Radiation hardness of diamond and silicon sensors compared

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The radiation hardness of silicon charged particle sensors is compared with single crystal and polycrystalline diamond sensors, both experimentally and theoretically. It is shown that for Si- and C-sensors, the NIEL hypothesis, which states that the signal loss is proportional to the Non-Ionizing Energy Loss, is a good approximation to the present data. At incident proton and neutron energies well above 0.1 GeV the radiation damage is dominated by the inelastic cross section, while at non-relativistic energies the elastic cross section prevails. The smaller inelastic nucleon-Carbon cross section and the light nuclear fragments imply that at high energies diamond is an order of magnitude more radiation hard than silicon, while at energies below 0.1 GeV the difference becomes significantly smaller.

1 Introduction

The advent of relatively low priced CVD diamond wafers has opened up its use as sensors for the detection of charged particles. The basic principle is the same as in silicon sensors: metallic electrodes on opposite sides are used to apply an electric field, which drifts the electron hole pairs of an ionizing particle towards the electrodes. The collected charge can be integrated by an integrating amplifier or if fast signals are required, the ionization current can be directly multiplied by a current amplifier. In harsh radiation environments, as expected e.g. at future high intensity colliders, the radiation damage by hadrons or heavy nuclei will be severe and silicon detectors are known not to survive too long. Several collaborations have investigated the alternatives, either by going to diamond sensors [RD42] or other materials [RD50] or cooling the silicon sensors [RD39]. The diamond sensors were shown to be rather radiation hard in high energy proton beams, albeit with a signal level an order of magnitude below the signals in silicon sensors. This improves by a factor around 3 with the advent of single crystal (sCVD) diamond wafers, which become available now.

The radiation damage causes two effects: the change of dark current and the signal decrease with increasing fluence of the detected particles. For silicon sensors the strong increase of dark current requires a cooling of the detectors in order to avoid reverse annealing and thermal runaway, while in diamond sensor the leakage current even at room temperature is negligible and usually decreases after irradiation. The signal decrease in silicon has been studied at various particle energies and fluences and was found to be in most cases proportional to the Non-Ionizing Energy Loss (NIEL) damage cross section, which is closely related to the creation of lattice defects. At low beam energies the NIEL cross section is dominated by the long-range Rutherford scattering, which falls like $1/E^2$ and creates many small scale lattice displacements. At intermediate energies (above a few MeV) the anomalous elastic Rutherford scattering from the nuclear interactions between the incoming beam and the nuclei in the sensor starts to play a role, while at energies...
above a few hundred MeV the inelastic cross section, which is almost energy independent, dominates. The inelastic collisions fragment the nuclei and the slow moving nuclear fragments lead to strong lattice defects by the Rutherford scattering again. Impurities like oxygen, can reduce the signal losses by forming stable non-trapping defects with the vacancies [ROSE], thus leading to a deviation from the NIEL scaling hypothesis, which states that the radiation damage is proportional to the NIEL damage cross section.

In diamond the expected increase in radiation damage by Rutherford scattering at low energies has never been measured. This study was triggered by the observation that the ionization signal in diamond sensors decreases surprisingly fast after irradiation with 26 MeV protons. In this paper the NIEL cross section in diamond has been calculated and compared with new data for the radiation damage from protons and neutrons at low energies for the first time.

2 Calculation of radiation damage

The total energy loss of an impinging particle on a detector is strongly energy dependent and is divided into an ionizing part and a non-ionizing part. The ionizing part is used for the detection and the non-ionizing energy loss (NIEL) represents the energy loss in phonons and lattice defects. The fraction of NIEL is defined by the Lindhard partition function, which gives the ratio of the ionizing energy loss over the total energy loss. This function is itself strongly energy dependent, as will be discussed below.

The damage cross section \( D \) is either given in \( \text{MeV m b} \) or in \( \text{keV cm}^2=g \) and the corresponding KERMA (Kinetic Energy Release in Matter) is given either by

\[
\text{KERMA} (\text{keV}) = \text{wt (g)} \times D (\text{keV cm}^2=g)
\]  

or

\[
\text{KERMA} (\text{MeV}) = \text{wt (g)} \times \frac{10^6 (\text{cm}^2=m b)}{10^3 (\text{cm}^2=m b)} \times D (\text{MeV m b})
\]

Here \( \text{wt} \) is the flux of incident particles per \( \text{cm}^2 \) and \( \text{wt} = \frac{\text{volume}}{\text{area} \times \text{target thickness}} \) is the weight of the target. For silicon (diamond) \( A = 28.086 \) (12). According to the ASTM standard, the displacement damage cross section for 1 MeV neutrons is set as a normalizing value: \( D_n (1\text{MeV n}) = 95\text{MeV m b}[\text{ASTM}] \). On the basis of the NIEL scaling hypothesis the damage efficiency of any particle with a given kinetic energy \( E \) can then be described by the hardness factor \( k \), defined as

\[
k_{\text{particle}} (E) = \frac{D_{\text{particle}}}{D_n (1\text{MeV n})}
\]

However, the normalizing value of \( 95\text{MeV m b} \) is only valid for neutrons interacting with silicon. For any other material 1 MeV neutrons will have another displacement damage cross section. In order to compare the absolute cross sections between silicon and diamond the NIEL values will be given in \( \text{MeV m b} \) without normalization to \( 1\text{MeV n} \).

A convenient package for the calculation of the energy loss of ions was developed by J. Ziegler and is available from the web [SRIM]. The package is called SRIM, which stands for the Stopping and Recoil of Ions in Matter. The stopping is important, since most damage is not caused by the primary particles, but by the recoil and nuclear fragments from the first atom hit, i.e. the primary knock-on atom (PKA). In our case the primary energies are so large that the PKA can create further defects, so a cascade develops. For inelastic collisions the nuclear fragments are so damaging that a cluster of defects develops. At low energies the elastic collisions dominate and only point like defects are created.
Recoil Energy [eV]

ionization loss / total loss

Si (E\text{d} = 20 eV)

C (E\text{d} = 40 eV)

Fig. 1 Lindhard partition function for silicon and diamond, as calculated with the SRIM software package [SRIM]. Notice that the NIEL is a significant fraction of the total energy loss only for collision energies well below 10 MeV.

### Table 1

A compilation of the fragments, labeled by their charge Z, as created by 10^4 10 GeV/c protons in Si and diamond sensors and the contributions of these fragments to the NIEL cross section.

| Z | \(n_{\text{fr}}\) | \(n_{\text{elel}}\) | C (E\text{d} = 40 eV) | \(n_{\text{elel}}\) |
|---|---|---|---|---|
| 14 | 417 | 4.2 | 0 | 0 |
| 13 | 910 | 9.1 | 0 | 0 |
| 12 | 1384 | 12.5 | 0 | 0 |
| 11 | 1021 | 8.9 | 0 | 0 |
| 10 | 1225 | 8.5 | 0 | 0 |
| 9 | 265 | 1.4 | 0 | 0 |
| 8 | 493 | 2.1 | 0 | 0 |
| 7 | 398 | 1.3 | 0 | 0 |
| 6 | 909 | 2.4 | 698 | 0.8 |
| 5 | 270 | 0.6 | 869 | 0.8 |
| 4 | 383 | 0.7 | 584 | 0.4 |
| 3 | 662 | 0.7 | 1133 | 0.6 |
| 2 | 11152 | 4.4 | 10625 | 2.0 |
| 1 | 46107 | 0.9 | 30465 | 0.6 |
| Total | 65590 | 57.4 | 44374 | 4.8 |

The energy loss is determined by collisions between two colliding atoms, which requires the knowledge of the wave functions. The quantum mechanical treatment of such collisions is complicated and has to take the screening of the nuclear charge by the electronic shells into account. Such calculations are of utmost importance for e.g. the implantations needed for electronic circuits. Therefore it is not surprising that SRIM was developed at the IBM Research Laboratory. It has been studied in great detail for many different nuclei and SRIM incorporates the state-of-the-art calculation of the energy losses in matter, including the creation of defects, interstitials, vacancies etc. Unfortunately the primary particles are considered to have only elastic Coulomb interactions with the atoms of the target.

This is not enough for our purpose, since the impinging particles are usually relativistic, which leads in addition to pure Coulomb scattering also to elastic and inelastic scattering by nuclear interactions. However, the interaction of the PKA and its nuclear fragments can be treated by the SRIM package. Therefore one can calculate the energy spectrum of the nuclear fragments and nuclear recoils from energetic collisions and send these fragments and recoils as input particles to the SRIM package, which then calculates the NIEL contribution. In such a way the NIEL has been studied in detail for silicon by [Huhtinen]. His study was adopted by adjusting the nuclear cross sections from silicon to diamond.

Before showing the results a few points are in order. The elastic Rutherford cross sections diverge for small scattering angles, so a cut has to be imposed for the minimum momentum transfer. This cut was chosen in such a way to effectively reproduce the NIEL at 1.3 MeV incident proton energy, as calculated by SRIM. SRIM includes all the charge screening, which is not taken into account by the Rutherford scattering formulae, so this cut is an effective way to reduce the cross section and it has to be different for carbon and silicon.

For energy transfers below the displacement energy the energy loss is into phonons, which is correctly taken into account in SRIM, but does not lead to defects. This fraction of NIEL into phonons is somewhat energy dependent, so the defect concentration is not strictly proportional to the NIEL cross section anymore. Therefore deviations from the NIEL scaling hypothesis can be expected, but these effects are estimated to be less than 20% for the energy range considered. The experimental uncertainties are considerably larger, so this effect is neglected.

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Fig. 2  Left: The observed ionization signal as function of the beam current after three different fluences with 26 MeV protons. Right: the decrease of the CCD for sCVD sensors as function of the fluence of 26 MeV p=cm \(^2\). The CCD was determined either from a Sr source with through going radiation from beta particles, thus filling the traps (priming) or with an alpha source (Am), for which the ionization is only created mainly in the first 10 \(\mu\)m of the sample.

Fig. 3  The decrease of the ionization signal in a pCVD diamond sensor after irradiation with 26 MeV protons (left) and 20 MeV neutrons (right).

The total NIEL can be calculated from the total energy loss via the Lindhard function. The Lindhard functions for diamond and silicon are compared in Fig. 1 as calculated with SRIM. The averaged energy to create a lattice displacement is about 15-20 eV for Si and in the range 37-47 eV for diamond (depending on the direction, Koike et al.). As the figure shows, for an incident energy above 10 MeV practically all the energy loss goes into ionization energy. However, the electrons have a high mobility, so this damage is repaired quickly. Low energies particles are created by the nuclear fragments from inelastic collisions or the nuclear recoils from either elastic or inelastic scattering. For silicon with an atomic number of 28 many nuclear recoils can be created, which cause a large amount of NIEL, as shown in Table 1 for an incident proton with a momentum of 10 GeV/c. The NIEL in C is shown as well. Here most of the secondary particles are the light He nuclei, which cause a relatively small amount of NIEL. This is the basic reason why diamond is an order of magnitude more radiation hard at high energies. But at energies well below 100 MeV the cross sections are dominated by the Rutherford scattering for charged incident particles. Here the radiation hardness of silicon and diamond is expected to be a factor \((2^{2}\frac{Z}{A_{S i}})\cdot(2^{2}\frac{Z}{A_{C}}) = (14^{2}\frac{28}{6}) = 35\) different, which is approximately the case, as will be shown in the next section.
Fig. 4  NIEL damage cross section of Si (left) and Diamond (right) for protons and neutrons (solid lines: upper one for p, lower one for n) as function of the incident energy. The different cross section contributions from elastic and inelastic scattering have been indicated as well.

3 Comparison with data

The radiation hardness for diamond sensors has been measured by the RD42 collaboration using a 24 \( \text{GeV/c} \) proton beam at CERN. They found that the decrease in signal was around a factor 2 after a fluence of \( (6 \pm 2) \times 10^{15} \text{p/cm}^2 \) [RD42-Report]. However, during a test of diamond sensors with 26 MeV protons, the signal decreased much more rapidly, as shown in Fig. 2 (left). The curves were obtained by irradiating the sample with a high intensity 26 MeV proton current and then reducing the current and measuring the ionization current for different beam currents. After a fluence of \( (4\pm 1\pm 5) \times 10^{14} \text{p/cm}^2 \) the ionization signal or the charge collection distance (CCD) is reduced by a factor two.

There are two experimental worries concerning our method: a) is the online measurement of the decrease of the ionization signal determining the real radiation damage? b)for these studies we used rather cheap diamond sensors from [E6], which were not their sensor grade, but the "heat spreader" grade. Therefore the results were repeated with a sensor grade pCVD diamond and a single crystal sCVD diamond, all from [E6]. The diamonds were either metallized with Al or (Au,Cr) on C. The diamonds were characterized before and after irradiation using the standard method of determining the charge collection distance with a radioactive source. The reduction in signal for sCVD sensors follows a similar decrease as for the online measurements with the pCVD sensors (see Fig. 2 right), showing that the bulk damage is an intrinsic property of the sensor material.

In order to check if this is due to the large increase in the cross section from multiple Coulomb interactions the samples were irradiated with neutrons. Since the neutrons yield much less ionization the ionization current could be monitored on line without saturating the electronics. For the electronics a sensitive "Current-to-Frequency" converter with a dynamic range from a few pA to a few mA was user. This 8 channel module with an USB readout was developed by the LHC machine group for the LHC beam monitoring with ionization chambers [Dehning]. The irradiation was performed with the neutron beam at Louvain la Neuve with a mean neutron energy of 20 MeV [Louvain]. The result is shown in Fig. 3.
twofold exponential is seen, indicating that a recombination effect is going on. Details can be found in [Müller]. However, one observes that the signal decrease by a factor two is reached after a fluence of about

\[(1.25 \pm 0.25) \times 10^{15}\]

which is already significantly better than the radiation hardness for protons.

In order to check if these results make sense, the NIEL cross sections has been calculated for diamond using the procedure outlined in the previous section. The NIEL cross sections for Silicon (Diamond) are shown on the left (right) panel of Fig. 4. The silicon data were taken from [Huhtinen], but scaled to fit the present calculation at low energies. The present calculation changes somewhat from the previous one because of using a newer SRIM version. The RD42 results at 24 GeV with

\[\frac{1}{2} = \begin{pmatrix} 6 \\ 2 \end{pmatrix}\]

were used as normalization for the diamond results and the NIEL calculation was used to determine the energy dependence. For the neutrons the normalization at 24 GeV was taken to be 0.69 times \(\frac{1}{2}\) of protons, as expected from theory (see Fig. 4). Both, the large increase in cross section for the charged particles and small increase for the neutrons, are reproduced by the data. Comparing the left and right hand side shows that for low energies the difference in radiation damage cross section between silicon and diamond is a factor of a few, while at high energies the difference is an order of magnitude.

The agreement of the energy dependence of the NIEL cross section in comparison with the data is remarkable, if one considers the large uncertainties in the experimental data, e.g. from the priming of the diamond to fill the traps, as shown in the right panel of Fig. 2 for the non-exponential decrease of the signal, as shown in Fig. 3 which implies an ambiguity in the definition of the radiation hardness. Note that only the shape of the energy dependence is relevant here, since the data were scaled to fit the data at low energy for silicon and high energy for diamond.

4 Summary

It is shown that for Si- and C-sensors, the NIEL hypothesis, which states that the radiation damage and the corresponding signal loss is proportional to the Non-Energy-Energy-Loss (NIEL), is a good approximation to the present data. At incident proton and neutron energies well above 0.1 GeV the radiation damage is dominated by the inelastic cross section, while at non-relativistic energies the elastic cross section prevails. The smaller inelastic nucleon-Carbon cross section and the light nuclear fragments imply that at high energies diamond is an order of magnitude more radiation hard than silicon, while at energies below 0.1 GeV the difference is significantly smaller. Such low energies are important even at high energy hadron colliders, because the underlying events from the soft collisions of spectator partons and secondary interactions in the detector material yield an appreciable fraction of particles in this energy range.

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