Isolation in Compound Semiconductors and the Risk of Neutron Generation with Implantation of Light Ions

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Abstract

A neutron detection study was performed on a high energy ion implanter with an ion source tuned to accelerate light ions from AMU 1 to 4. For all species, under specific conditions of beam impact location and placement of the detector, for the beam current range and energy range regularly used in production, the radiation levels from neutron producing reactions were found to be well under the legal Occupational Safety and Health Administration (OSHA) limit of 0.570 mrem/hr. For the highest energy and beam current, the radiation levels were observed to be above the implanter maker specification (maker spec) of 0.054 mrem/hr, and the 0.010 mrem/hr recommended limit by the International Commission on Radiological Protection (ICRP) [1]**. Extra care must thus be used when performing implantation of light ions in semiconductor compounds.**

INTRODUCTION

The recent increased interest in the use of light ions such as $^{1}H^{+}$, $H_2^{+}/^{2}D^{+}$, $^{4}He^{+}$ and $^{4}He^{++}$, for implantation into silicon-based semiconductors and especially into compound semiconductors has led us to investigate potential risk for neutron producing reactions associated with these processes. These light ions are showing a better damage control in dose and depth without any detrimental charge doping, along with a larger process window margin than heavier ions.

However, for these light ions constituted of a few nucleons less strongly bound than heavier ions, the likelihood of a nuclear reaction when accelerated and colliding with a target is higher. They indeed exhibit the largest cross sections for neutron producing reactions [2] [3] [4] [5]. In typical ion implanter tools, there are a few places such as the mass analyzer, the Faraday flag also called resolver, the wafer to be implanted, which constitute point of impacts for the ion beam and are potential source locations for such neutron producing reactions to occur. In addition, these points of impact are usually made of graphite which not only by itself constitute a producing target as being made of carbon ($^{12}C/^{13}C$) but also due to its high absorbance characteristic, accumulate different type of ions when the tool is used with various ion species, *e.g.*, $^{10}B/^{11}B$. These absorbed ions along with carbon present very high absorption cross sections and will constitute target for subsequent light ions to strike and potentially generate neutrons [6].

The energy thresholds for such reactions can be as low as 0 MeV for some particles like deuterium, $^{4}He^{+}$ and $^{4}He^{++}$, on atom targets like ^{9}Be, ^{10}B, ^{11}B and ^{13}C [3] [7] [8] [9] [10]. This paper outlines a few characteristics of some of these reactions and the potential risks associated with them. A few considerations are to be set forth. First, the several radiation level limits mentioned throughout the paper are for total yearly exposure divided by the number of hours per year. For instance, the OSHA limit is of 5 rem per year. This translate into a 0.570 mrem/hr dose rate only by assuming that a person would have to be staying stationary all year long on the side of the tool. The actual hourly maximal limits are less strict (see Table 1 in Appendix from [2]).

1. EXPERIMENTAL DETAILS

To assess the actual neutron production risk in common ion implanters used for semiconductor compound processing, a high energy ion implanter along with a helium-3 Meridian Model 5085 neutron detector, were used. By adjusting the magnetic stiffness at the mass analyzer, the following ions were accelerated: H^{+} (proton-p), H_2^{+} (molecular hydrogen), $^{2}D^{+}$ (deuterium-d), He^{+} (Helium-α) and He^{++} (doubly charged-α). Considering that target atoms such as boron (B), Carbon (C), Beryllium (Be) could be present in ion implanters, the following possible reactions were considered:

- Hydrogen ions: $^{2}D(p,n)2p$ and $^{11}B(p,n)^{11}C$
- Deuterium ions: $^{2}D(d,n)^{3}He$, $^{10}B(d,n)^{11}C$, $^{10}B(d,p)^{11}B$, $^{11}B(d,n)^{12}C$ and $^{12}C(d,n)^{13}N$
- Helium ions: $^{9}Be(\alpha,n)^{12}C$, $^{10}B(\alpha,n)^{13}N$, $^{11}B(\alpha,n)^{14}N$ and $^{13}C(\alpha,n)^{16}O$

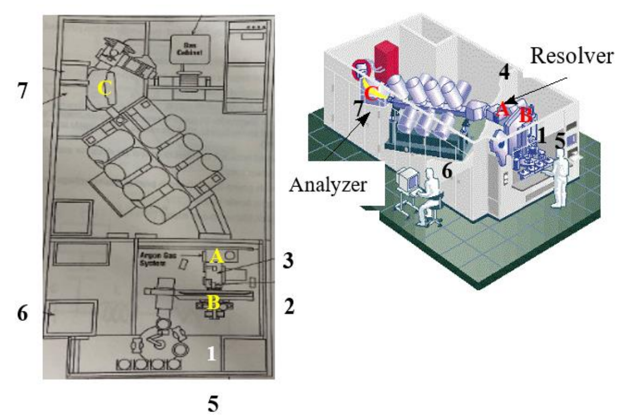

Figure 1. Locations of point of impacts A, B and C, and detector position 1 to 7.

This list of reactions is not meant to be exhaustive and is shown here only to serve as a guide to the potential ions and targets that would present a risk.

For better accuracy of the neutron dose rates reported thereafter for all experiments were integrated over a 5 min period.

The points of impact A, B, C, and the detector locations 1 to 7, as shown on Figure 1, were used.

2. NEUTRON PRODUCING REACTION CHARACTERISTICS

2.1. AS A FUNCTION OF ION ENERGY

The radiation measurements due to neutron generation from $^{1}H^{+}$, $H_2^{+}/^{2}D^{+}$, $^{4}He^{+}$ and $^{4}He^{++}$ ions when impacting the Faraday-resolver with the detector on its side (A3) as a function of energy, are shown on Figure 2. The dose rates are normalized by 300 uA of beam current for scaling purposes. For all species we notice a nearly exponential increase of the radiation dose rates with increasing energy.

Due to identical magnetic stiffness, by selecting AMU 2 for a H_2^{+} implant, some amount of deuterium ions $^{2}D^{+}$ are passing through the mass resolver and result in being accelerated along and in striking the target. In that particular scenario, it is believed that the major reactions contributing to the neutron generation are the deuterium-deuterium, $^{2}D(d,n)^{3}He$), and deuterium-carbon, $^{12}C(d,n)^{13}N$, reactions. For $^{1}H^{+}$ implantation it is believe the major reactions contributing to the neutron generation are the proton-deuterium, $^{2}D(p,n)2p$, and proton-boron, $^{11}B(p,n)^{11}C$, reactions. For helium implantation, it is hard to determine which reactions contribute principally to the neutron generation as most of them have a threshold energy of 0 MeV. For all cases, neutron generated dose rates increase nearly exponentially with the energy of incoming ions, with the $H_2^{+}/^{2}D^{+}$ reaction producing the largest neutron yield. This reaction was thus the one used and referenced in most tests throughout the paper as proving to be the worst-case scenario.

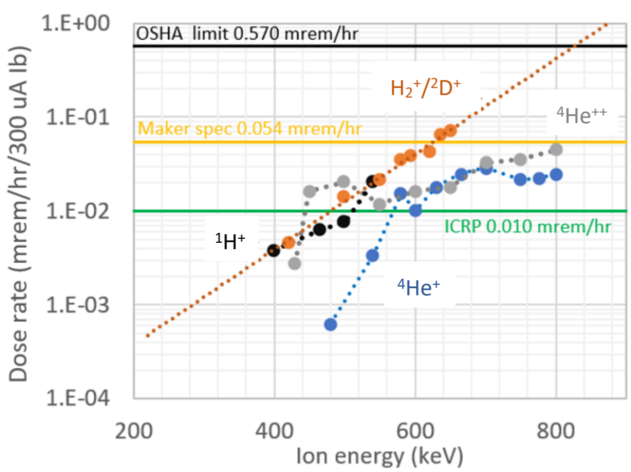

Figure 2- Relative neutron dose rate normalized by 300 uA of beam current and produced by light ion implants into the resolver (A3) recorded as a function of energy of incoming ions.

2.2. AS A FUNCTION OF ION BEAM CURRENT

The radiation measurements due to neutron generation from the same light ions as a function of the beam current at the highest energies of incoming ions are shown on Figure 3. A linear to logarithmic increase of the radiation dose rate with increasing beam current can be seen. At these high energies, only the $H_2^{+}/^{2}D^{+}$ acceleration presents a risk of neutron generation yielding a higher dose rate than the tool maker specification, but under the OSHA limit.

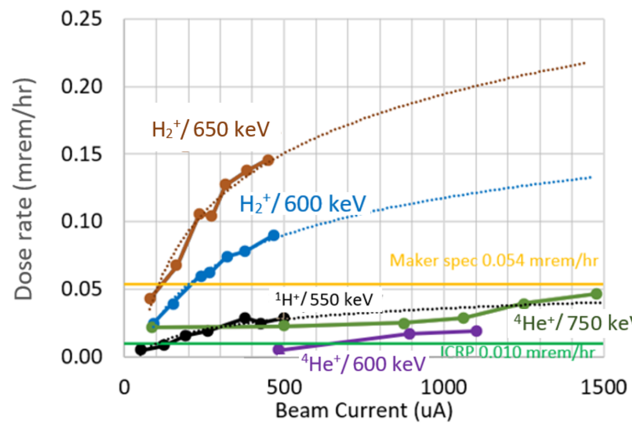

Figure 3- Absolute neutron dose rate produced by light ion implants into the resolver (A3) recorded as a function of the beam current of incoming ions.

3. TARGET MATERIAL AND DIRECTIONALITY

3.1. IMPACT AT THE RESOLVER (1A VS. 3A)

With a selection of AMU 2 (deuterium or molecular hydrogen ion), and an impact on the resolver (spot A), about 4 times more radiations were being detected when the detector was placed at 90 degrees at the side of the faraday/resolver (spot 3) compared to when it was placed at the enclosure (spot 1). The distance is about double between the side of the resolver to the impact (spot 3 to spot A), and the distance from the enclosure to the impact (spot 1 to spot A). That would be equivalent to $2^2 = 4$ times less radiation detected at the enclosure for an isotropic neutron generation. Considering deuterium ions ($^{2}D^{+}$ or d) and deuterium target, this disagrees with what Yao Zeen *et al.* [11] measured for the $^{2}D(d,n)^{3}He$ reaction and reported a more forward directional neutron generation. However, for the particularly low incoming ion energy used in this report, this is in good agreement with an isotropic neutron generation as reported by Burke *et al.* [10] for other reactions such as: $^{10}B(d,n)^{11}C$ and $^{11}B(d,n)^{12}C$ reactions, and by Cremer *et al.* [12] for $^{12}C(d,n)^{13}N$ reactions. Same results were obtained for this present study, with both $^{1}H^{+}$ and $^{4}He^{+}$ accelerations, *i.e.*, a high level of radiations was detected at 90 deg on the side of the Faraday/Resolver (spot 3) when the impact was at the resolver (spot A).

Possible false positive detection from parasitic Gamma ray emissions from the proton to boron and proton to carbon reactions were disconfirmed. The experiment was indeed replicated with increasing thickness of Pb shielding between the point of impact and the neutron detector. It yielded close to un-shielded radiation detection levels. The slight decrease in detected radiation level was attributed to the shielding of neutron realized by Pb which amount to about a 4% radiation decrease per cm of shielding.

3.2. ABOVE AND BELOW THE POINT OF IMPACT

As seen on Figure 4, with $H_2^{+}/^{2}D^{+}$ acceleration, the measurements taken at about 115 cm on the top of the resolver (A4) show a relatively high level of neutron generation but slightly lower in amplitude than the readings on the side next to the resolver (A3). Since it was found an isotropic neutron generation thus far, and literature reports quasi-isotropicity for the same reactions at these energies [5] [10] [12], using values taken at 115 cm away from the resolver to 115+35 cm from it, corresponding to the enclosure height, and to 115+35+200 cm corresponding to 2 m on top of the tool, were extrapolated. Neutron radiation levels were found to be of similar intensity to the ICRP. See Figure 4. These simulated values were using an isotropic $1/R^2$ decreasing relationship from the source of the neutrons. It showed that the level of produced neutron radiation was at the IRCP limit at 2 m above the tool, a typical value of clearance height for most fabs.

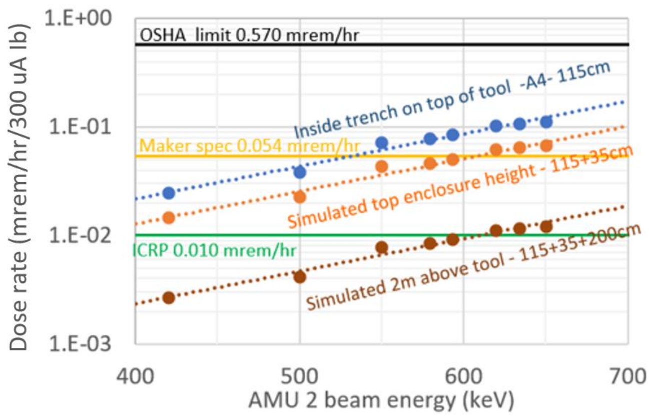

Figure 4 –Neutron generation from $H_2^+/^2D^+$ ion acceleration, normalized by 300 uA beam current and measured in the trench above the tool (blue) and simulated values at the top height of the tool (orange) and 2 m (brown) above when the impact was at resolver.

4. CONCLUSION

A neutron detection survey performed on a high energy ion implanter revealed that non negligible radiation dose rate levels were measured from neutrons being produced by reactions from light ions accelerations at a few locations around the tool under high energy and high beam current. The radiation levels were found to be all under the OSHA limit of 0.57 mrem/hr, some above the maker specification of 0.054 mrem/hr, and nearly all above the International Commission on Radiological Protection limit of 0.01 mrem/hr.

In conclusion, special considerations and care should be followed for the implantation of light ions into semiconductor compounds.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. The authors have no competing interests to declare that are relevant to the content of this article.

APPENDIX

Table 1- Effects of whole-body exposure received within few hours. Data extracted from [2].

Dose (Sv)	Dose (rem)	Effect
0.01	1	No detectable change
0.1	10	Blood changes detectable
1.5	150	Some injury; no disability
2.5	250	Injury and disability
5	500	50% deaths occur within 30 days

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