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ORIGINAL PAPER

Neutron radiation due to high energy boron ion beams

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Abstract

Axcelis' next generation high energy implanter, the Purion XEmax, can achieve ultra-high energy boron beams. At these energies nuclear fusion can occur due to quantum tunneling which can result in elevated neutron dose rates. Neutron radiation is a serious safety concern, because unlike x-rays, neutrons are much more difficult to safely manage. This paper discusses in detail, the neutron dose rates for boron energies 4–8 MeV, various beam currents, target materials (C, Si, BN and pre-implanted graphite), neutron detectors as well as shielding materials.

Introduction

The fabrication and future development of leading-edge CMOS image sensors are likely to require high energy boron ion beams, in an energy range of about 1 to ≥ 5 MeV. Axcelis' next generation high energy implanter, the Purion XEmax, can achieve these ultra-high energy boron beams easily (for more details of the Purion XEmax see [1]). However, at these energies nuclear fusion can occur resulting in neutron radiation as was discussed in a previous study by N. White et al. [2]. Neutron radiation is difficult to attenuate as lead shielding is relatively ineffective and other shielding materials, such as polyethylene or high density concrete, need to be tens of cm thick in order to ensure radiation safety limits are met (typically 30–50 µrem/h). Thick neutron shielding can lead to a substantial increase in footprint and limited serviceability of next generation high energy ion implanters. These consequences are undesirable as clean room space is very costly and system maintenance is required to achieve the uptime targets set by semiconductor manufactures.

Two reactions are of particular concern for ion implanters. Boron ions can fuse with carbon atoms in the graphite liners commonly used in ion implanters due to the $^{12}C(^{11}B,n)^{22}Na$ reaction (also referred to in the next pages as the B-C reaction). Additionally, there is a reaction that can occur when boron nuclei fuse with pre-implanted boron nuclei. The $^{11}B(^{11}B,n)^{21}Ne$ reaction or for short the B-B reaction can result in much higher dose rates due to the greater cross-section as compared to the B-C reaction. Neutron radiation from pre-implanted boron conditions has been studied. Methods of limiting neutron dose rates by limiting boron beam currents, increasing the distance to the target/neutron source and/or by shielding with polyethylene have been tested. A comparison of commercially available neutron detectors is also presented.

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Nuclear fusion reactions

As mentioned above, for very high energies the positive nuclei of the high energy projectile can tunnel through the Coulomb barrier of the target nuclei, which is a well-known quantum mechanical effect. This mechanism in turn leads to a fusion reaction of the projectile with the target nuclei and typically results in either high energy gamma and/or neutron radiation. The reaction probability for the projectile to penetrate the Coulomb barrier can be calculated while the cross-section has the basic form [3]:

$$\boldsymbol{\sigma}(\boldsymbol{E}) = \frac{\boldsymbol{S}(\boldsymbol{E})}{\boldsymbol{E}} \boldsymbol{e}^{(-2G)}, \quad (1)$$

with

$$G = Z_a Z_X \sqrt{\frac{\hat{A}}{E(MeV)}},$$

and

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$$\hat{A} = \frac{A_a A_X}{A_a + A_X},$$

G is called the Gamow factor and $\hat{A}$ is the effective mass number. We didn't measure the S-factor and are assuming that the reactions considered here are non-resonant.

In Fig. 1a the cross-sections for the three main reactions of concern: $^{12}C(^{11}B,n)^{22}Na$, $^{11}B(^{11}B,n)^{21}Ne$ and $^{11}B(^{10}B,n)^{20}Ne$ were plotted according to Eq. (1) assuming the S-factor is about the same for all three reactions in order to make a rough comparison. As is apparent by the trends of the graph, the higher the energy the more probable it is for the neutron producing reaction to occur. According to this theoretical estimate, the neutron flux from B 7.5 MeV is ~ 10 × higher than at 6.0 MeV and ~ 1000 × higher than at 4.0 MeV.

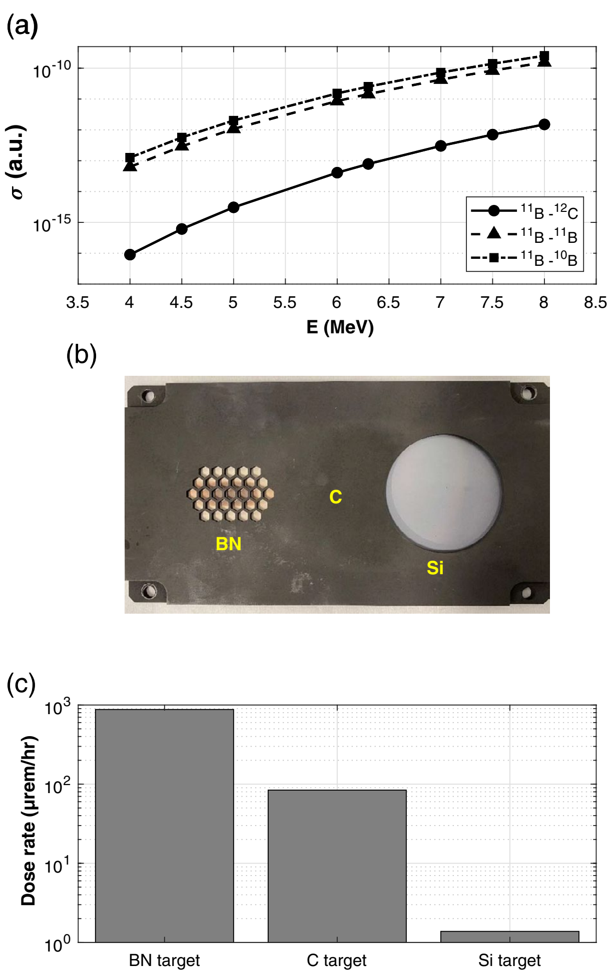

Fig. 1 **a** Cross section estimates using the Gamow factor for the $^{12}C(^{11}B,n)^{22}Na$, $^{11}B(^{11}B,n)^{21}Ne$ and $^{10}B(^{11}B,n)^{20}Ne$ fusion reactions. **b** Target holder made of graphite with a silicon and BN target. **c** Measured dose rates at about 1 m from target for B 7.5 MeV 0.45 pμA

Another trend that is apparent is that the lighter the target ions the higher the probability for the reaction to occur. This is consistent with the notion that the higher the Coulomb barrier, the less likely its penetration (larger Z nuclei contain more protons, hence they are more positively charged and repel the positively charged projectile nuclei). The theory predicts that, for B 7.5 MeV beams, the neutron flux from the ^{11}B-^{11}B reaction is ~ 120 × higher than from the ^{11}B-^{12}C reaction.

Risk from these reactions must be contextualized for the ion implanter. The cross section for the $^{11}B(^{10}B,n)^{20}Ne$ is the largest, but this reaction is unlikely to occur due to pre-implanted boron (in graphite liners), which is always done with ^{11}B ions. However, there is a chance for the reaction to occur due to pre-doping of silicon wafers during crystal growth, giving a $^{10}B/^{11}B$ ratio of 20%/80%. As pre-doped concentrations can be as high as 5×10^{15} atoms/cm^{-3} for new p-doped silicon wafers, neutron dose rates are expected to be significant when implanting p-doped silicon wafers with high energy boron beams.

To obtain a better understanding of the actual dose rates several target materials were tested (see Fig. 1b and c). A target holder was made of graphite, which allowed for a large enough graphite surface to be exposed to the boron beam. A boron nitride (BN) target was mounted behind a graphite grid to avoid charging due to the fact that BN is an insulator (ceramic) and subsequent deflection of the beam. An n-doped silicon target (boron free) was also mounted to the target holder. Each target was exposed to the same B 7.5 MeV 0.45 pμA beam, which could be directed precisely via the scanner of the Purion XEmax (operated in DC offset mode) until enough counts were detected with one of the neutron detectors described below to achieve statistical significance. For the BN target results are compensated for the facts that only 50% of the atoms were boron and that the grid partially blocked the target (32%). As is seen in Fig. 1c the dose rate generated from the B-B reaction was 30 × larger than for the B-C reaction, which included ^{11}B and ^{10}B. The dose rate for B-Si was about 60 × smaller compared to B-C, and 1800 × smaller compared to B-B, however, only 2 counts in an hour were measured for silicon. To obtain reliable results of > 100 counts, an unreasonable amount of test time would be needed (50 h). The discrepancy of a factor of 4 × between theory and experiment when comparing the B-B to the B-C reaction can be explained by the fact that S(E) in Eq. (1) can differ from reaction to reaction (even though it might be constant over an extended energy range) and that without knowing the S-factor Eq. (1) can only serve as a rough estimate.

Pre-implanted boron

As seen from the Gamow cross-section estimates in Fig. 1a, the higher the energy the more probable it is to generate neutron radiation. However, as the boron ions penetrate the target, they lose energy quickly as shown in Fig. 2a for a B 7.5 MeV beam directed onto a graphite target. This data was generated with the simulation program SRIM [4]. As a result, for the B-B reaction to occur, the pre-implanted boron needs to be shallow or, in other words, only previous boron implants at low energy will contribute to neutron radiation when subsequently implanted with high energy boron. In Fig. 1a the boron distribution after a high energy implant is also shown (dashed line). The peak of this distribution coincides with the solid energy loss curve where it approaches zero, so previous high energy implants of the same energy will not generate any neutron radiation (disregarding long term sputter effects).

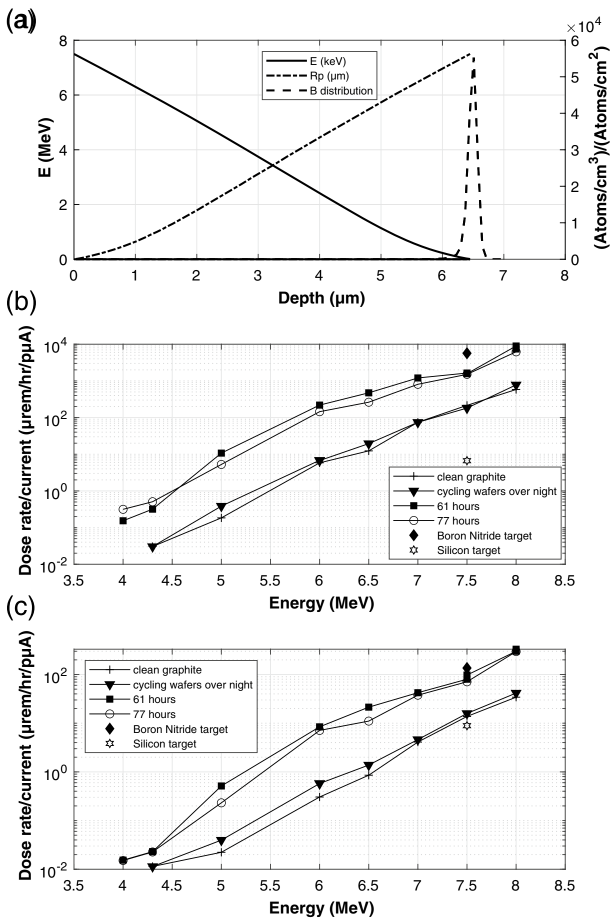

Fig. 2 **a** Energy loss of B 7.5 MeV into Carbon. For comparison B concentration and projected range is also plotted. Dose rates vs energy for neutron (**b**) and gamma radiation (**c**)

To verify the effect of increased neutron radiation due to pre-implanted boron at low energies a clean graphite target was first exposed to low energy boron beams for a certain amount of time and subsequently to high energies boron beams in order to measure the generated neutron and gamma dose rates (Fig. 2(b) and (c)). For the first round mechanical wafers were cycled over-night and implanted with low energy boron at 0.5 MeV, 1 MeV and 2 MeV with a beam current of 700 pµA exposing the graphite target intermittently for a total implant dose of about $4 \times 10^{17} cm^{-2}$ per implant. The subsequent dose rates for the high energy boron beams at 4.3 MeV, 5 MeV, 6 MeV, 6.5 MeV, 7 MeV, 7.5 MeV and 8 MeV were almost identical to the ones measured for the clean graphite target. For the next two rounds of measurements, the same low energy beams mentioned above were cycled, but the graphite target (no wafers) was exposed for 61 h, which is equivalent to an implant dose of about $4 \times 10^{19} cm^{-2}$ per low energy implant. Dose rates increased by about 10× for both neutrons and gammas. Following this, another round of low energy beam implant cycles was implanted into the graphite target (no wafers) for an additional 16 h (about $1 \times 10^{19} cm^{-2}$). This last round changed the dose rates insignificantly and were basically identical. An estimate of the implanted boron concentration in the graphite target suggests that surface concentration reached saturation by exceeding the concentration of solid/bulk boron of 1.28×10^{23} cm^{-3}, which explains why the neutron and gamma dose rates did not increase further. Figure 2(b and c) indicate that the measured dose rates for gamma radiation show almost an identical trend but are about 10–30× lower compared to the neutron radiation. For comparison the data points from the BN and Si target tests (Fig. 1c) were plotted. As expected, Si generates very low levels of radiation because it has much higher Z and therefore a higher Coulomb barrier. The data point for the BN target, which was scaled to solid boron, is even higher than the 77 h data point because it also contained about 20% ^{10}B. The theoretical and experimental data suggest that neutron radiation can be avoided using different surfaces for the low and high energy boron implants, such as for Faraday cups and beam dumps. In addition, using silicon surfaces for these devices would also avoid neutron generation due to the $^{12}C(^{11}B,n)^{22}Na$ reaction.

Shielding of neutron radiation

Assuming there is no significant shielding, the maximum beam currents that can be safely run on the Purion XEmax without special neutron shielding measures are depicted in Fig. 3a. For this calculation the highest dose rates were added as measured for the neutron and gamma radiation (61 h), which means that the graphite target was saturated

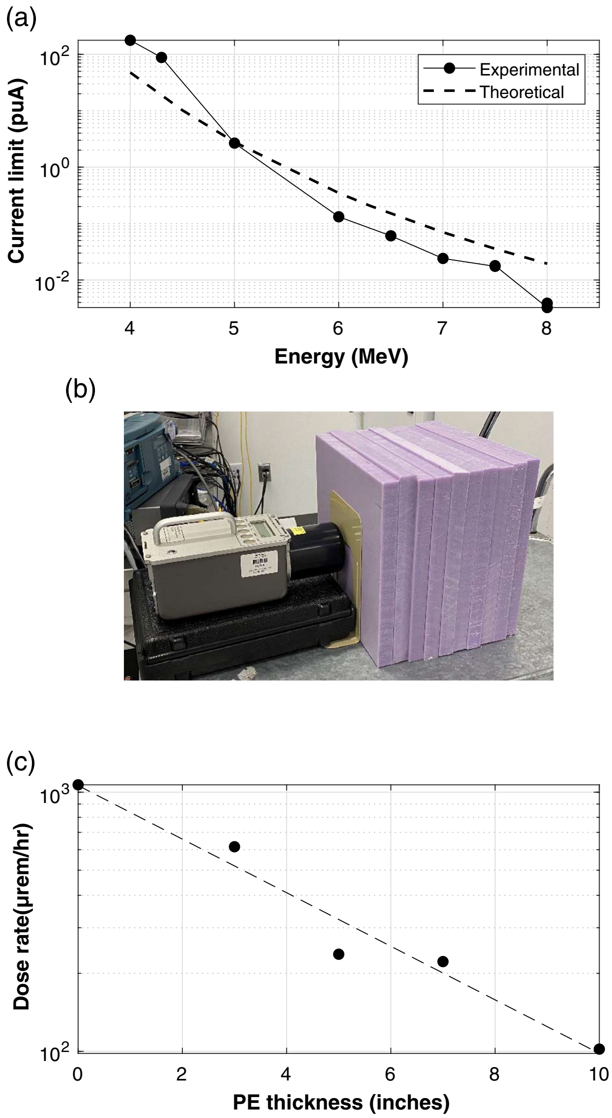

Fig. 3 **a** Maximum beam currents with no shielding assuming a maximum dose rate of 30 µrem/h at about 1 m from the boron loaded graphite target (worst case). A theoretical trend is also plotted for comparsion. **b** REM500 detector with 10″ of borated polyehtylene shielding. **c** Dose rates vs shielding thickness for B 7.5 MeV 2.5 pµA

with low energy boron and can therefor serve as a worst-case scenario. It was further assumed that the radiation spec at about 1 m from the graphite target cannot exceed 30 µrem/hr. The data show an almost perfect inverse exponential trend for the energy range 4–8 MeV. For comparison we also plotted the expected theoretical trend in Fig. 3a based on Eq. 1, which does not fit the experimental data very well probably because the S-factor is not constant.

As can be seen from Fig. 3a, the maximum beam currents without shielding for energies > 5.3 MeV become too small to be of practical use for ion implantation as wafer throughput would be prohibitively small (extremely long implant times) and even simple measurements such as beam parallelism with the current metrology devices would be too noisy to be reliable.

To overcome the quite restrictive beam current limitations, either an increase in distance from the neutron source or shielding can be employed. Neutron and gamma radiation drops off according to the inverse square law $I_2 = I_1(d_1/d_2)^2$ (see Fig. 4c), with I_1 being the dose rate at distance d_1, and I_2 the dose rate at distance d_2. Therefore, increasing the distance for example by 3 × will reduce dose levels by 9 ×, which can help to decrease dose rate levels significantly. However, clean room space is very costly, so the implanter footprint including the enclosure needs to be kept as small as possible. Neutron shielding, on the other hand, is a more viable solution if other solutions such as different surfaces and materials are not an option. Shielding materials that contain large quantities of hydrogen are most effective in thermalizing neutrons because the momentum transfer is optimal due to the practically identical mass of protons and neutrons. The thermalized neutrons can subsequently be absorbed by the hydrogen itself (leading to a buildup of 2.2 MeV photons) or by added boron compounds (producing 0.5 MeV photons, which can easily be shielded) [5]. A commonly used neutron shielding material, borated polyethylene (containing copious amounts of hydrogen) was tested with the Purion XEmax (see Fig. 3b and c) for B 7.5 MeV 2.5 pµA. We found that 10 inches of polyethylene reduced the neutron dose rate by 10 × (Fig. 3c) confirming its effectiveness.

Detectors

Using the Q-value of 14.996 MeV for the $^{11}B(^{11}B,n)^{21}Ne$ reaction it can be calculated that the maximum energy of the resulting neutrons is around 20 MeV for a boron beam of 7.5 MeV. Both the WENDI-2 by Thermo Scientific and the REM500 by Health Physics Instruments can detect neutrons of this energy range. A comparison was made between two REM500's and a WENDI-2 using a PuBe source with an activity of 20 Curies (Fig. 4a–c). Both REM500s measured doses within 10%. The REM500 and WENDI-2 measured doses within 10–30%. All the detectors were in good agreement.

Conclusion

Neutron radiation is a serious safety concern. In this study we found that boron beams interacting with targets previously implanted with boron can result in much higher levels of neutron radiation than for the reaction with graphite. However, it was also found that neutron radiation can be mitigated by

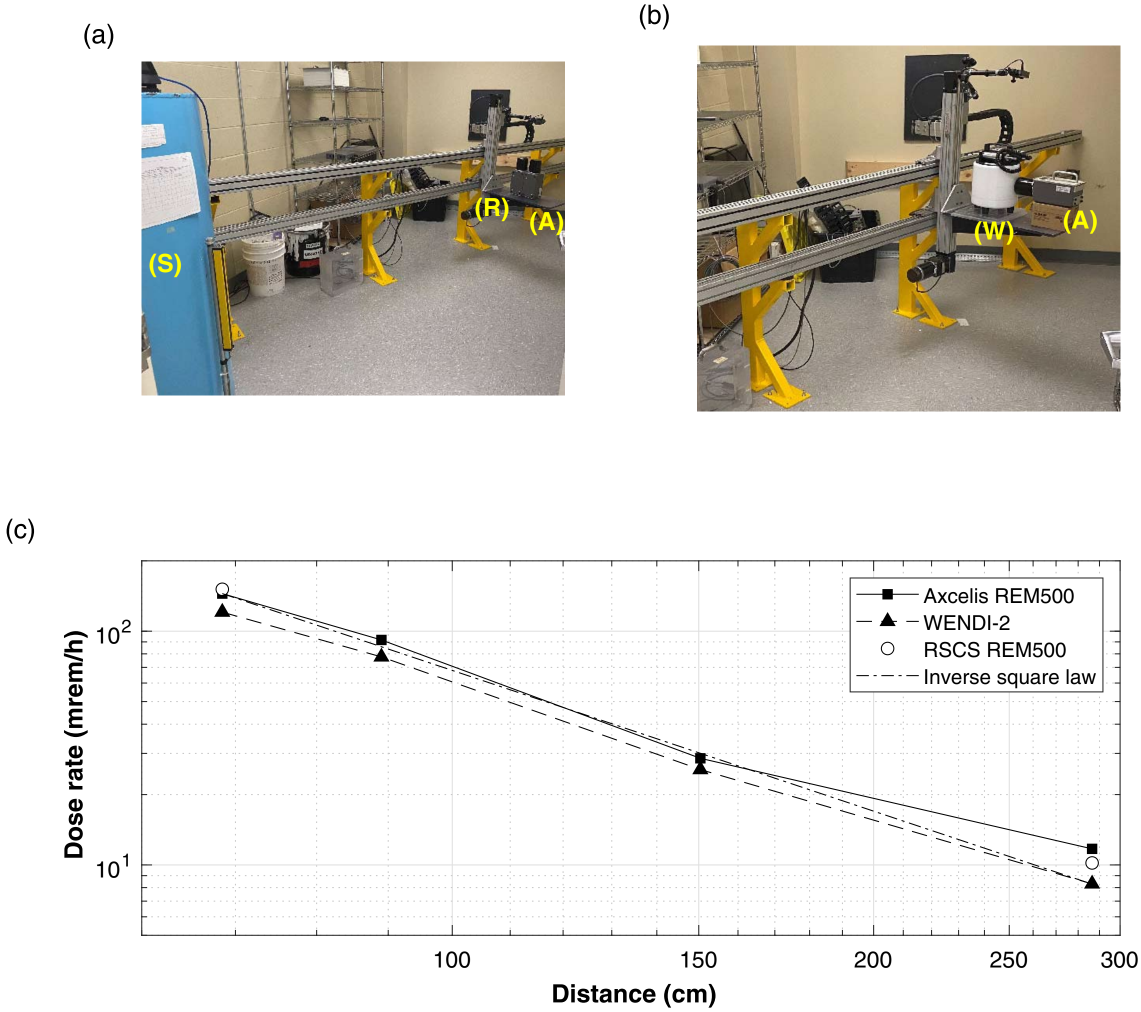

Fig. 4 Setup of detector comparsion with PuBe source (**a**, **b**). Dose rate vs distance from neutron source for various detectors (**c**). Labels in figures refer to PuBe source (S), RSCS REM500 (R), Axcelis REM500 (A) and WENDI-2 (W)

appropriate choices of target surfaces, materials, distance to the neutron sources, shielding or by limiting the beam currents.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest No funds, grants, or other support was received.

References

1. S. Satoh, W. Platow, S. Kondratenko, L. Rubin, P. Mayfield, R. Lessard, G. Bonacorsi, P. Whalen, R. Newman, Purion XEmax, Axcelis Ultra High Energy Implanter with Boost Technology, Presented at the 23rd International Conference on Ion Implantation Technology, San Diego, CA (2022)
2. N. White, N. Tokoro, E. Bell, Radiation issues surrounding very high energy ion implantation, AIP Conference Proceedings 1066, 277 (2008)
3. K. S. Krane, Introductory Nuclear Physics, pp. 773–774 (Wiley, 1987)
4. SRIM-2013 simulation program, James F. Ziegler, “Stopping and Range of Ions in Matter”, srim.org

5. NCRP Report No. 144, “Radiation Protection for Particle Accelerator Facilities”, (National Councilon Radiatioin Protection and Measurements, 2003)