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Novel high-energy ion implantation facility using a 15 MV Tandem Van de Graaff accelerator

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DISCLAIMER

Novel high-energy ion implantation facility using a 15 MV Tandem Van de Graaff accelerator

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ABSTRACT

The implantation depths required for the development and fabrication of future generations of silicon carbide (SiC) semiconductor devices require ion energies that are well above the capabilities of most conventional ion implanters. To generate implantation profiles that extend from more than 10 μm to the surface of the wafer, a wide range of energy ions (kV to 10s of MeV) is required. We developed a novel multi-energy implantation system that satisfies these requirements using heavy ion beams from one of the Brookhaven National Laboratory's two 15 MV Tandem Van de Graaff accelerators. This system is described, including the dosimetry approach and the available ion species and intensities. Finally, an example of a measured implantation profiles in SiC is shown and compared to simulations

1- INTRODUCTION

The power electronic industry has adopted Silicon Carbide (SiC) for the next generation of medium voltage and high frequency applications. From electric vehicles to solar converters, wide band-gap SiC provides lower conduction loss and more efficient switching. Also, the high thermal conductivity of SiC compared to Silicon, makes it an attractive material for high temperature operations (>150 °C) that are not feasible with Si technology.

Ion implantation of SiC is one of the main process steps in fabrication of diodes, unipolar/bipolar transistors and thyrsitors. For Silicon devices, low energy ion implantation is followed by thermal diffusion to generate deep junctions. However, dopants diffusion constants in SiC are smaller than in Si even at high temperatures and therefore, for the same junction depth, higher energy implantation is needed. This limitation makes deep junction in SiC impractical and therefore implanted junction depth in SiC is limited to 1um using conventional ions implanters. The next generation of SiC devices require junctions deeper than 1um and therefore novel approaches to satisfy this requirement are pursued.

Implanting heavy ions such as Boron, Nitrogen or Aluminum into SiC substrates to depths up to, e.g., 15 μm requires maximum beam energies of 18 , 28 and 60 MeV respectively [1]. In addition, to achieve concentration profiles that extend to the surface of the wafer, these energies need to be variable down to at most a few keV. No single implanter can cover these ~4 orders of magnitude in energy. Having to process wafers at more than one facility is time consuming and expensive and may lead to discontinuities in the implantation profiles.

Solutions based on degrading the ion energies using variable thickness absorbers and fixed energy beams have been proposed or implemented in two different ways. In the first case [2] the energy is varied by tilting a uniform absorber foil to a series of selected angles that increase the traversed thicknesses in a preprogramed sequence. In the second case [3] a stationary absorber is appropriately patterned so that its designed non-uniformity produces an energy loss profile that results in the desired depth profile. In both cases, the maximum absorber thickness in the path of the beam equals or exceeds the range of the ions in order to obtain very low ion energies.

The ion implantation system described here uses variable ion energies and a fixed, uniform-thickness absorber foil located close to the wafers. The main purpose of this foil is to reduce the ion energies so that very low energies can be achieved for implantation profiles that start at the very surface of the wafer. To illustrate how this works, we show a simulation [1] in Fig. 1 where about half the ions stop in the absorber foil and the rest stop in the SiC wafer starting from the surface.

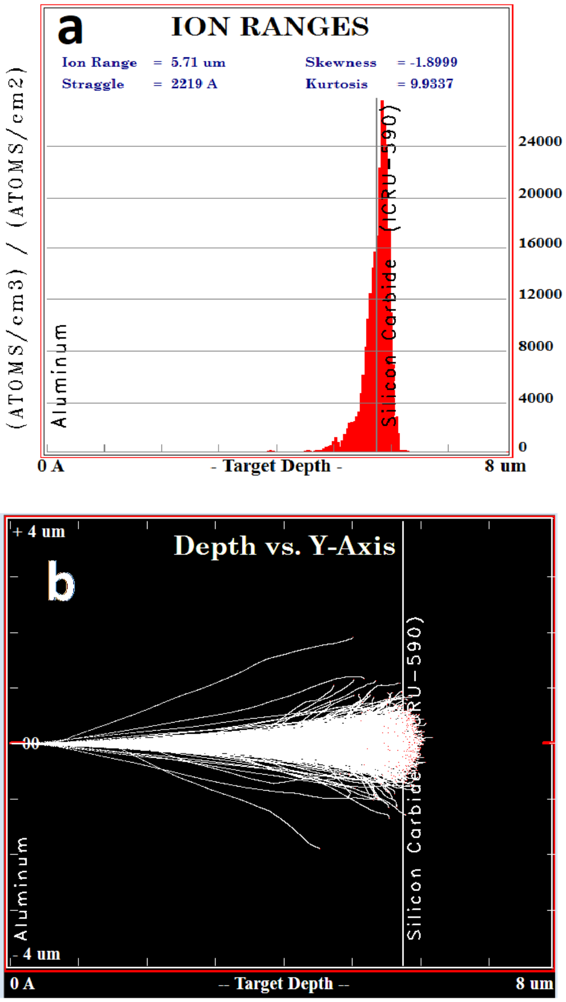

Figure 1 – Simulation [1] of a 12.4 MeV aluminum beam incident on a 5.75 μm thick aluminum absorber followed by a SiC wafer. About half of the ions stop in the aluminum absorber while the remaining ones are implanted in the SiC wafer starting from its surface. In reality the aluminum foil is at some distance from the wafer under vacuum but the result, in terms of ions stopping at various depths in each material, is the same.

A secondary benefit of the absorber foil is to increase the energy spread of the beam which reduces the number of discrete energies required to achieve a smooth depth profile. The additional energy spread is due both to energy-loss straggling in the aluminum foil as well as the effect of any foil non-uniformities. The range straggling due to energy loss straggling has been simulated by using SRIM, and the results with and without absorber are shown in Fig. 2

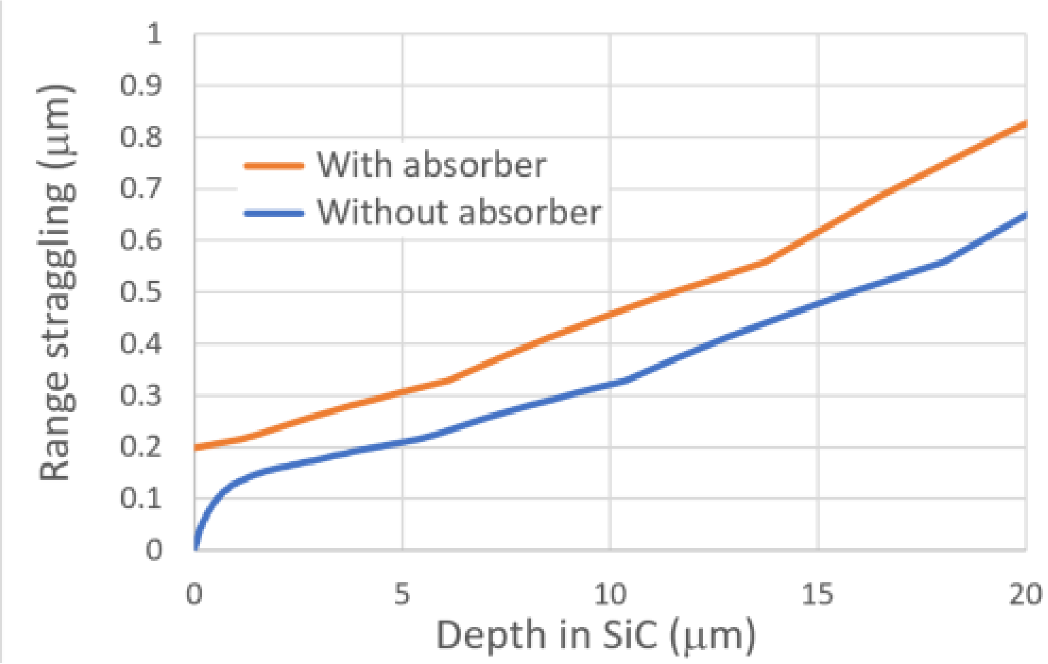

Figure 2 – Simulated range straggling of Al in SiC with and without absorber. Here the 5.75 μm thick aluminum absorber was replaced by a 4.28 μm thick SiC layer which produces the same energy loss and nearly the same energy-loss straggling.

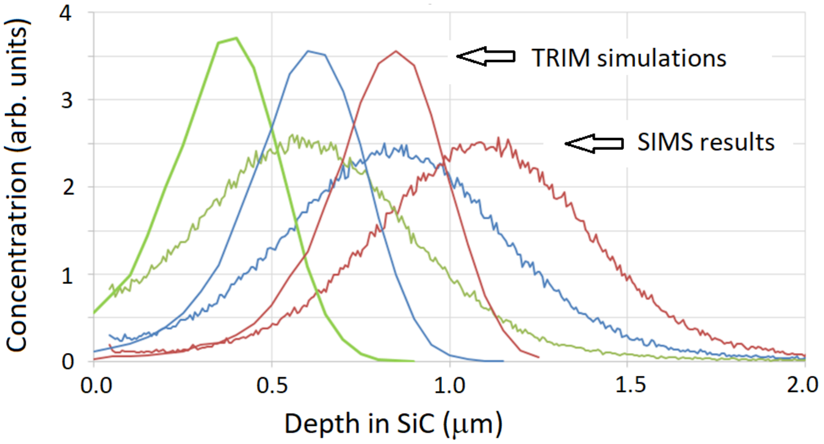

Figure 3 - Simulated and measured Al depth profiles in SiC for 13.8, 14.8 and 15. 8 MeV aluminum beams traversing a 5.75 μm-thick aluminum absorber. The effect of measured aluminum non-uniformity has been included in the simulations. The discrepancies may be due to SiC crystalline structure effects or to deficiencies of the model. The approximate beam energies required to reach similar implantation depths without the use of an absorber are 375, 650 and 900 KeV which are too low be generated at this facility.

Measured depth distributions for single-energy implantations are wider than expected from these simulations as shown in Fig. 3 for three aluminum beam energies.

In the ion implantation system described here, the wafer support plate is driven up and down at uniform speed by a linear actuator while the ion beam sweeps back and forth horizontally, also at constant velocity to achieve a uniform irradiation dose for all the wafers.

This implantation system has been installed at the Brookhaven National Laboratory (BNL) Tandem Van de Graaff (TVDG) accelerator facility [4, 5]. In the following sections we describe the capabilities of the accelerators, the wafer irradiation system, the absorber foil, the dosimetry and the control system. Next, we show how a maximum of eight 4” wafers are arranged on the linear translation stage and we provide estimates for implantation times. We then show an example of the simulations used for irradiation-planning and compare the simulation with an actual depth-concentration profile measured with Secondary Ion Mass Spectroscopy (SIMS). Finally, we summarize the experiences gained from operating this facility and we briefly mention future developments.

2- THE BNL TVDG ACCELERATOR FACILITY

The facility uses two large tandem Van de Graaff accelerators (see Fig. 4) capable of 15 MV maximum terminal voltage operation. Both accelerators can deliver light- and heavy-ion beams to two target rooms, one of which contains the vacuum chamber where the implantations are performed. The terminal voltage of these accelerators, and thus the ion energy are continuously and easily variable down to relatively low values (~1 MV for the terminal voltage) but beam intensities are not optimal at the lowest energies. A large selection of ions is available covering practically the entire table of the elements except for the noble gasses. Helium, the only noble gas that forms negative ions, will become available in 2019. In Table 1 we list the maximum energies and ranges of four ions that are of particular interest for implantation in SiC.

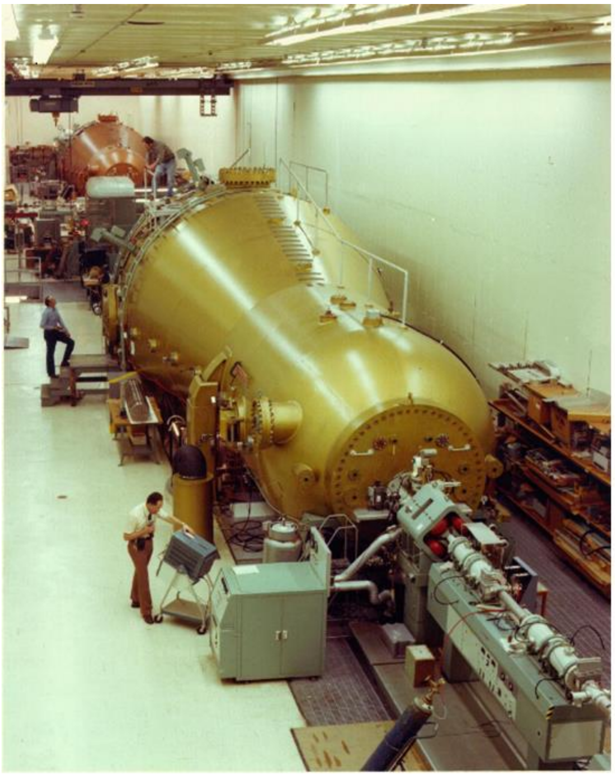

Figure 4 – View of the two BNL Tandem accelerators. Each of them can deliver ion beams either of the two target rooms.

Table 1 – Maximum energies and ranges of four typical beams

Ion species	Maximum energy	Range in SiC
	(MeV)	(μm)
B	84	131
N	77	52
Al	91	20
P	126	23

The maximum ranges in SiC listed in Table 1 include the effect of the 5.75 μm thick aluminum absorber presently in use for implantations of Al in SiC. This thickness was chosen because it provides adequate beam energy reductions to allow the accelerator to operate in an energy range where beam intensities are close to optimal. For B and Al beams the optimum thicknesses will probably be larger larger given their smaller dE/dx values.

3 - WAFER IRRADIATION SYTEM AND ALUMINUM ABSORBER FOIL

A horizontal cross section of the wafer irradiation system is shown schematically in Fig. 5. The ion beam is swept across the wafers horizontally at a frequency of 400 Hz while the wafer mounting plate moves up and down vertically at constant speed of the order of 10 mm/s. The linearity of both motions is ensured through the use of a precise triangular wave generator [6] driving the high voltage supplies [7] for the horizontal deflection and by the use of a high precision linear stage [8] for the vertical motion.

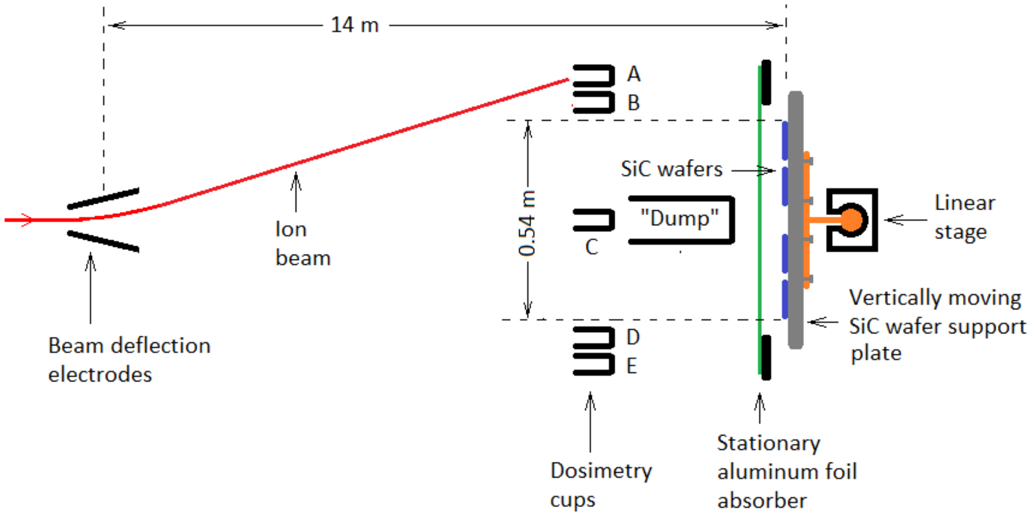

Figure 5 – Not-to-scale schematic plan view of the implantation and dosimetry system.

The 565 × 57 mm^2 aluminum foil is mounted on a fixed frame located 13 mm upstream of the wafers. The nominal thickness of the aluminum foil [9] is 5.08 μm (0.002”) while micrometer measurements show a thickness distribution centered around 6.35 μm. By weighing measured portions of the foil, and assuming a 2.70 g/cm^3 density, an effective thickness of 5.75 μm is obtained indicating the presence of some microscopic porosity.

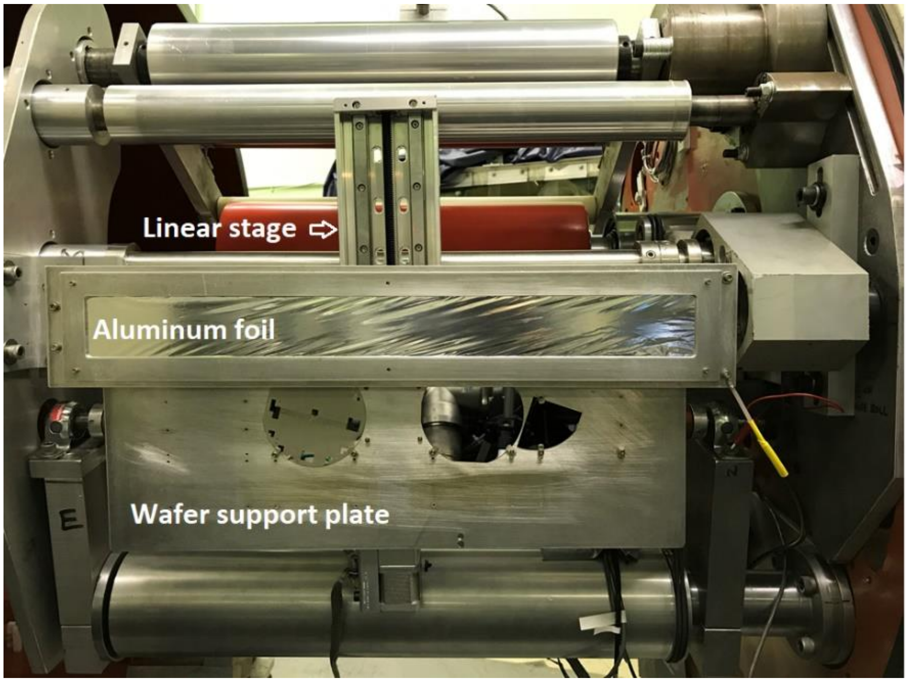

Figure 6 – Wafer support plate mounted on the linear translation stage with the absorber foil in the foreground.

A photograph of the wafer mounting plate, the linear stage and the aluminum foil can be seen in Fig. 6. The aluminum foil shows evidence of slight shrinkage due to radiation damage after about 24 hours of Al implantation runs. At present, the wafer mounting plate accommodates a maximum of eight 4” wafers or a combination of four 6” and two 4” wafers. These numbers of wafers can be increased somewhat in the future by using a larger plate mounted on a longer linear stage.

Fig. 7 shows the measured thickness distribution corrected for the porosity. The RMS thickness distribution width is 2.75% which is excellent for such a thin foil.

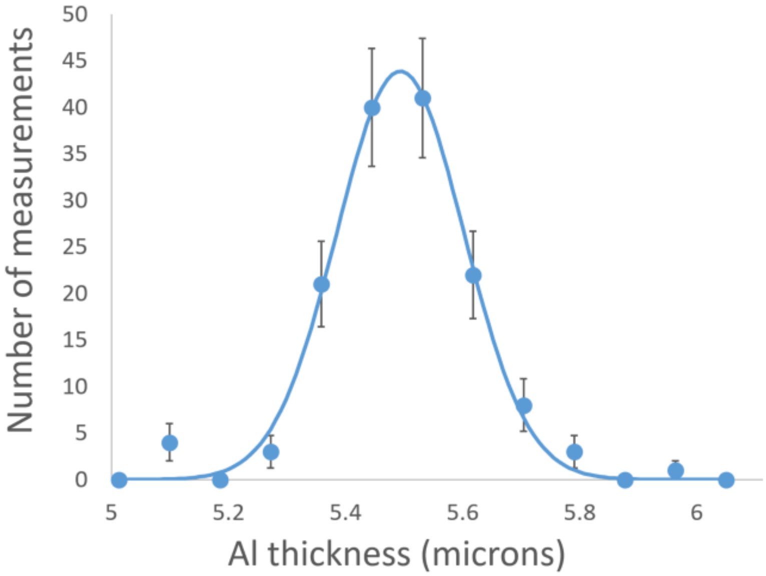

Figure 7 - Aluminum foil-thickness measurements showing an average effective thickness of 5.46 μm with a standard deviation of 0.15 μm. The foil used at present is similar but has a slightly larger effective thickness of 5.75 μm.

4 - DOSIMETRY AND CONTROL SYSTEM

The Faraday-cup-based dosimetry system is shown schematically in Fig. 5. The insertable cup labeled "dump cup" is a 95 mm diameter, 300 mm long cylinder with magnetic suppression for precision measurements used before each implantation for calibrating the much narrower (10 mm wide) "center cup" C. This cup remains inserted during the irradiation to provide the accumulated dose by counting pulses from a digital electrometer [10]. The pairs of right and left Faraday cups are utilized to adjust and monitor the width and centering of the sweep.

The user interface for the dosimetry and control system resides on a Windows pc that communicates directly with the linear-stage driver and, through an interface [11], with the electrometer [10], the Faraday cup insertion controls and various interlock switches. During operation, the stage translation velocity is readjusted automatically after each cycle to compensate for beam intensity drifts, thus ensuring that at the end of the last cycle a fluence is reached that is very close to the specified value. The system continuously updates a log that can be used for verification and for recovery from unexpected beam interruptions.

5. – WAFER ARRANGEMENTS AND IMPLANTATION-TIME ESTIMATES

Figure 8 shows the arrangement of eight 4” diameter wafers on the linear translation stage. This is the maximum number of 4” wafers that can be irradiated simultaneously at present, given the maximum linear stage travel distance of 300 mm. This maximum number of wafers can be increased to twelve in the future with a different linear stage. A typical vertical translation velocity is 10 mm/s while the beam is horizontally deflected back and forth by a linearly varying electric field with a typical frequency of 400 Hz. Since the vertical beams size is about 38 mm, there are many overlapping sweeps ensuring good implantation uniformity.

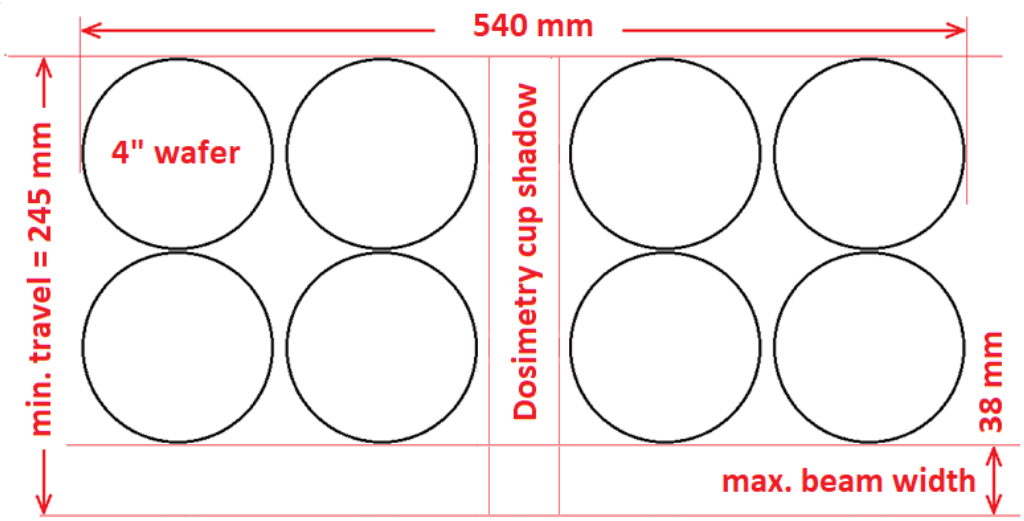

Figure 8 – Schematic showing the arrangement of eight 4” diameter wafers on the irradiation stage depicted in its uppermost position. The vertical travel distance is chosen to be large enough so that the wafers clear the horizontally sweeping beam area in both the uppermost and lowest positions to insure to insure uniform beam coverage. For the same reason and to reach the dosimetry cups A, B, D and E shown in Fig. 5, the horizontal beam sweep width is approximately 650 mm.

This somewhat unusual implantation scheme was dictated by the existing beam transport and horizontal beam deflection system originally designed for irradiating rolls of plastic films, the material being guided by a web transport. The same approach with the energy degrading aluminum foil will work for a more conventional implantation system with horizontal and vertical beam deflection. The required aluminum foil area would be much larger, but that should not be a problem.

As indicated in Fig 8, the total rectangular irradiated area is somewhat larger than the extent of the wafers to accommodate the areas required for dosimetry and to avoid non-uniformities at the top and bottom edges. Taking this into account and using typical aluminum beam intensities available at present, we show estimates in Fig. 9 of irradiation times for a set of 8 4" wafers and various combinations of concentration and maximum depths in SiC. These estimates are based on the available Al beam intensity of about 3E12 ions per second.

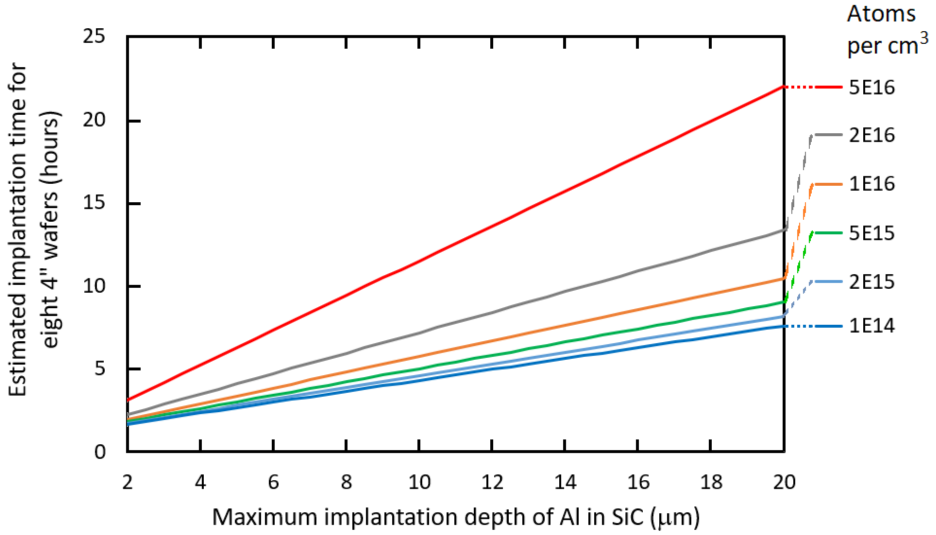

Figure 9 – Estimated Al implantation times in SiC as function of maximum implantation depth for uniform ("box") profiles with several concentration values. For concentrations larger than 5E16 atoms per cm^3, the time required for energy changes becomes nearly negligible and implantation times can be estimated with linear scaling. For the other ions listed in Table 1, estimated Implantation times for the range of depths shown here will be approximately the same

Aluminum foil lifetime due to radiation damage has not been a limiting factor. After ~24 hours of implantation, the foil exhibits some stretch-marks (see Fig. 6) and is changed at this time as a precaution. At that point, the maximum fluence is estimated to be of the order of 3E15 Al ions per cm^2.

6. – SIMULATED AND MEASURED DEPTH PROFILES

An Excel spreadsheet simulation based on TRIM [1] results is used for planning the sequence of beam energies and fluence values which when superimposed will generate the desired implantation profile. For this simulation the individual energy depth profiles are modelled as Gaussian distributions centered on the range values predicted by TRIM, and on widths that are larger than predicted by TRIM considering results from single-energy implantations. The reasons for this widening can only be partially accounted for by foil porosity or non-uniformity as determined by absorption measurements using a α-ray source.

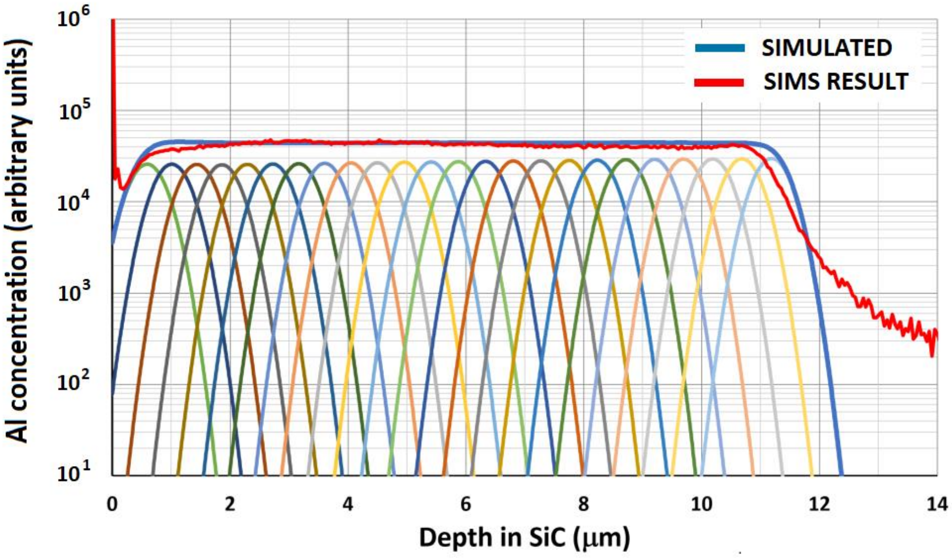

Figure 10 – SIMS results [12] and simulated Al implantation profile in SiC with a 5.75 μm thick Al absorber using 24 Al beam energies ranging form 13.8 to 59.8 MeV.

A comparison of the SIMS-measured profile [12] with the model prediction is shown in Fig. 8 for one of the latest implantations. In this case, the requested dose differed from the SIMS-measured dose by only 0.87 %. Much larger discrepancies have been seen in the past; but always within acceptable ranges. The dosimetry should be accurate within at most ±2%. Possible reasons for these apparent discrepancies are being investigated.

7 - DISCUSSION AND CONCLUSIONS

The multi-energy implantation through a uniform absorber-foil has proven to be a good solution for obtaining well controlled implantation profiles. A disadvantage of this approach compared to the approaches described in references [2] and [3] is the time required for the beam energy changes. The experience with a recent implantation was that the total time spent for energy changes amounted to approximately 30% of the total time the facility was used. This percentage will be reduced in the future by implementing greater automation. Advantages of the present approach include excellent dosimetry, total flexibility in shaping the implantation profiles and the use of very inexpensive and relatively robust absorber foils that can be easily changed as often as necessary.

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