Fundamental limits to detection of low-energy ions using silicon solid-state detectors

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Recent advances in solid-state detector (SSD) technology have demonstrated the detection of ions and electrons down to 1 keV. However, ions at keV energies lose a substantial amount of energy Δ_N in a SSD through Coulombic interactions with target nuclei rather than through interactions that contribute to the SSD output pulse, whose magnitude is a measure of the ion's incident energy. Because Δ_N depends on the ion species, detector material, and interaction physics, it represents a fundamental limitation of the output pulse magnitude of the detector. Using 100% quantum collection efficiency silicon photodiodes with a thin (40–60 Å) SiO_2 passivation layer, we accurately quantify Δ_N for incident 1–120 keV ions and, therefore, evaluate the detection limits of keV ions using silicon detectors.
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Solid-state detectors (SSDs), in which an incident ion generates electron-hole pairs that are collected and form an output pulse whose magnitude is a measure of the incident ion energy, are used extensively in a broad array of applications. As an example, hundreds of instruments using SSDs have been flown in space to characterize the ambient space environment. However, the utility of SSDs is limited to detection and measurement of ions with energies greater than several tens of keV due primarily to three effects, collectively known as the pulse height defect. These effects represent the equivalent energy lost by an incident ion to processes that do not contribute to the electron-hole pairs that form the detector's output pulse.[1] Understanding the pulse height defect is critical for optimizing the design of SSDs fabricated for detection of low energy ions, for specifying the detection electronics based on expected pulse magnitudes, and for interpreting and understanding the results obtained from SSDs.

The pulse height defect is the sum of three components: $\Delta_{\mathrm{PHD}} = \Delta_W + \Delta_R + \Delta_N$. First, an incident ion loses an energy Δ_W in the entrance window of the detector, which depends on the material and thickness of the window. Recent advances in delta-doped, back-thinned CCDs[2,3] and EUV photodiodes,[4–6] which have extremely thin entrance windows, have enabled detection of ions and electrons below 2 keV.[2,3,7,8] Second, the ion-generated carriers can recombine in the device before they are collected by an external circuit, representing an ion energy loss Δ_R. This recombination loss has been reduced by careful device design and fabrication, resulting in detectors having no device recombination and, therefore, 100% quantum detection efficiency.[2,4–6] Recombination loss from high density electron-hole pair generation along the ion track is neglected here since the ion energies needed for this are much higher than used here.[9,10] Third, an incident ion loses an energy Δ_N to Rutherford-type (Coulombic) collisions with detector nuclei that do not lead to electron-hole pair formation. This is the nuclear stopping defect and is typically estimated within the framework of LSS stopping theory.[11,12]

In contrast to Δ_R and Δ_W losses, both of which can be minimized by better device engineering, the Δ_N loss is a direct result of the physics of the interaction kinematics between the incident ion and the detector material and therefore cannot be overcome. Furthermore, Δ_N becomes increasingly important at low ion energies as an ion loses more energy to target nuclei rather than target electrons. Accurate measurement of Δ_N therefore allows critical insight into the largest possible output pulse magnitude, and therefore the usefulness of SSDs for low energy ion detection. In this study, we use unique *n*-*p* silicon photodiodes with $\Delta_R \approx 0$ and $\Delta_W \ll \Delta_N$ to measure the nuclear stopping defect Δ_N.

The 1 cm^2 active area *n*-*p* silicon photodiodes have previously been used to study the interaction processes and detection limits of low energy electrons in silicon.[7] These devices have 100% internal quantum collection efficiency as determined using EUV measurements[4–6] and few, if any, electron-hole pairs recombine before being measured so that $\Delta_R \approx 0$. As will be discussed later, the results of this study also indicate that Δ_R is negligible relative to Δ_N. Additionally, these devices have an extremely thin SiO_2 passivation layer window, ranging from 40 to 60 Å, so that $\Delta_W \ll \Delta_N$. Furthermore, Δ_W can be estimated using the SRIM semi-empirical Monte Carlo computer code.[12] Because Δ_N is a significant fraction of E_0 at low ion energies, use of these devices yields $\Delta_{\mathrm{PHD}} = \Delta_N$ within experimental uncertainty.

To measure the average number N of electron-hole pairs created per incident ion in silicon, a 2.7-mm-diameter, mass-resolved ion beam of incident energy E_0 is first directed into a Faraday cup for measurement of the beam current I_0, which is kept low enough so that the photodiode is not dam-

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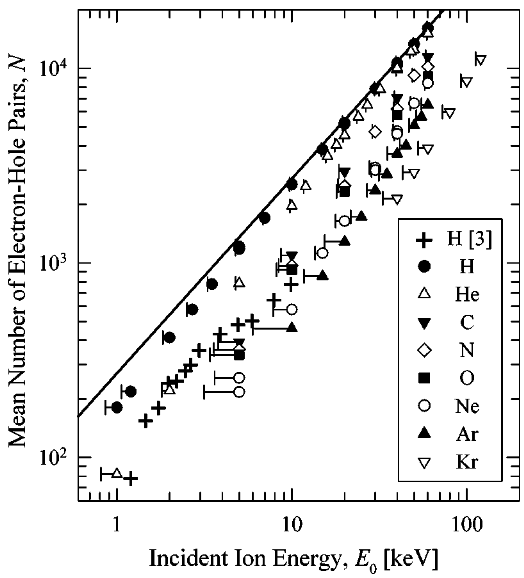

FIG. 1. Measured number of electron-hole pairs is shown as a function of the incident energy for several ion species and represents the maximum pulse magnitude possible from a silicon SSD. The line represents the case in which all of an ion's energy is lost to processes that generate electron-hole pairs. The H^+ data shown as (+) are from a back-thinned delta-doped CCD (Ref. 3).

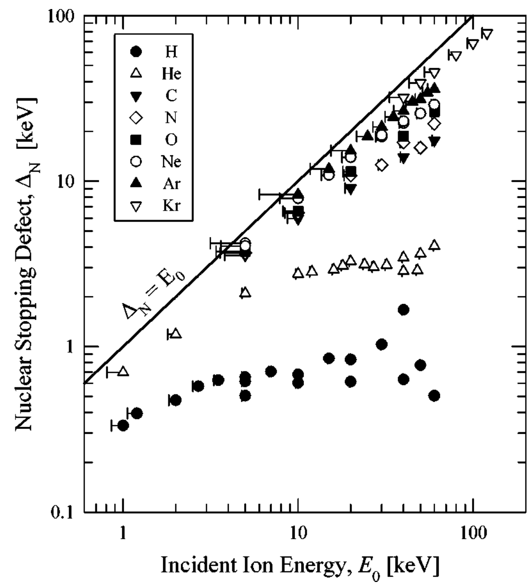

FIG. 2. Nuclear stopping defect Δ_N for silicon detectors, which is shown as a function of incident ion energy, is due to the interaction physics of an ion in the detector material and fundamentally limits the output pulse magnitude from SSDs.

aged by the irradiation.[13] The beam is then directed onto the photodiode, which is operated with no reverse bias, and the photodiode's output current I_{PD} is measured. The mean number N of electron-hole pairs generated in the active region of the detector per incident ion is simply $N = I_{PD}/I_0$. The reduced transmission of heavy ions at low energies in the SiO_2 passivation layer is accounted for by multiplying I_0 by the transmission calculated using SRIM.[12] In contrast to a detector operated in single particle detection mode, in which the signal from a low energy ion can be comparable to the intrinsic detector noise, the photodiode operated in current mode enables a large signal-to-noise ratio (>1000). The measurement accuracy is limited by the stability of the ion beam, which varied by less than 2%.

Figure 1 shows N as a function of incident ion energy E_0 for incident H^+, He^+, C^+, N^+, O^+, Ne^+, Ar^+, and Kr^+. The line represents the ideal case $\Delta_{PHD} = 0$ in which all of an ion's incident energy is lost to processes associated with electron-hole pair creation, i.e., $N_{IDEAL} = E_0/\varepsilon$, where ε is the electron-hole pair creation energy and equals 3.7 eV for silicon.[14] The error bars to the left of the data points represent the mean energy lost by an incident ion after transiting the SiO_2 passivation layer (i.e., the window defect Δ_W) as computed using SRIM.[12]

Data for H^+ incident on a delta-doped, back-illuminated CCD[3] are also shown in Fig. 1 and exhibit a significantly smaller response than the H^+ data of this study. It can be shown that the pulse height defect Δ_{PHD} for the CCD data increases almost linearly with increasing ion energy, and this proportionality suggests significant recombination within the CCD or signal loss within the analytical electronics. This effect is absent in the present study.

Since $\Delta_{PHD} \approx \Delta_N$ for the detectors used in this study, we obtain the nuclear stopping defect using $\Delta_N = E_0 - \varepsilon N$, which is shown in Fig. 2. The solid line represents the extreme case in which no electron-hole pairs are generated in the detector, i.e., $\Delta_N = E_0$, and would correspond to no observed ion-generated output current from the photodiode.

We note that some error bars, which represent Δ_W, extend beyond the solid line and suggest that Δ_N is greater than the net energy $E_0 - \Delta_W$ deposited in the active region of the device, which is not physically possible. Previous studies using low energy electrons[7] and ultraviolet light[4–6] incident on the same type of devices indicate that electron-hole pairs can be generated in the SiO_2 layer (although at a lower rate since $\varepsilon = 17$ eV for SiO_2[15]), diffuse to the device's active region, and contribute to the output signal. This contribution, combined with observation of an ion-generated output current from the photodiode, indicate that the calculated values for Δ_W overestimate energy loss in the window that does not contribute to the output signal.

The magnitude of the energy lost to Coulombic collisions is substantial for ions at the lowest energies and highest masses, a general result that was theoretically derived and experimentally demonstrated long before the development of solid-state detectors[16,17] but has not been accurately measured because of the comparatively large values of Δ_W and Δ_R in traditional solid-state detectors. In Fig. 2, approximately half of the energy lost in the detector by 2.5 keV He^+, 8 keV C^+, and 55 keV Ne^+ is through processes that do not lead to electron-hole pair formation. For 22 keV Ar^+ and 65 keV Kr^+, about 75% of the ion's incident energy is lost to processes that do not generate electron-hole pairs. Importantly, Fig. 2 quantitatively represents the fundamental limitations of low energy ion detection by silicon detectors.

The higher energy H^+ and He^+ data in Fig. 2 approach constant values of $\Delta_N = 0.7$ keV and $\Delta_N = 3.2$ keV, respectively. This behavior is expected since the nuclear stopping powers of these ions, and therefore the energy lost to processes that do not generate electron-hole pairs, decreases substantially at these higher energies. It also demonstrates that Δ_R, which should increase linearly with incident ion energy (i.e., $\Delta_R \propto E_0$) over the energy range in which Δ_N is observed to be constant, is negligible and that the approximation $\Delta_N \approx \Delta_{\mathrm{PHD}}$ is valid.

The only method of increasing detector response is to select a different detector material having a lower value of ε or having a smaller value of Δ_N. Germanium possesses both qualities: $\varepsilon = 2.9$ eV and SRIM calculations[12] predict that the ratio of the electronic to nuclear stopping powers in Ge is higher than that for Si at incident ion energies less than ~ 10 keV, indicating that $\Delta_N(\mathrm{Ge}) < \Delta_N(\mathrm{Si})$ at energies less than several tens of keV. Thus, provided that Ge detectors can be engineered having $\Delta_W \approx \Delta_R \approx 0$, and provided that the additional noise that accompanies a lower value of ε can be suppressed by cooling the detector, Ge should be superior to Si for detection of low energy ions.

In summary, we have used unique photodiodes to accurately measure the average number of electron-hole pairs per incident ion in silicon. This is a fundamental property of the interaction physics of the projectile in the detector material and represents the largest possible mean charge magnitude that can be generated by an ion in a silicon SSD.

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