at fluences greater than 10^{14} protons/cm^2; a lowering of the detector bias significantly reduced the noise level.

If it is desirable to detect higher energy particles in the presence of a high flux of low-energy protons, for example in a dE/dx - E system, reversal of the Au - n - Si detectors so that the rear, aluminum contact is the entrance window can be very beneficial. In this arrangement, the low-energy protons will cause an effective window to be formed near the entrance surface, but the detector will operate with low noise and nearly a full depletion depth for fluences several orders of magnitude more than if the gold, surface-barrier contact was used as the front entrance window. These considerations do not hold if the particle of interest has a range which is nearly the same or less than the range of the protons causing the damage.

In light of these many effects of radiation damage, the experimenter whose detectors are required to operate in a high-flux radiation field must make a critical choice of the type of detector used, the geometry of the detector and collimators and the static electrical operation of the detector throughout the lifetime of the experiment.

Table 1

Proton Range - Energy Relationship in Silicon

Energy (keV)	Range (μm)
50	~ 0.6
200	2.3
600	8.6
1000	17.4
2000	48.5
3000	92.7

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