Introduction to Charged-Particle Detectors

Silicon Charged-Particle Detector Manufacturing

Table 1	
Atomic density, atoms/cm^3	4.96 X 10^{22}
Mass density, g/cm^3	2.33
Dielectric coefficient	12
Energy gap, eV	1.115
Average energy per electron-hole pair, eV/pair	3.62 at 300 K 3.76 at 80 K
Mobility, cm^2 • V^{-1} • s^{-1}	
Electron	1350 (2.1 X 10^9 $T^{-2.5}$)
Hole	480 (2.3 X 10^9 $T^{-2.7}$)

Table 1 summarizes the major physical properties of silicon. To produce silicon charged-particle detectors, ORTEC employs both ion-implantation and surface-barrier technologies. The two processes are complementary in that each technique is best for manufacturing certain types of detectors. Fig. 1 (A and B) shows simplified representations of the two manufacturing processes.

There are several advantages to using ion implantation:

(a) A thinner and more rugged front contact; better energy resolution for some alpha spectroscopy applications

(b) Lower electronic noise

(c) Higher geometric efficiency for some alpha spectroscopy applications

(d) Operation to 60°C and bakeout at 200°C.

The advantage of surface barrier technology is that it allows production of transmission detectors as thin as 10 µm or as thick as several mm (see Selection Chart).

Depletion Depth and Capacitance

Silicon detectors are reverse-biased diodes with parallel, planar electrodes and therefore have the capacitance of the corresponding parallel-plate capacitor. The electric field in the detector, however, is not constant but decreases linearly from the contact at which the p-n junction is made to the end of the depletion region (Fig. 2).

The nomograph in Fig. 3 shows the depth **W** of the depletion region as a function of the bias voltage applied to the detector and the resistivity of the silicon material. For a given value of bias, the depletion depth increases with increasing resistivity, and correspondingly, the slope of the electric field in Fig. 2 decreases with increasing material resistivity, that is, as the silicon material behaves more and more like an insulator. If, as shown in Fig. 2, **L** is the overall thickness of the silicon slice, the detector is totally depleted when **W = L**.

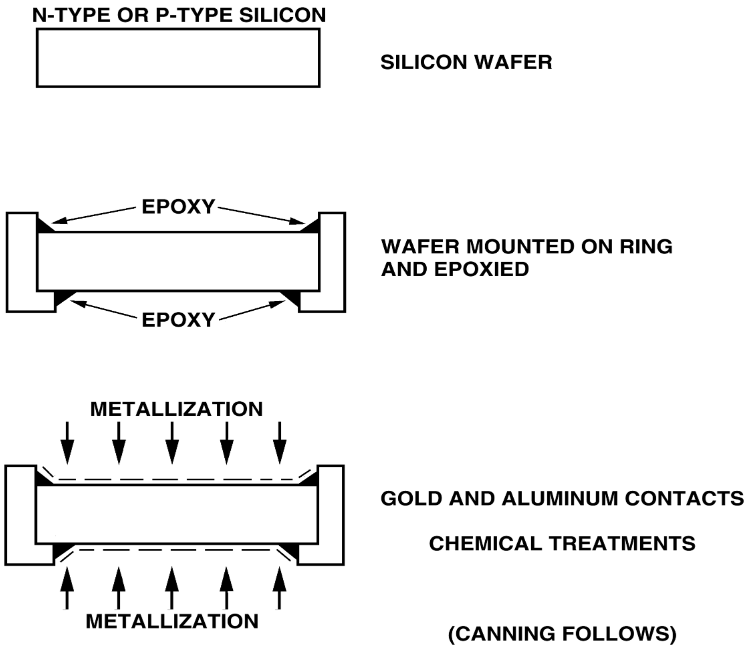


Fig. 1(A). Simplified Diagram of Surface Barrier Si Detector Manufacturing.

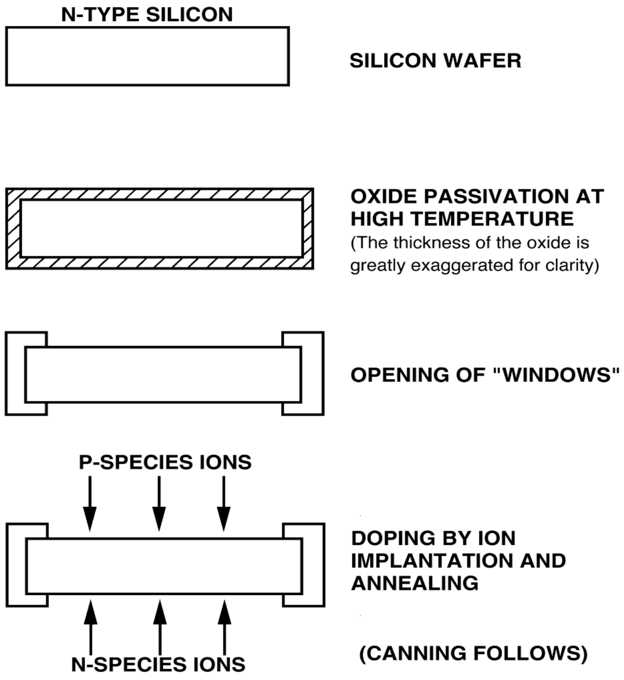


Fig. 1(B). Simplified Diagram of Ion-Implanted Si Detector Manufacturing.

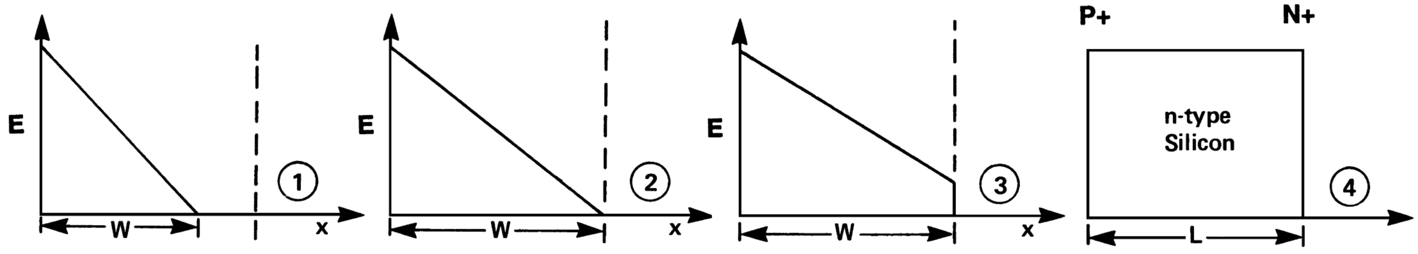


Fig. 2. Representation of Electric Field E in Silicon Surface Barrier Detectors.

The nomograph of Fig. 3 also shows the "specific capacitance" (capacitance per unit area) of silicon detectors for any given value of **W**. A detector's capacitance can be read directly from this nomograph once the active area has been determined.

The value of the capacitance is of interest because the effective electronic noise of preamplifiers used with silicon detectors increases with increasing capacitance values (Fig. 4). The electronic noise increase per unit capacitance increase is called the preamplifier's "slope."

Leakage Current

A silicon detector, just like any reverse-biased silicon diode, has a temperature dependent leakage current. At room temperature, ion-implanted detectors, such as the ULTRA Series, have a leakage current in the range of {D/100} X {~1–10 nA/cm^2 active area}, where D is the depletion thickness in microns; surface barrier detectors, on the other hand, have leakage current an order of magnitude higher, in the range of {D/100} X {~20 to 100 nA/cm^2}. As shown in Fig. 5, the leakage current is a strong function of the detector temperature and detector type.

The value of the leakage current is of interest, because, as shown in Fig. 5, the electronic noise increases with increasing leakage current.

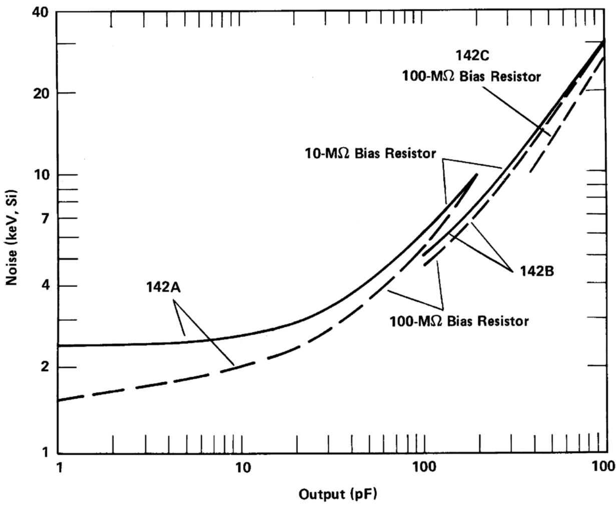


Fig. 4. Typical Noise Data for Model 142 Preamplifiers.
(Using ORTEC Shaping Amplifier with 0.5-µs shaping time constant.)

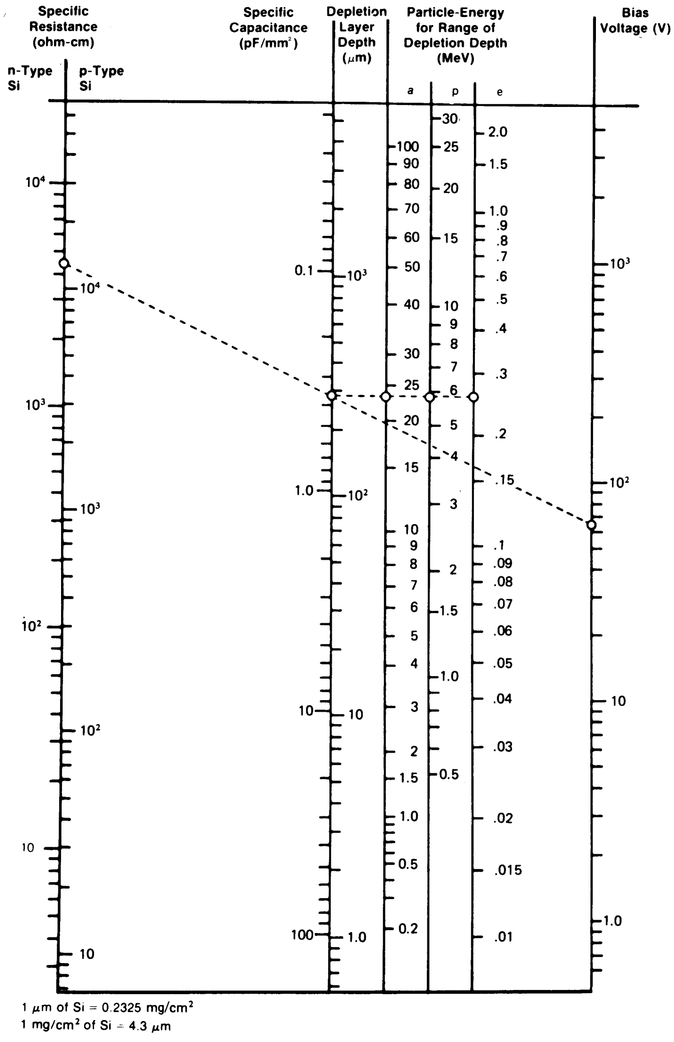


Fig. 3. Silicon Detector Parameters Nomograph. [Similar to Nomogram reported by J. L. Blankenship, *IEEE Trans. Nucl. Sci.* **NS7** (2–3), 190–195 (1960).]

A straight edge intersecting the center vertical line at the required depletion depth will give combinations of resistivity and detector bias that may be used to achieve that depth. (Shown, for example, is the voltage that must be applied to a 13,000 Ω-cm p-type or 4500 Ω-cm n-type silicon detector to stop a 23-MeV alpha, a 6-MeV proton, or a 250-keV electron within the depletion depth.)

Energy Resolution and Noise

A typical nuclear electronic chain is shown in Fig. 6.

The warranted energy resolution is measured in keV FWHM using a thin-window, 5.486-MeV ^{241}Am alpha particle point source placed at a distance from the detector equal to at least twice the detector diameter. The time constant in the main amplifier is also indicated: ORTEC uses 0.5 µsec pulse width at half the maximum pulse height for surface barrier detectors and 1 µsec for ULTRA detectors. The electronic noise of the detector is measured with the chain of Fig. 6, with an electronic pulser replacing the alpha source. This noise has historically been referred to as the "Beta resolution" because when the detector is used with very low specific ionization particles such as conversion electrons (Fig. 7), the energy resolution is approximately equal to the noise. The energy resolution, measured as described above, depends on a number of factors; the most important are:

a) Electronic noise due to the detector leakage current and capacitance. This noise component can be minimized by choice of preamplifier and by optimum amplifier time constant selection. The time constant is preset at its optimum value in all ORTEC alpha spectrometers.

b) Electronic noise due to the bias resistor. This noise component increases with decreasing values of the bias resistor. Typically, the value of the bias resistor is sufficiently high to make this component negligible. However, at elevated detector temperatures, it may become necessary to decrease the value of the bias resistor, with a concomitant noise increase.

c) Energy loss and straggling in the detector entrance window. This factor is important when striving for high geometrical efficiency with the alpha source positioned as close as possible to the detector entrance contact. In this situation, alpha particles emitted perpendicular to the detector front contact pass through the entrance dead layer specified in the following summary table and, therefore, undergo the minimum energy loss; alpha particles that enter the front contact at an angle pass through a thicker dead layer, thereby losing more energy in the contact. The energy resolution is thus degraded.

Effects of Operating Temperature on Noise and Energy Resolution

ULTRA ion-implanted detectors, used primarily for alpha spectroscopy, are generally operated at room temperature. When optimum resolution is required, it is useful to reduce the detector noise by operation at low temperature. This is best accomplished by using surface barrier detectors instead of ULTRA detectors. The noise and energy resolution of surface barrier detectors can be substantially decreased by operating below room temperature, down to approximately –60°C. Below that temperature no further improvement is obtained because, with the leakage now ≈pA, the noise is dominated by the preamplifier noise and the detector capacitance, the latter, of course, not being a function of temperature. Figs. 8 and 9 show typical electronic noise and energy resolution measurements obtained with surface barrier detectors.

With ion-implanted ULTRA detectors, the noise is substantially lower at all temperatures, making them a clear choice at higher temperatures. The energy resolution **increase** that can be expected with ULTRAs at elevated temperature is approximately 15–20 keV FWHM at 60°C.

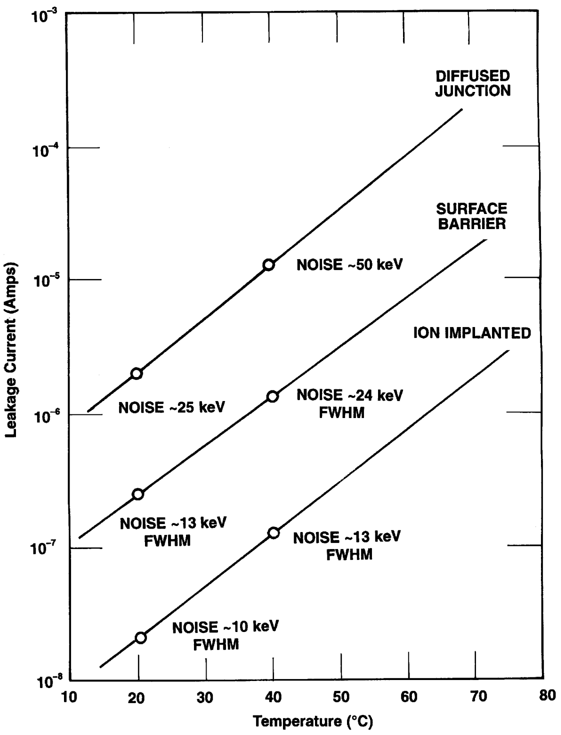


Fig. 5. Leakage Current and Noise vs. Temperature for 3 Types of Si Charged-Particle Detectors.

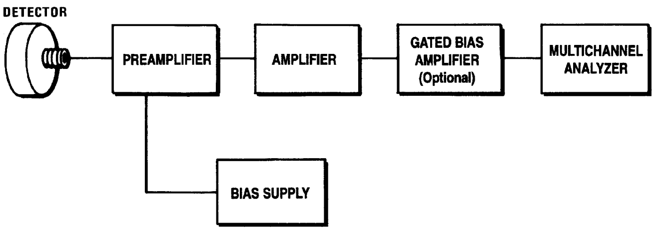
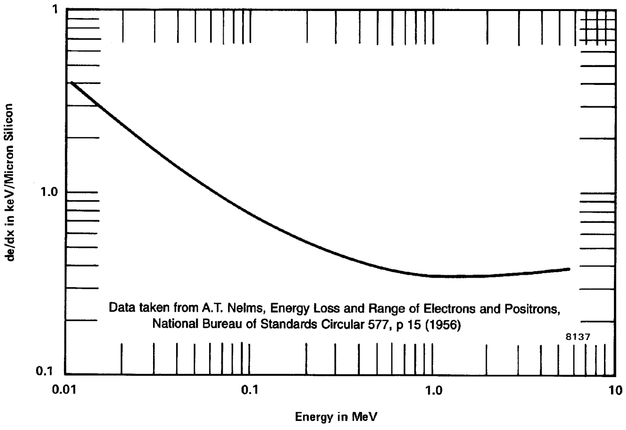


Fig. 6. Typical System for Charged-Particle Spectroscopy.



Data taken from A.T. Nelms, Energy Loss and Range of Electrons and Positrons, National Bureau of Standards Circular 577, p 15 (1956)

Fig. 7. Specific Energy Loss for Electrons in Silicon.

NOTE: Channeling of ions between crystal planes can result in significant variations from the data shown here.

Selecting the Appropriate Si Detector for Your Application

Alpha Spectroscopy

The detectors of choice for alpha spectroscopy are ULTRAs with a depletion depth of ≥100 microns and ULTRA-AS detectors for ultra-low background applications. Many established installations are equipped with reliable Ruggedized (R-Series) Surface Barrier Detectors. As these require negative bias, the U Series are not a direct replacement in alpha spectrometer units. (All other ORTEC charged-particle detectors require positive bias.)

The reasons why the ULTRA and ULTRA-AS lines are widely used in alpha spectroscopy are the following:

- Alpha spectroscopists with low activity samples often position samples as close as possible to the front detector contact. As noted above, the thin (500 Å silicon equivalent) window results in optimal energy resolution.
- The front contact is cleanable. (This is also true of R-Series Surface Barrier Detectors, but not of other surface barrier detectors.)
- The type of edge passivation used with ULTRA Series Detectors permits positioning the sample as close as 1 mm from the detector entrance contact; the minimum distance with surface barrier detectors is 2.5 mm. As, in many cases, the efficiency of the detector depends strictly on geometrical factors, ULTRA detectors provide higher efficiency than surface barrier detectors.
- The low leakage current results in low noise, also contributing to good energy resolution.

An issue of particular importance in alpha spectroscopy is the need to perform **low-background** measurements. As health physics regulations become more stringent, it is becoming increasingly important to be able to analyze samples with extremely low activity. Measurements performed at ORTEC have confirmed that the ultimate limit to the low- background performance of silicon detectors, when manufactured and packaged with special materials and following strict cleaning procedures, is associated with the omnipresent **cosmic radiation**. This limit in the energy range from 3–8 MeV is 0.05 counts/hr/10^{-2} cc of active volume. This means that for a 450 mm^2 active area, 100-µm thick, low- background ULTRA-AS (AS denotes low background), a background counting rate of about 6 counts/day is expected. **To achieve such a low level, one must take exquisite care both concerning previous or present vacuum chamber contamination and in detector handling procedures.**

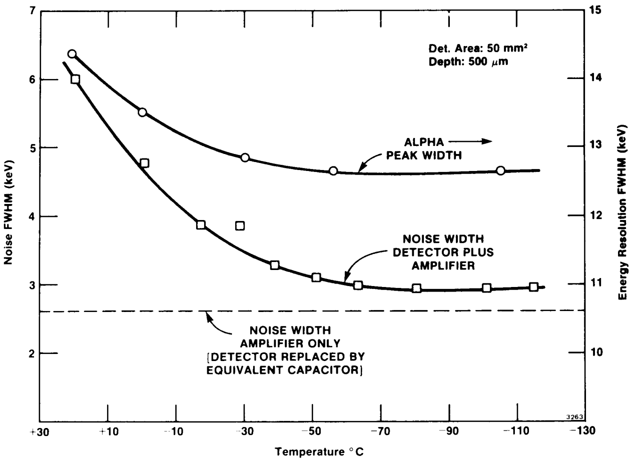


Fig. 8. Detector Noise and Alpha Energy Resolution as a Function of Temperature.

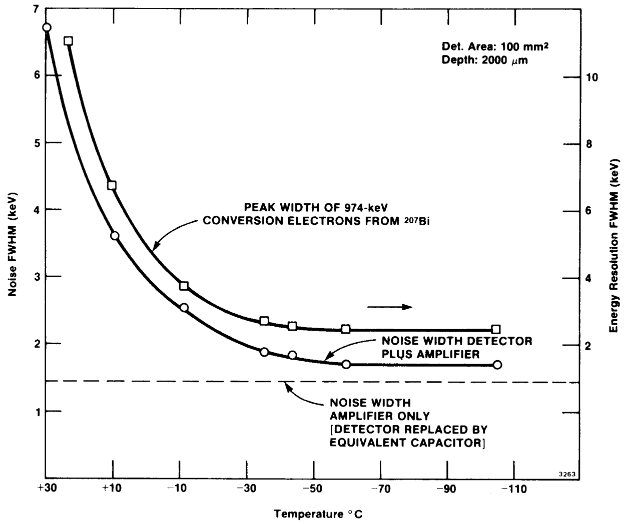


Fig. 9. Detector Noise and Electron Energy Resolution as a Function of Temperature.

To minimize cosmic ray interactions, ULTRA-AS series are made as thin as possible, consistent with achieving good resolution. As natural alpha particles have a range not exceeding 30 microns in silicon, it would seem that a depletion depth not exceeding 30 microns should be sufficient. It would be were it not for the fact that such a high-capacitance detector would display excessive noise. A depletion depth close to 100 microns provides the best tradeoff.

Some alpha spectroscopists employ an alpha recoil avoidance package to reduce the tendency for a gradual increase of background contamination on the detector surface. Information on this package is contained in the description of the ORTEC RCAP-2 system.

For rough spectroscopy and for simple counting applications (as in continuous air monitors), ORTEC offers the ruggedized ULTRA CAM line. ULTRA CAM detectors are light tight and moisture resistant.

Beta Spectroscopy and Counting

A key concern when selecting a silicon detector for room temperature beta spectroscopy or counting is the generation of a sufficiently large signal to well exceed the detector beta resolution. For example, 1 MeV electrons, which are minimum ionizing particles, deposit only 0.4 keV/micron of silicon (Fig. 7). The average energy loss in a 100-µm thick detector is 40 keV. As the threshold of the discriminator must be set 2.5 times above the beta resolution (noise), the beta resolution of the detector must be well below 15 keV FWHM to obtain meaningful data.

High quality beta spectroscopy cannot be obtained with room temperature silicon detectors. ORTEC offers A Series, thick, coolable silicon detectors.

Nuclear and Atomic Physics

The selection of appropriate detectors for nuclear and atomic physics is experiment dependent. Here are responses to frequently asked questions on this subject:

Q. Which detectors should be used for heavy-ion spectroscopy?

Because of the short, highly-ionized track of heavy ions, detectors with high electric field at the front contact (Fig. 2) are best. The F-Series Detectors have a warranted minimum electric field of 20,000 V/cm at the front contact.

Q. Which detectors and what techniques should be applied for low-energy ion and charged-particle spectroscopy?

For ions or particles in the energy range from 0 to 50 keV, one should cool both the detector and the first stage of the preamplifier. See "Detection Of Low Energy Heavy Particles With Silicon Barrier Detectors" by J.A. Ray and C.F. Barnett, IEEE Trans on Nuc. Sci. Vol NS-16, N1 (1969), pp. 82–86. An example of the results given in this paper is the spectrum shown in Fig. 10.

Q. Which detectors and what techniques should be applied for fast timing?

A silicon detector used for fast timing must have a high and uniform electric field throughout the depletion depth. Totally depleted detectors, such as an ULTRA or a high field partially depleted detector, capable of withstanding overbias should be used (Fig. 2). With particles in the MeV range and above, subnanosecond FWHM timing values are achievable (Ref: T.J. Paulus, et. al., IEEE NS-24, N1-1977).

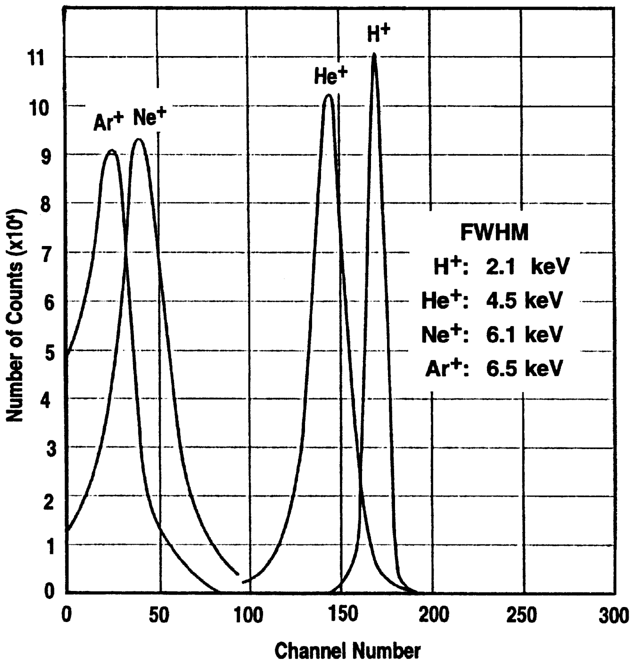


Fig. 10. The Pulse Height Spectrum of 40 keV H^+, He^+, Ne^+, and Ar^+ Ions from a 7 mm^2 Detector (700 Mm Depletion Depth, 20 k□-cm Resistivity).

Radiation Damage

Table 2 shows threshold doses for radiation damage with different types of charged particles.

The symptoms of radiation damage are: higher leakage current/noise followed by peak broadening and, sometimes, double peaking. In order to prolong the usable "life" of a detector in a radiation field causing damage, the detector must be kept cold (any cooling below room temperature helps; ideally the detector should be cooled to –60°C).

Table 2. Effects of Radiation Damage in Silicon Detectors.

Threshold Doses (particles/cm^2)				
Electrons	Fast Neutrons	Protons	Alpha Particles	Fission Fragments
10^{13}	10^{12}	10^{10}	10^{9}	10^{8}

Parameters Affecting Performance Characteristics

Many parameters affect the performance of silicon charged-particle detectors. A description of the major parameters follows.

Area

The sensitive area is important because it affects both efficiency and energy resolution. When a low-intensity radiation source is used or when an accurate particle count is required (within the count-rate limits of the system), a large-area detector is desirable. However, since detector capacitance and electronic noise are proportional to the area, smaller detectors give much better resolution. Selecting the right detector size requires a compromise between efficiency and resolution.

Sensitive Depth

For energy spectrometry each output pulse must be generated with an amplitude proportional to the energy of the charged particle. Therefore, for these common applications the detector's sensitive depth must be sufficient to completely absorb all the particle energy (Fig. 3). As the sensitive depth increases, the detector capacitance C_D decreases, and this results in a decrease in preamplifier noise. However, the increase in sensitive depth also increases the sensitive volume of the detector, and this may increase the detector leakage-current-noise contribution. Minimum total system noise is obtained by matching the capacitance of the detector to the appropriate preamplifier.

In applications involving spectrometry of heavy charged particles, rather large electric fields are required to ensure complete charge collection and to ensure linearity and optimum resolution. Consequently, for heavy-ion or fission-fragment spectrometry the maximum sensitive depth is established by the need for large electric fields.

For high-resolution timing applications, in which the rise time of the information pulse must be very short, the charge transit distances have to be kept as small as possible and large electric fields maintained. In such cases, the sensitive depth may be restricted by the need for very precise timing information and occasionally by the need to discriminate against unwanted background.

Introduction to Charged-Particle Detectors

Capacitance

The major effects of detector capacitance are its influence on the noise contribution from the preamplifier and its deterioration of the preamplifier rise time. In applications that require low total noise, it is necessary to minimize the capacitance C_D by restricting the active area and/or by optimizing the sensitive depth. Stray capacitance from cables, connectors, etc., must be added to the detector capacitance to establish the total capacitive load that determines the preamplifier contribution to the noise, and therefore must be minimized.

Electric-Field Strength

The minimum electric-field strength required for complete charge collection (i.e., optimum resolution and response linearity) depends on the mass (specific ionization density) of the charged particle being analyzed, with the more massive particles requiring higher field strengths. For charged particles (alpha particles or lighter), this minimum field is attained by meeting the required resolution specifications. For heavy-ion (fission-fragment) detectors, however, and for very thin totally depleted detectors, in which the resolution cannot be routinely tested, the minimum specified electric-field strength has been established by experimental data obtained during actual use in the field. In applications requiring very high-resolution timing, it is desirable to keep the average field strength as large as possible, consistent with optimum noise and sensitive depth.

Breakdown Voltage

For a given resistivity material the breakdown voltage of the diode establishes an upper limit on the electric-field strength and on the depletion depth. ORTEC does not use breakdown voltage as a basic specification, because it is redundant if the sensitive depth, noise, resolution, and/or field strength are specified.

Reverse-Leakage Current

A large reverse-leakage current results in detector noise and excessive voltage drop across the bias supply resistor (R_b).* Since a quantitative relation between the detector leakage current and noise can be established only through a detailed knowledge of the origins of all current components, detector noise performance has been selected by ORTEC as the basic performance specification. Detectors whose leakage currents would produce excessive voltage drops across R_b are rejected by our quality-control standards. All ORTEC detectors are furnished with detailed data on their original leakage current so that this information may be used for troubleshooting and for estimates of the drop anticipated across R_b.

Silicon detectors made with ion-implantation and silicon-dioxide-passivated technologies have leakage current values substantially lower than surface barrier detectors of the same geometrical dimensions.

Detector Noise

Noise sources in the detector and the preamplifier introduce a dispersion that broadens a pulse-height spectrum of mono-energetic particles. Noise is customarily specified in terms of FWHM (full width half maximum) broadening of a mono-energetic peak. The detector and the preamplifier are separate and independent sources of noise, and the total system noise is equal to the square root of the sum of the squares of the individual noise contributions. Noise specifications for ORTEC detectors include the total noise width for the detector and standard ORTEC electronics at a temperature of 21 ±1°C. These noise widths and actual resolutions therefore can be guaranteed only when the contribution from any other electronics does not exceed that from the appropriate ORTEC electronics.

Energy Resolution

The noise-broadening effect previously mentioned establishes a lower limit on the energy resolution (FWHM) of any given detector-preamplifier combination. However, factors such as statistical effects, imperfect charge collection, and variations in energy lost in the dead layer of the source and of the detector can cause additional broadening of the peak; their relative contribution is a strong function of the mass of the incident particle. For beta particles, the resolution is nearly always determined solely by the electronic noise broadening. For alpha particles, the ultimate resolution (with no significant contribution from noise) appears to be less than 10 keV. For very heavy ions such as ^{127}I, the typical resolution for nonchanneled particles is about 1 MeV.

Pulse Rise Time

The pulse rise time associated with any ionizing event is a complex function of the mass, energy, range, and orientation of the ionizing particle; the detector parameters (depletion depth, electric-field strength, diode series resistance, and sensitive area); and the characteristics of the associated electronics. Pulse rise times for typical ORTEC charged-particle detectors range from the order of one nanosecond to tens of nanoseconds. The charge collection time in silicon detectors at room temperature is ~100 ns/mm. In many experiments requiring nanosecond or subnanosecond time resolution, good energy resolution is also desired, usually resulting in a need for compromises in detector parameters. Consequently, this high-resolution-time requirement, together with all other relevant experimental information, should be specified at time of first inquiry.

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*Resistor, usually located in the preamplifier, has a value of 10 MΩ.

Stacked Detectors

For some applications, such as ($\Delta E/\Delta x$)(E) mass deter-minations and telescopic arrays, the energy range of the analyzed particles requires more depth than is provided by a single detector. Two or more detectors can then be combined so that the energy of the particle is totally absorbed in the detectors. The sum of the output pulses from the detectors will be proportional to the energy of the particle. For these applications the effective dead layer is the sum of the front and back dead layers (approximately equal to the electrode thickness) of all the detectors except the last one in the stack. For the last detector, only the front dead layer is considered. (Although all the detectors preceding the last one must be totally depleted, the last one need not be.) Quantitative, independent evaluation of this dead-layer thickness is supplied with each detector.

Parallel Connection of Two or More Detectors

In applications that require unusually large areas of sensitive depths, it is desirable to connect several detectors in parallel to the same preamplifier. In these circumstances, the total noise contribution to the energy resolution broadening can be determined by the following procedure:

The individual contributions of detector noise (total noise less preamplifier noise) are added by the mean-squares process:

$$N_{d,t}^2 = N_{d,1}^2 + N_{d,2}^2 + \cdots + N_{d,i}^2 \qquad (1)$$

where $N_{d,t}$ is the total noise contribution from the detectors and $N_{d,i}$ is the contribution of the ith detector.

The total capacitive load on the preamplifier is obtained by summing the detector capacitances and the stray capacitance:

$$\begin{aligned} C_t &= C_{d,i} + C_{d,2} + \cdots + C_s \\ &= C_s + \sum_i C_{d,i} \qquad (2) \end{aligned}$$

where C_t is the total load, $C_{d,i}$ is the capacitance of the ith detector, and C_s is the total stray capacitance, including that from cables, connectors, interconnections, etc. The value of C_t and the appropriate curve for preamplifier noise versus input capacitance are used to determine the preamplifier contribution to the noise. The total noise broadening is then obtained from

$$N_t^2 = N_{d,t}^2 + N_A^2 \qquad (3)$$

where N_t is the total noise width and N_A is the preamplifier's contribution to the noise.

Charged-Particle Detector Multiplexing

Often in low-level counting applications, multiple spectrometers are employed to keep up with large numbers of low-level samples to be counted. Because these are low- or ultra-low-level applications, count rates are extremely low. For this reason, it is possible to employ a multiplexed system, where a gated multiplexer-router is used to send pulses from multiple detectors to separate memory segments in an MCA system. This can lead to substantial cost savings. The more advanced of these systems provide for independent start, stop, and preset of the multiplexed inputs.

Thickness Uniformity

Inadequate thickness uniformity of totally depleted ΔE detectors has undoubtedly been responsible for many disappointing experiments. A 10-MeV ^{4}He particle incident on a 50-µm-thick silicon detector will lose approximately 5.9 MeV in traversing the detector. The rate of energy loss (dE/dx) of the exiting particle, however, will be about 160 keV/µm. This means that a detector thickness variation of 1 µm would cause an energy spread of 160 keV, which is many times greater than the detector resolution for particles that are completely absorbed in the detector. Considerations such as these show that precise control over the thickness uniformity of a device is highly desirable for many experiments. ORTEC uses an exclusive mechanical electrochemical wafer-polishing process that produces damage-free surfaces that are optically flat and parallel. By testing the wafers with optical interference techniques and by profiling the thickness of each wafer with an x-ray transmission technique, ORTEC ensures that each silicon wafer meets stringent thickness-uniformity specifications before being accepted as a planar totally depleted surface barrier detector (D Series). The measured mean detector thickness and uniformity are given on the Quality Assurance Data Sheet that accompanies each D Series detector.

Channeling and Crystal Orientation

The channeling of ions between crystal planes can produce significant differences in the rate of energy loss (and total range) between channeled and unchanneled ions. For very heavy ions this same effect can produce pronounced differences in the pulse-height linearity and energy resolution. Consequently, the silicon wafers for ORTEC totally-depleted and standard heavy-ion detectors are cut from the parent crystal at an angle that has been carefully selected to minimize channeling effects. Silicon charged-particle detectors that are cut at specific orientations are available on special order.

Test Data and General Information

Alpha Resolution

Alpha resolution is specified as the maximum peak width for a standard alpha source measured at one-half the peak height (FWHM) expressed in keV. The total system alpha resolution is measured and warranted for 5.486-MeV alphas from ^{241}Am with an ORTEC preamplifier chosen to be consistent with the detector capacitance and an ORTEC amplifier using equal differential and integral time constants as follows:

0.5 µs for A, B, C, F, and R Series;

1.0 µs for ULTRA, ULTRA-AS, and ULTRA CAM.

For totally depleted B Series detectors with ≤500-µm thicknesses, the alpha resolution is measured through the exit (low-field strength) contact, and >500-µm detectors measured with alpha particles through the front contact. The D and F Series are not warranted for alpha resolution but are warranted for system noise with suitable ORTEC electronics. Unless specified otherwise, resolution measurements are performed and warranted at 21 ±1°C.

Beta Resolution (System Noise)

The system noise width guaranteed maximum FWHM (which approximates beta resolution) is listed for each type of detector. Unless specified otherwise, measurements are performed and warranted at 21 ±1°C.

Electrons (beta particles) are, to a first approximation, sufficiently light to cause zero energy loss in the entrance window of silicon detectors. The beta energy resolution of silicon detectors is thus determined by the electronic noise of the detector and preamplifier; hence, the interchangeable "beta resolution/system noise" terminology.

Discriminator Threshold Setting

When silicon detectors are used as beta spectrometers, the threshold of the lower-level discriminator in the electronics must be set at 2.5 times the "beta resolution" to avoid spurious noise counts. Because the specific ionization of electrons is very low (e.g., 0.35 keV/µm for minimum ionizing betas), it is often necessary to cool silicon detectors used as beta spectrometers. (Detectors with cryogenic epoxy must be special-ordered.) When this is done, the electronic noise caused by the detector leakage current is eliminated and the detector becomes equivalent to a pure capacitor. The electronic noise of the system can then be easily calculated from the noise vs. capacitance characteristics of the preamplifier.

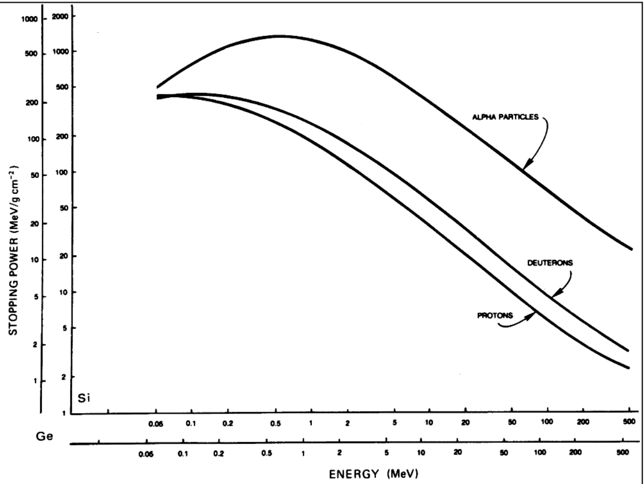

Fig. 11. Stopping Power vs. Energy for Photons, Deuterons and Alpha Particles in Si and Ge.

Heavy Charged Particles

Heavy charged particles lose energy by Coulomb interaction with the electrons and the nuclei of the absorbing materials. The collision of heavy charged particles with free and bound electrons results in the ionization or excitation of the absorbing atom, whereas the interaction with nuclei leads only to a Rutherford scattering between two types of nuclei. Thus the energy spent by the particle in electronic collisions results in the creation of electron-hole pairs, whereas the energy spent in nuclear collisions is lost to the detection process.

The concepts of specific ionization loss dE/dx and of range R can be used to summarize the interaction of heavy charged particles in semiconductor detectors when nuclear collisions are unimportant. The specific ionization loss measures the amount of energy lost by the particle per unit-length of its track; the range indicates how deeply the particle penetrates the absorbing material. Figure 11 shows the stopping power as a function of the energy, and Fig. 12 shows the range as a function of the energy in silicon and in germanium for alpha particles, protons, and deuterons.

Nuclear collisions can become an important part of the energy loss process, especially in the case of heavy ions and fission fragments. The theory describing this process is too complicated for a brief summary. We refer the reader to specialized literature such as the IEEE Transactions on Nuclear Science and the references footnoted here.[1, 2]

Finally, it should be mentioned that channeling effects (the steering of charged particles in open regions in the lattice) can reduce the specific ionization loss. Again, we refer the reader to the referenced literature for details on this particular phenomenon.[1, 2]

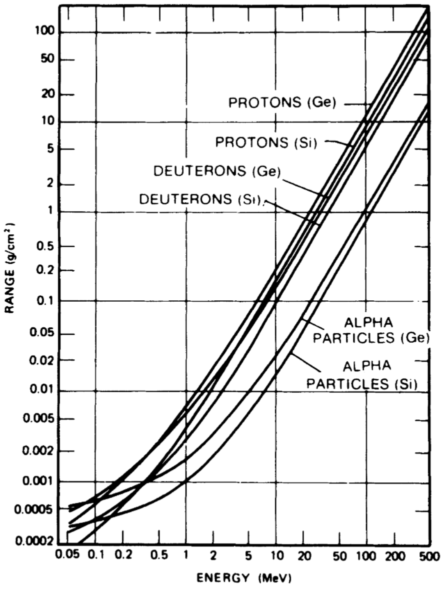

Fig. 12. Proton, Deuteron and Alpha Particle Ranges in Si and Ge.

Introduction to Charged-Particle Detectors

Electrons

The interaction of electrons with matter is similar to the interaction of heavy particles, with the following differences:

1. Nuclear collisions are not part of the interaction because of the very light electron mass.
2. At energies higher than a few MeV, radioactive processes (bremsstrahlung) must be considered in addition to the inelastic electron collision.
3. Again because of their light mass, electrons are so intensely scattered that their trajectory in the material is a jagged line; therefore, the concept of range as previously used cannot be applied. Rather, the concept of zero-transmission range is introduced. This is done by means of absorption experiments, which permit definition of the absorber thickness resulting in zero-electron transmission at a given energy. Figure 13 shows the zero-transmission range as a function of energy in silicon and germanium.

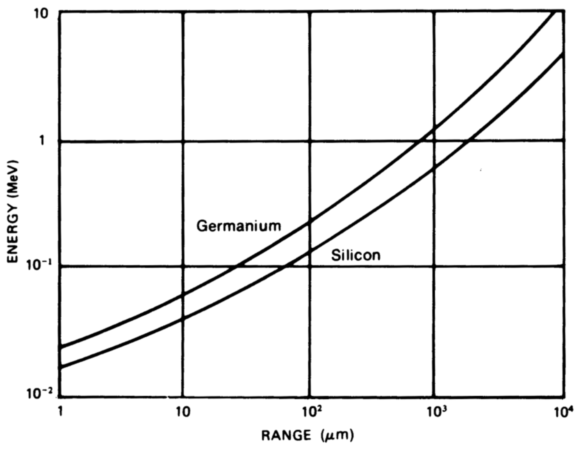

Fig. 13. Zero Transmission Range vs. Energy for Electrons in Si and Ge.

ORTEC Charged-Particle Detector Data Summary and Selection Chart

Series	Chief Application	Starting Material	Range of Active Area (mm²)	Range of Active Thickness (µm)	Warranted Operating Temperature Range*	Diode Structure	Nominal Structure** Stopping Power of Wndows	
							Entrance	Exit
ULTRA†	High-resolution, high-efficiency alpha and beta spectroscopy	Si	25–3000	100–500	+50°C to –30°C	Implanted Boron. — N-type Si Implanted As Partial Depletion	500 Å Si	
ULTRA AS†	Ultra-low background high-efficiency alpha spectroscopy	Si	300–1200	100	+50°C to –30°C	Implanted Boron — N-type Si Implanted As Partial Depletion	500 Å Si	
ULTRA CAM†	Alpha and beta continuous air monitoring (counting in adverse environment)	Si	300–2000	100	+50°C to –15°C	Implanted Boron — N-type Si Implanted As Partial Depletion	N/A	
A	High-Resolution charged-particle spectroscopy (Nuclear Physics and Chemistry-Space Physics)	Si	25–450	1000–2000	+25°C to –30°C	Gold — N-type Si Aluminum Partial Depletion	800 Å Si	
B	Particle identification, telescopes of detectors (Nuclear Physics and Chemistry-Space Physics)	Si	50–450	150–2000	+25°C to –30°C	Gold — N-type Si Aluminum Total Depletion	800 Å Si	2250 Å Si
C	Backscattering from a collimated source or beam target-angular correlation measurements (Nuclear Physics)	Si	50–450	100–1000	25°C to –30°C	Gold — N-type Si Aluminum Partial Depletion	800 Å Si	2250 Å Si
D	Time-of-flight measurements with heavy ions (Nuclear Physics)	Si	10–450	15–100	10°C to 25°C	Gold — N-type Si Aluminum Total Depletion Planar	800 Å Si	2250 Å Si
F	Heavy-ion spectroscopy (Nuclear Physics)	Si	100–900	≥60	+25°C to –30°C	Gold — N-type Si Aluminum Partial Depletion High Field Strength	800 Å Si	
R	Charged-particle spectroscopy operable in air and ambient light	Si	50–2000	100–500	+25°C to –30°C	Aluminum — P-type Si Gold Partial Depletion	2300 Å Si	

** Measured with 5.486-MeV natural alpha particles.

† ULTRA series detectors are manufactured by ion-implantation silicon-dioxide passivated technologies. Versions bakeable at 200°C available on special order.

[1] *Radiation Detection and Measurement* (2nd Edition) by Glenn F. Knoll, New York: John Wiley and Sons, 1989, and *Semiconductor Detectors*, edited by G. Bertolini and A. Coche, North Holland Publishing Co., 1968 (distributed in the U.S. by American Elsevier Publishing Co.), New York City.

[2] F.S. Goulding and R.H. Pehl, "Semiconductor Detectors," Section IIIA, *Nuclear Spectroscopy and Reactions*, J. Cerny, Ed. Academic Press (1974).