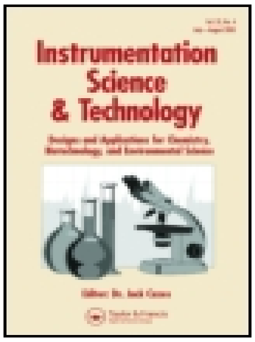

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Characterization of a single electrode focusing lens for ion beam deceleration

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ABSTRACT

An ion beam deceleration system was studied for the high-current ion implanter at the Laboratório de Aceleradores e Tecnologias de Radiação at the Campus Tecnológico e Nuclear, of Instituto Superior Técnico. The installed system consists of a target plate and one electrostatic focusing lens with one electrode. This article describes the results of the evaluation of the new system. With this upgrade, the ion implanter provides enhanced versatility for decelerating to 5 keV a high current ion beam at the µA level. This implantation provides a wide area and allows for a continuous magnetic beam scanning, extending the energy range to lower values, opening up a wider set of applications.

KEYWORDS
Deceleration; electrostatic Einzel lens; fluence; ion implantation

Introduction

Low energy ion implantation is very important, not only to microelectronics technology,[1,2] but also to simulate plasma wall interaction processes in fusion reactor conditions[3,4] and nanopatterning.[5–7] High current ion implanters like the one installed at the Laboratório de Aceleradores e Tecnologias de Radiação (LATR) are not efficient for low-energy (less than 15 keV) implantation due to the ion optics, so in order to maintain the reliability and quality of existing implanter, it is necessary to decelerate the ion beam before hitting the target. The most widely used method to decelerate a positive ion beam is to bias the sample target using a high voltage power supply, thus creating an electric field opposed to the beam trajectory, focusing the beam by the use of electrostatic lenses.[1,8]

Other systems, like the Varian Extrion Series 400 implanter,[9] modified a conventional ion implanter with the purpose of implanting at ultralow energies (0.5–5 keV). To perform this type of implantations, the ion beam is decelerated to the desired energy just prior to impacting the substrate, thereby minimizing beam expansion and beam current reduction. Due to the fact that the ion source presents some variations, an acceleration source

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is directly connected from the ion source to the target with a voltage range from $-1\,\text{kV}$ to $-5\,\text{kV}$. Thus, variations on the acceleration source have no effect on the deceleration voltage. This system is only applicable in developments in which the dimensions are reduced, so beam scanning is only possible by moving the sample mechanically.[9]

Another example of a deceleration system is at the Dresden Laboratory[10] that consists on a converging and a diverging lens in a compact arrangement. Therefore, implantation into larger areas at low energies may be performed with high fluence uniformity. Using a beam energy of 30 keV, ions may be decelerated down to 2 keV with a fluence uniformity better than 5% over 100 mm diameter. This ion implanter allows beam scanning of the sample, although the focusing system does not permit a clear view of the target.[10] Also, the fluence control only allows beam sweeping over the entire area of the target, limiting the implantation to one sample at a time.

Another deceleration system, at the Philips Research Laboratories in the Netherlands, specially designed for low-energy implantation, is composed of two ion sources biased at 30 kV.[11] The deceleration is performed using a multiple electrode system with the beam passing through the Einzel lens to be focused on the target.[11] This system has the whole deceleration assembly biased and all dimensions and biasing were set with low-energy implantations of standard Si wafers in mind, so it is not a general purpose system. In these cases, the goal was to implant one large target with high uniformity, typically a silicon wafer, using the whole lens area for fluence control with Faraday Cup system installed at the lens aperture.

The objective of the system developed at LATR was to fully use the beam offset and scanning possibilities of the implanter while decelerating and focusing the beam from 15 keV to 5 keV. The high current ion implanter at LATR is a standard medium energy Danfysik 1090, from 1992, model for use of general purpose implantations, with a maximum acceleration voltage of 50 kV (extraction) plus 160 kV (pos-acceleration), allowing a minimum of approximately 15 kV at the ion source for extraction of a focused beam. Hence, the minimum energy is 15 keV for monoionized species. With this implanter model, low energy (below 5 keV) uniform implantations were shown to be possible across a 100 mm diameter circular area, either using a standard deceleration system as in Gwilliam et al.[12] or an enhanced deceleration system as in Teichert et al.[10]

The purpose of the deceleration system at LATR was to produce general purpose low-energy ion implantations from 15 keV to less than 5 keV on several small targets with different energies and fluences while maintaining uniformity and fluence control. Hence, it is necessary to have a clear view of the target through the glass window installed on the chamber side, which is not possible with the compact systems described in Hong et al.[9] and Teichert et al.[10]

Installed deceleration system

The designed deceleration system, shown in Figure 1, consists of an insulated target plate mounted over the implanter target and a single electrode lens to compensate beam dispersion due to target biasing, on a larger as possible area. The target is 28 cm in diameter, and the lens, composed by a group of 6 stacked aluminium rings with 30 cm diameter, 5 cm length, and 1 cm width, is positioned 10 cm downstream of the target (Figure 1a). The stacked rings

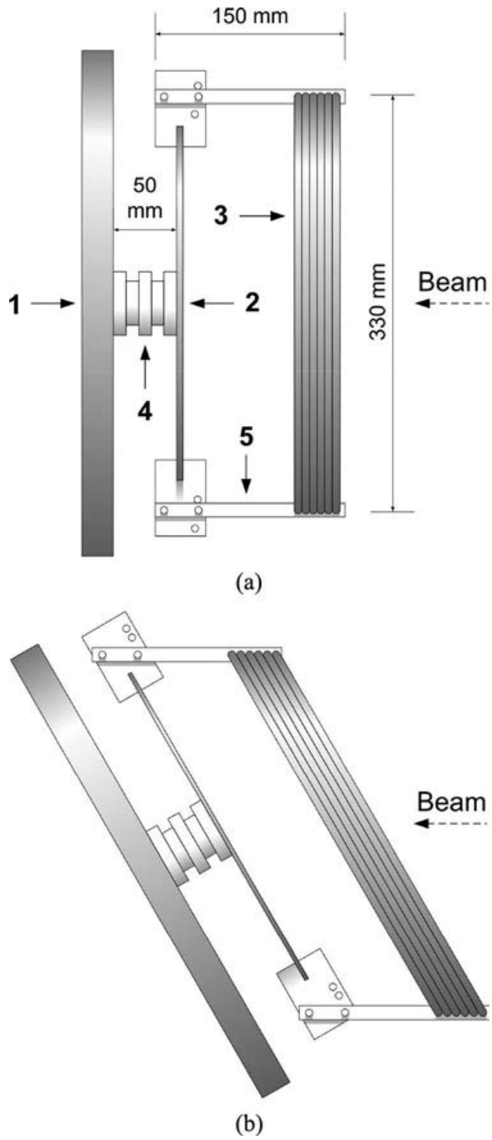

Figure 1. Deceleration system: (a) components include the (1) implanter target; (2) deceleration target; (3) lens; (4) deceleration target support (insulator); and (5) lens support (insulator) and (b) system tilted to allow 30° beam incident angle.

were oriented so that the lens may be tilted up to 30°, allowing different beam incident angles (Figure 1b).

The calculations involved on establishing the dimensions, such as length of the lens, distance between target and lens and voltages applied to target and lens, were made using electrostatic principles and equations including the electric field created by a charged disc and ring and the effects of a non-uniform electric field over a moving positive ion. These calculations helped establishing the best overall geometry for the system as well as the system's maximum useful area for implantation and are described in detail in Lopes and Rocha.[13] In order to characterize the system, the simulation software Simion 8.0[14] was used.

For Ar^+ beam simulation, 15 trajectories of 40 amu single ionized particles were used, spread over an angle from +5° to −5°, with initial energy of 15 keV and starting point at 1460 mm from the target, which is about the same distance from the center of sweeping magnets to the target on the implanter. The simulation provided a beam trajectory correction of less than 5 mm from the non-charged target position, thus obtaining a useful beam sweeping area of about 15 cm × 15 cm, which may vary depending on the desired final energy. Several trajectories were simulated for an ion beam with an initial energy of 15 keV.

Figure 2 shows a simulation with an initial energy of 15 keV and the target potential equal to 10 kV. Beam trajectories are represented in blue. Field equipotentials are represented in red. Figure 2 shows the way in which the beam is deflected when the target is biased. To compensate for the deflection, a charged lens with only one electrode was used. Several simulations were made using the deceleration system with Ar^+ beam on a biased target with the potentials of 5 kV, 10 kV, and 14 kV, corresponding to final energies of 10 keV, 5 keV, and 1 keV, as shown in Figure 3.

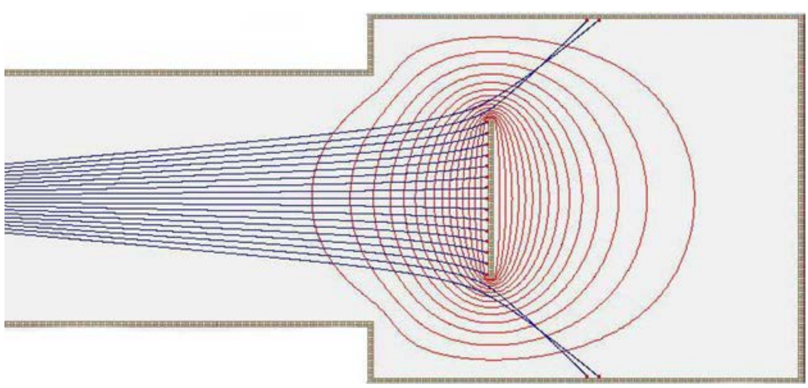

Figure 2. Simulation for an initial beam energy of 15 keV, a final beam energy of 5 keV, and a target bias of 10 kV.

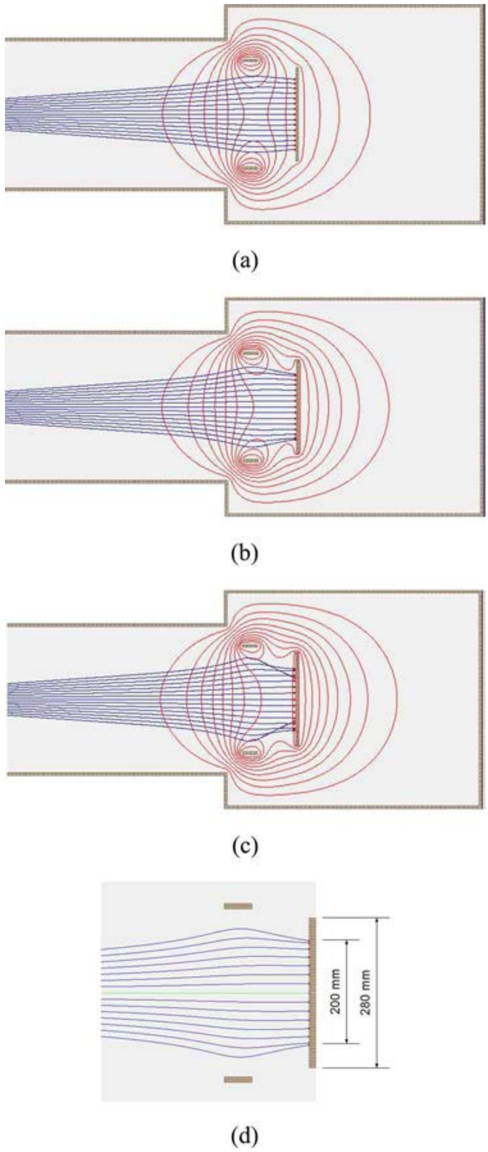

Figure 3. Simulations for equipotential surfaces for deceleration beam for an initial energy of 15 keV Ar^+: (a) final beam energy of 10 keV, target bias of 5 kV, lens of 12.5 kV; (b) final beam energy of 5 keV, target bias of 10 kV, lens of 15.5 kV; (c) initial beam energy of 15 keV, final beam energy of 1 keV, target bias of 14 kV, of lens 17 kV; and (d) details with dimensions of the target diameter and useful area diameter for a final beam energy of 5 keV.

Hence, the simulation demonstrated that using a charged lens with a single electrode biased at a calculated potential, most trajectories may redirected to its original path, thus avoiding beam dispersion caused by target biasing. The simulation also shows over-deflection of outmost trajectories. In addition, the simulation also shows that, for a beam energy of 5 keV, the useful implantation area is expected to be about 20 cm in diameter, and for an energy of 1 keV, due to over deflection of the beam near the target border, the diameter is reduced to about 15 cm.

Experimental measurements

Two sets of implantations were made to validate the designed system, one to characterize the energy accuracy and the other the fluence uniformity. First, to characterize the energy accuracy, four graphite samples were placed on the deceleration target, as shown in Figure 4a. The samples were implanted with Xe^{+} beam using a beam sweep of 3 cm × 3 cm with a different energy each: sample 1 with 50 keV, target grounded; sample 2 with 30 keV, target grounded; sample 3 with 10 keV, 20 keV beam and target at 10 kV; and sample 4 with 5 keV, 20 keV beam and target at 15 kV. All implantations were made without breaking the vacuum.

To characterize the fluence uniformity, 12 identical silicon samples taken from the same wafer were implanted in 3 sets of 4 samples. Each set of samples was placed on the deceleration target as shown on Figure 4b and implanted with 5 keV Ar^{+} beam with a nominal fluence of 5×10^{15} at cm^{-2} and a beam sweep of 10 cm × 10 cm. The first set was implanted with initial beam energy of 5 keV and target grounded while the second set had an initial beam energy of 15 keV, 10 kV target bias, and no lens. The third

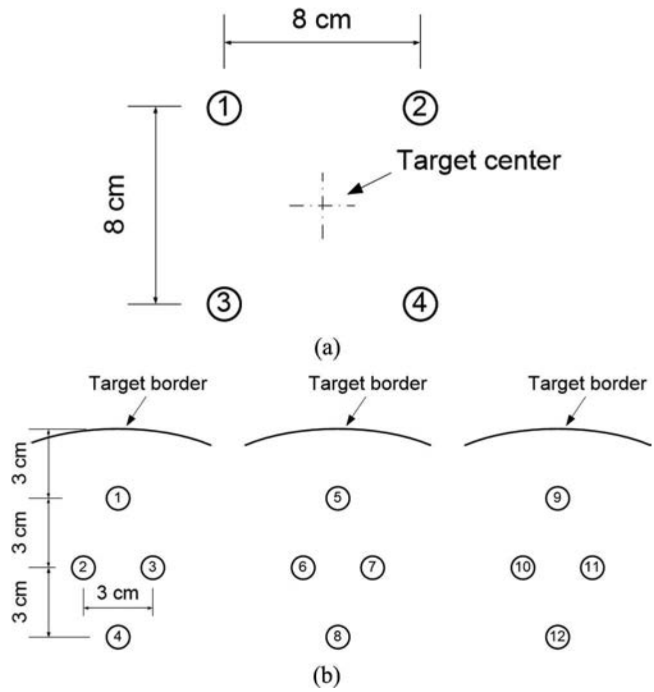

Figure 4. Characterization of (a) 4 graphite samples to characterize the energy accuracy and (b) 12 silicon samples for the fluence uniformity.

Sample	1	2	3	4
Beam energy (keV)	50	30	20	20
Target bias (kV)	0	0	10	15
Final energy (keV)	50	30	10	5

(a)

Sample	1	2	3	4	5	6	7	8	9	10	11	12
Beam energy (keV)	5	5	5	5	15	15	15	15	15	15	15	15
Target bias (kV)	0	0	0	0	10	10	10	10	10	10	10	10
Lens bias (kV)	-	-	-	-	-	-	-	-	15.5	15.5	15.5	15.5
Final energy (keV)	5	5	5	5	5	5	5	5	5	5	5	5

(b)

Figure 5. Conditions for (a) energy accuracy and (b) fluence uniformity.

set was implanted with beam energy of 15 keV, 10 kV target bias and 15.5 kV lens bias. The sample conditions for these measurements are shown in Figure 5.

Results

Rutherford backscattering spectrometry (RBS) was used to analyze the elemental composition of the near-surface region. A depth resolution of ~10 nm for 1.5 MeV He^+ was obtained in the grazing-angle geometry, using a 1 mm diameter collimated beam of 1.5 MeV He^+ ions incident angle of 30°, scattering angle of −140. The resulting spectra for the energy accuracy are shown on Figure 6. The RBS spectra show a Gaussian profile with increased implantation energy, due to the energy loss of a penetrating ion in the sample The depth distribution is in agreement with previous results SRIM[15] after convolution of the RBS resolution. In each sample, several points were measured in order to test the fluency homogeneity. The fluency variations are lower than the error in the measurement.

The fluence results are shown in Figure 7. The implanted fluence is determined from the RBS analysis; a more uniform fluence is achieved with the target and lens biased. On the first set of samples, with target grounded, the beam with initial energy of 5 keV suffers too much dispersion along the beam line.[16–18] The results with deceleration but without the lens show that, as expected, that fluence was lower on the samples located near the target border due to beam divergence (Figure 2).

The set, with deceleration and the lens, shows some homogeneity. As predicted by the simulation, the fluence is higher for the outermost samples due to beam over-deflection, although the uniformity inside the predicted

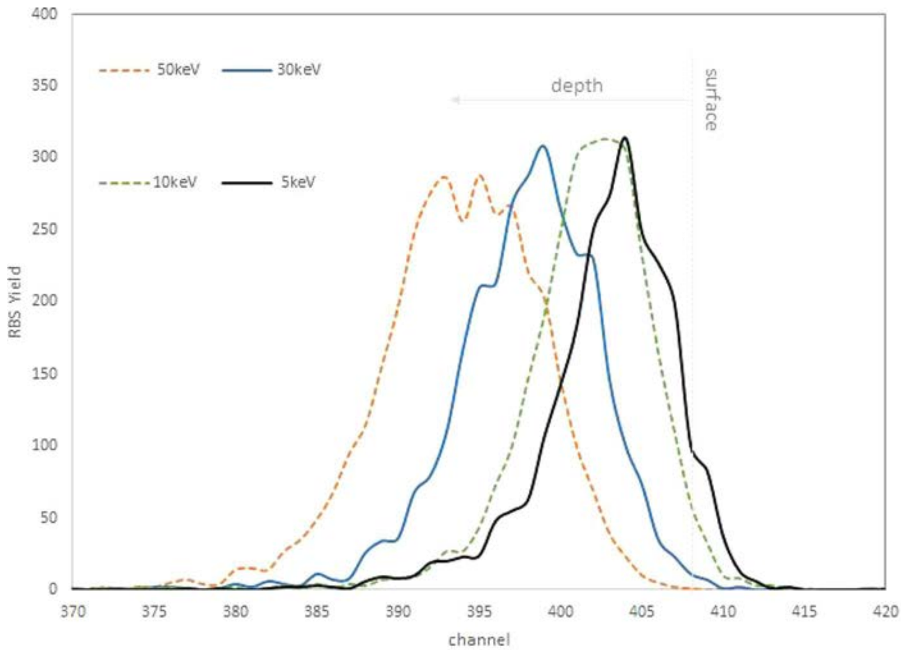

Figure 6. Comparison of RBS spectra for Xe^{+} implanted in C as a function of energy.

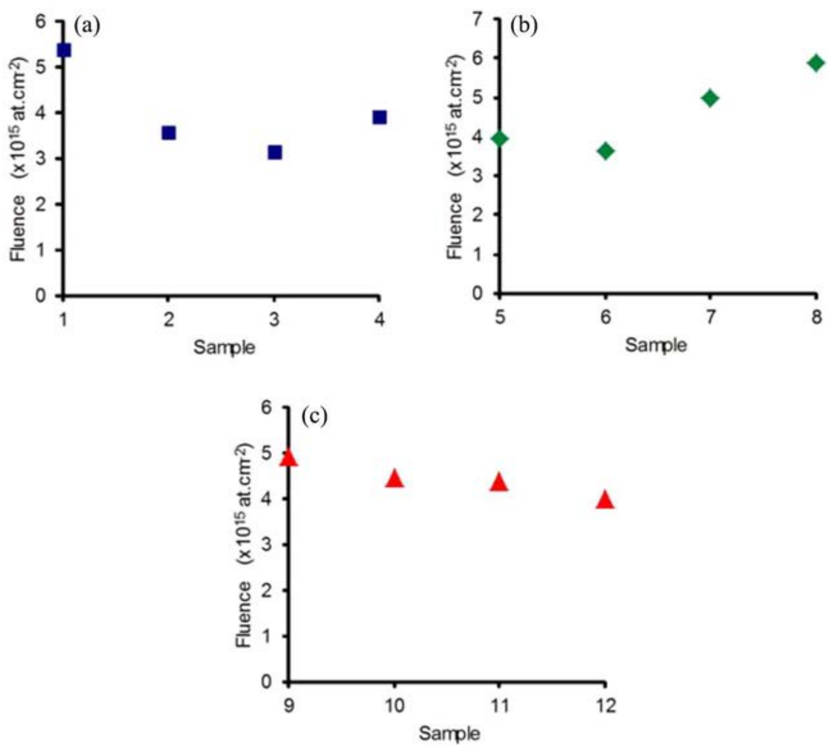

Figure 7. Fluence uniformity on a (a) grounded target; (b) target at 10 kV with no lens; and (c) target at 10 kV and lens at 15.5 kV.

area of 20 cm in diameter is within 10%. These results demonstrate well-behaved deceleration system for low energy implantations that is versatile, easy to assemble on the implantation chamber, and with a clear view of the target.

The lens system demonstrated good energy accuracy on the 15 keV to 5 keV energy region. Hence, it was possible to implant up to 4 small samples on the same batch with different energies, where the samples are spaced only by 8 cm, focusing the beam on each sample individually.

Conclusions

The reported system enables implantations at low energies (down to 5 keV) allowing continuous scanning of the ion beam on a sample. In addition, the system shows good uniformity and fluence accuracy when restricted to an area of 15–20 cm diameter on the center of the target depending on the deceleration required. In order to improve the fluence control, and considering the results shown on Figure 7c, a calibration of fluence is necessary by inserting a correction factor as mentioned in Teichert et al.[10] or another procedure. Further implantation protocols are needed for fluence calibration and also for focus and deceleration calibration, which is a subject for future study. Future goals are to optimize the system for deceleration and focus for ion implantation with final energies lower than 2 keV.

References

[1] Kase, M.; Kubo, T.; Niwa, H.; Fukuda, T. In *Issues of Ultra Shallow Junction Formation using Sub-1 keV Ion Implantation*, Proceedings of the 1998 International Conference on Ion Implantation Technology, Vol. 1, IEEE, Kyoto, June 22–26, 1998; pp. 110–113.

[2] Wan, Z; Chen, J.; Tang, D.; Chen, L. In *Energy Contamination Control during Ion Beam Deceleration for Low Energy Ion Implantation*, Proceedings of the 14th International Conference on Ion Implantation Technology, IEEE, Taos, New Mexico, 2002; pp. 221–224.

[3] Mateus, R.; Dias, M.; Lopes, J.; Rocha, J.; Duarte, P.; Gomes, R. B.; Fernandes, H.; Silva, C.; Livramento, V.; Correia, J. B.; Carvalho, P. A.; Hanada, K.; Alves, E. Blistering of W-Ta Composites at Different Irradiation Energies. *J. Nucl. Mater.* **2013**, *438* (Supplement), S1032–S1035.

[4] Mateus, R.; Dias, M.; Lopes, J.; Rocha, J.; Catarino, N.; Franco, N.; Livramento, V.; Carvalho, P. A.; Correia, J. B.; Hanada, K.; Alves, E. Effects of Helium and Deuterium Irradiation on SPS sintered W–Ta Composites at Different Temperatures. *J. Nucl. Mater.* **2013**, *442*(1–3;Sup. 1), S251–S255.

[5] Hershcovitch, A. Ion Sources for High and Low Energy Extremes of Ion Implantation, 35th International Conference on Plasma Science, IEEE, ICOPS 2008. Karlsruhe, 2008, pp. 1–1.

[6] Graf, M. A.; Vanderberg, B.; Benveniste, V.; Tieger, D. R.; Ye, J. Low energy ion beam transport, Proceedings of the 14th International Conference on Ion Implantation Technology, Taos, New Mexico, USA, pp. 359–364, 2002, IEEE.

[7] Gotoh, Y.; Sakai, Y.; Tsuji, H.; Ishikawa, J.; Sakai, S. Differences in Deceleration Performance of Electrons Emitted from Field Emitter Arrays with Different Electrode Geometries, 23rd International Vacuum Nanoelectronics Conference (IVNC 2010), IEEE, Palo Alto, CA, 2010; pp. 203–204.
[8] Ziegler, J. F. *Ion Implantation: Science and Technology*, 6th ed. Academic Press, Inc., 2006.
[9] Hong, S. N.; Ruggles, G. A.; Paulos, J. J.; Wortman, J. J.; Ozturk, M. C. Formation of Ultrashallow p+−n junctions by Low-energy Boron Implantation using a Modified Ion Implanter. *Appl. Phys. Lett.* **1988**, *53*, 1743.
[10] Teichert, J.; Borany, J. Decel Lens for System for Low-energy Ion Implantation with High Dose Uniformity, Conference on Ion Implantation Technology, Alpbach, 2000; pp. 388–391.
[11] Gottdang, A.; Eich, K.; Hassenburger, A.; Schulte, W. H.; Clef, B.; Mous, D. J. W.; Koudijs, R.; van de Walle, G. F. A.; Politiek, J. A Dual Source Low-energy Ion Implantation System for Use in Silicon Molecular Beam Epitaxy. *Nucl. Instrum. Meth. Phys. Res. Sec. B Beam Interact. Mater. Atoms* **1991**, *55*(1–4), 310–313.
[12] Gwilliam, R.; Nejim, A.; Knights, A.; Sealy, B. In Uniformity and Dosimetry Study of the 30 kV Danfysik Decel Lens System. Proceedings of 1998 International Conference on Ion Implantation Technology, vol. 1, 1998, Kyoto; pp. 377–380.
[13] Lopes, J.; Rocha, J. Simple General Purpose Ion Beam Deceleration System Using a Single Electrode Lens. *World J. Eng. Technol.* **2015**, *3*, 127–133.
[14] Dahl, D. A. *Simion 3D version 8.0 - User's Manual, Idaho National Engineering and Environmental Laboratory*, I D 3415, 2000.
[15] Ziegler, J. F.; Ziegler, M. D.; Biersack, J. P. SRIM - The Stopping and Range of Ions in Matter. *Nucl. Instrum. Meth. Phys. Res. Sec. B Beam Interact. Mater. Atoms* **2010**, *268* (11–12), 1818–1823.
[16] Shimizu, S.; Sasaki, N.; Ogata, S.; Tsukakoshi, O. Ion Beam Deceleration Characteristics of a High-current, Mass-separated, Low-energy Ion Beam Deposition System. *Rev. Sci. Instrum.* **1996**, *67*, 3664–3671.
[17] Ranganathan, R.; Krull, W.; Sundstrom, H.; Mack, M.; Sedgewick, J.; Eddy, R. In *Characterization of a High Current Ultra Low Energy Ion Implanter*, Proceedings of 1998 International Conference on Ion Implantation Technology, vol. 1, Kyoto, 1999; pp. 618–621.
[18] Fukaya, T.; Hara, S.; Tanaka, Y.; Matsumoto, S.; Suzuki, T.; Fuse, G.; Kudo, T.; Sakuragi, S. Formation of Ultra-shallow Junction with ~10 nm in Si Combined with Low Temperature and Laser Annealing, 5th International Symposium on Advanced Science and Technology of Silicon Materials (JSPS Si Symposium), Kona, Hawaii, Nov. 10–14, 2008.