A 1.2MeV, 100mA Proton Implanter

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Abstract

A high energy, high current proton implanter has been developed for producing thin layers of c-Si crystalline silicon with thicknesses in the range of 5-20 µm. The implanter described is designed to operate at energies between 0.4-1.2 MeV with proton beam currents up to 100 mA. This system can also be used to exfoliate other materials such as GaAs and SiC.

Introduction

There is an increasing demand for renewable energy using photovoltaic technology. In particular, photovoltaic cells are commonly fabricated on crystalline silicon wafers which are conventionally produced by slicing an ingot of single crystal silicon. This method of producing photovoltaic cells accounts for approximately 80% of the present worldwide production of solar cells. Unfortunately 50% or more of the silicon is lost as a result of the kerf consumed in the slicing process. Furthermore, the minimum wafer thickness that can be produced by sawing or slicing is ≥115 µm, which is much thicker than needed for optimum photovoltaic devices (1). Thinner silicon lamina can be made by implanting hydrogen ions to the desired depth below the surface of the silicon wafer. After a suitable number of ions have been implanted, a thin layer of micro bubbles is formed and on subsequent heating of the wafer, the top layer exfoliates to produce a thin layer of silicon with a thickness precisely equal to the depth of the original implanted layer (2). Using this technique, as many as 10 or more layers of silicon can be peeled from a standard silicon wafer, each having the ideal thickness for the fabrication of an efficient photovoltaic cell. In this way the cost of the single crystal silicon material, which is generally the dominant cost component of the finished cell, can be reduced by 80%. An added benefit is the fact that the cells made from the thin lamina are flexible.

In the last 3 years we have investigated the potential advantages of lamina based photovoltaic cells in detail (1). Early work was based on an air insulated DC accelerator operating with a ribbon beam of protons in the energy range of 350-420 keV and beam currents of 10-75 mA (3). Critical process steps including light trapping schemes, and metal contact techniques have been developed using the 4.5 µm lamina produced by this machine. As the lamina thickness increases the cell efficiency can increase but the cost of increasing the energy and operating voltage of the accelerator also increases. The implanter described here operates routinely at energies between 0.4-1.2 MV and beam currents up to 100 mA. These basic parameters represent an optimum compromise between cell performance and total implanter operating cost.

An ion implanter suitable for solar cell production of the type described has three primary requirements: an acceleration scheme which will accelerate the ions to the velocity required for penetration to the appropriate depth below the surface, a beam current intensity that results in the required system productivity and high speed wafer handling.

The novel implanter described operates with proton currents up to 100 mA and energies up to 1.2 MeV and the wafer handling non-productive time is <8% of the total cycle time.

System Architecture and performance targets

The high beam power requirements outlined present two primary challenges. First the 120 kW ion beam must be generated with reasonable power efficiency and second the process chamber must be capable of absorbing this power without excessive heating of the target wafers.

The challenges have been met by adopting the system architecture shown in Figure 1 which identifies the major components of the implanter. There are 4 basic types of ion accelerator structures that can be used to accelerate ions to the MeV energy range: linear high frequency (LINAC), circular high frequency (Cyclotron, synchrotron), RFQ (RF quadrupole accelerators) and DC (Single ended or Tandem). The power conversion efficiency of these systems can be defined as the ratio of final beam power to total input power. In the case of RF type accelerators the power efficiency is generally low (≤20%) as a result of losses in the amplifier and resonant cavity components. For this reason a DC approach was adopted using standard commercial high voltage power supplies

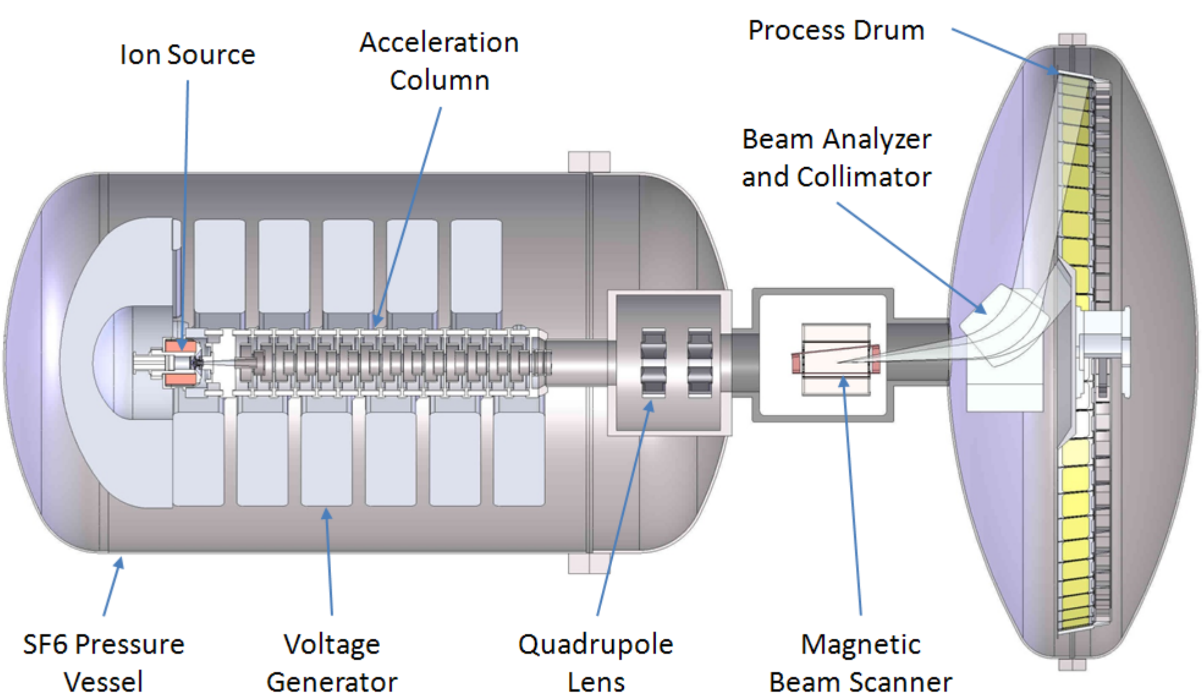

Figure 1 System architecture

The ion source, the acceleration tube and the high voltage generator are contained within a pressure vessel with a diameter of 2.1 m and a length of 4.1 m. The vessel contains compressed SF_6 gas at a pressure in the range 50-100 psi to facilitate operation at voltages up to 1.2 MV. The ion beam which emerges from this beam generation system is focused by a magnetic quadrupole lens and directed into a magnetic scanner system which deflects and scans the beam in the horizontal plane as shown. The scanned beam is then deflected and analyzed by a magnetic dipole magnet which serves to filter out unwanted ion beams and direct the collimated beam onto the inside of a large diameter rotating process drum. The pseudo-square silicon wafers are mounted on the inside of the drum during implant and between implants, high speed robots are used to load and unload these wafers through a vacuum load-lock system.

The basic performance targets for the system are summarized in Table 1.

Table 1 Implanter design targets

Lamina Thickness	5-20microns
Lamina Production rate	150 /hour
System Energy requirements	<2kWhrs/lamina
Ion Beam Energy	0.4-1.2MeV
Proton beam current	100mA
Power efficiency (Beam power/total power)	>40%
Machine utilization	>90%

Voltage Generator

Most high power DC ion accelerators have incorporated some form of cascade-rectifier voltage multiplier based on the concepts of John Cockroft and Ernest Walton to generate the high potentials required to accelerate the ions(4). The output of the generator is connected to the ion source and determines the final energy of the ions. Ions extracted from the source pass into an acceleration tube consisting of several electrodes and the appropriate bias voltages for these electrodes is generally derived from potential divider resistors connected to the output of the high voltage generator. As the beam current in such a system is increased, several difficulties can be encountered. The two primary challenges are summarized in Table 2.

Table 2 Fundamental challenges for high current, high voltage DC accelerators

1.High voltage generation and power efficiency	Since the output power must flow through each multiplier stage in series, the available output power, the voltage regulation and the system efficiency declines as more stages are added.
2.Production of a stable electrostatic acceleration field	Small beam currents intercepting the acceleration electrodes can result in large perturbations of the accelerating field which in turn leads to break down and avalanche effects. These intercepted beams may originate as a result of small aberrations or charge exchange with residual gas molecules in the vacuum system. Attempts to minimize these effects by decreasing the value of resistive dividers results in wasted power and further loss of efficiency.

We have developed a novel power supply system which overcomes the two primary challenges outlined above. The system concept is shown schematically in Figure 2.

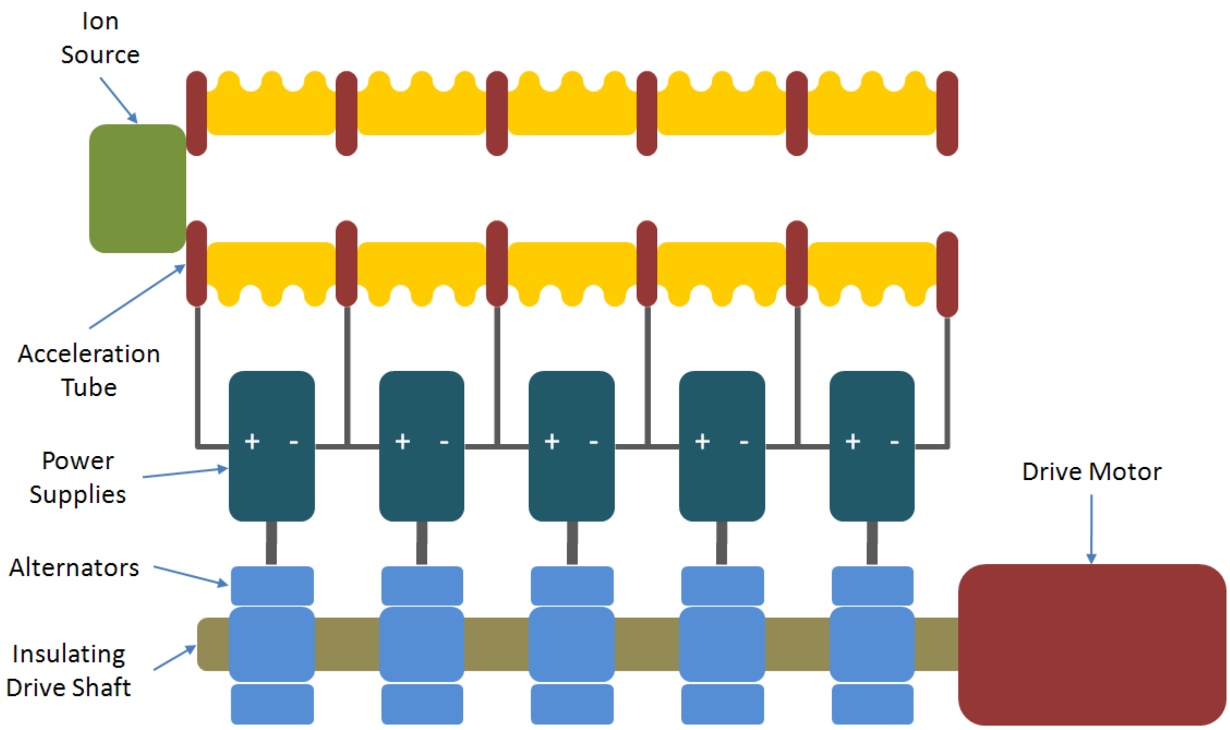

Figure 2 Schematic of the high voltage generator concept

A system is shown schematically with five electrically isolated alternators mounted on a common insulating drive shaft which in turn is driven by a common drive motor. Each alternator provides an electrically isolated source of power for its corresponding high voltage power supply. As shown, these power supplies are connected in series with the final output attached to the ion source and each intermediate output is connected to the corresponding electrode of the acceleration tube. The main advantages of this architecture are summarized in Table 3.

Table 3 Advantages of the system architecture

1	The electrostatic field in the accelerator tube is precisely controlled by the regulated output settings of the individual power supplies which are capable of regulating voltage over a wide range of current loads. The influence of spurious beam strike or scattered beam and secondary particles is virtually eliminated.
2	Field gradients along the tube can be easily controlled to give optimum ion optical properties simply by adjusting the output settings of each individual power supply.
3	Individual sections of the acceleration tube can be 'voltage conditioned' without influence from other regions of the tube.
4	The maximum voltage and current can be scaled by selecting the appropriate number of power supplies and alternators.
5	Standard commercial power supplies can be used

The high power implanter itself has been constructed using three high voltage generator assemblies inside the high pressure containment tank. Each generator stack consists of a 100 HP,3-phase AC induction motor with an efficiency of 94%, five 12 kVA , permanent magnet, 3-phase AC alternators operating at 80% efficiency and five series Cockroft-Walton power supplies (5) operating at voltages up to 80 kV, currents up to 125 mA and efficiencies of 85%.

One of these generator assemblies is shown in Figure 3.

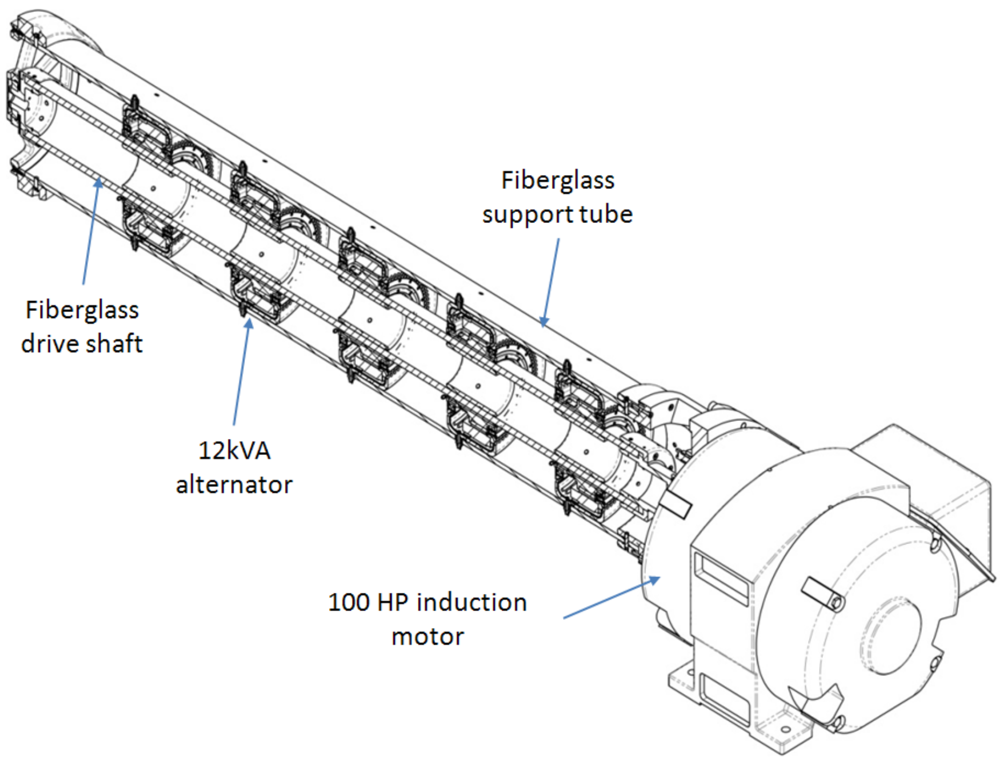

Figure 3 High voltage generator assembly

A photograph of the complete high voltage generator section of the machine is shown in Figure 4.

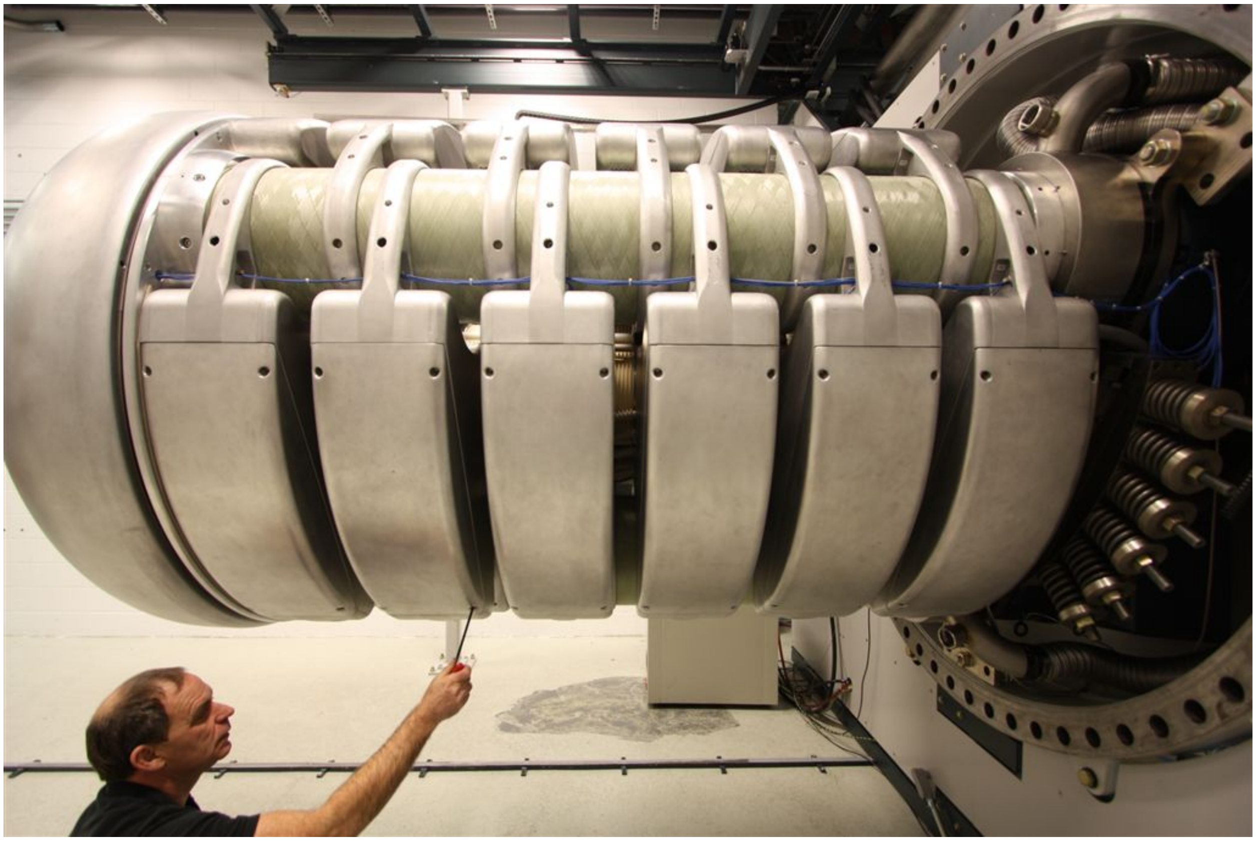

Figure 4 The high voltage generator

In this configuration there are 15 isolated alternators and 15 independent high voltage power supplies connected in series which result in a maximum combined capability of 1.2 MV and 125 mA.

Ion Source and acceleration tube optics

The proton beam is developed using a high current electron cyclotron resonance (ECR) microwave ion source coupled directly into a conventional electrostatic acceleration column. Figure 5 shows a schematic of the source and column.

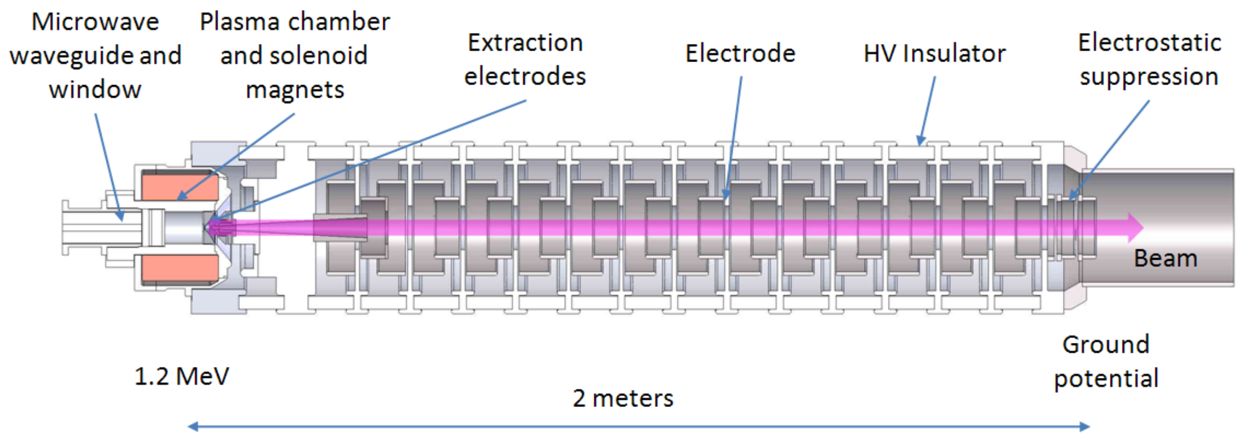

Figure 5 Schematic of ion source and acceleration column

The source consists of three solenoid electromagnets surrounding a circular plasma chamber fed with H_2 gas. The plasma chamber is excited by up to 1 kW of 2.45 GHz microwaves fed through a three layer vacuum window (6) into the chamber. A three stub tuner and ridged tapered waveguide match the impedance of the microwave system to the plasma. The source architecture is based on previous ion sources developed at Chalk River (7) and Los Alamos (8). The source components are displayed on the left side of Figure 5. The magnetic field is adjusted such that the field is slightly above resonance at the vacuum window, tapering to the 875 G resonant field towards the exit of the chamber. The boundary element code Lorentz-3D (9) was used to model the solenoidal fields and optimize the design to achieve the desired field shape.

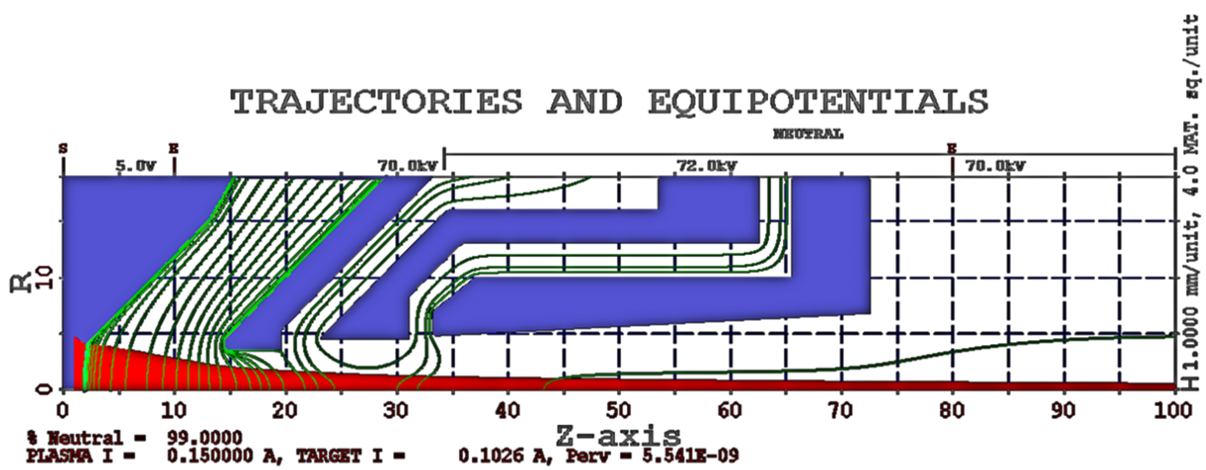

Figure 6 PBGUNS simulation of the beam extraction for a 70kV, 100mA beam

The beam is extracted at a DC voltage of up to 80 kV at currents up to 125 mA (power supply limited) using a tetrode extraction geometry with electrostatic suppression of back streaming electrons. The 2D code PBGUNS (10) was used to model the extraction geometry and optimize the beam emittance and current to be fed into the acceleration column. A screenshot from PBGUNS is shown in Figure 6.

The ECR source provides many advantages over conventional ion sources including a high proton fraction of 90% or more, high current density of 200 mA/cm^2 and above, low gas load to the vacuum system, and long periods between services with no filaments to wear out. The high proton fraction allows the beam to be injected directly into the acceleration column without pre-acceleration magnetic analysis, greatly simplifying the terminal design.

The acceleration column consists of 14 acceleration stages (the 15th being the source itself), each capable of accelerating the beam up to 80 keV per section. Since each stage is driven by an independent high voltage power supply, the voltage on each electrode can be easily adjusted to optimize the tune of the system and also aid in the initial high voltage conditioning of the column. Simulation of the column optics were again studied using Lorentz-3D. Figure 7 shows a ray tracing simulation of the acceleration column including space charge effect for a 1.2 MeV, 100 mA proton beam.

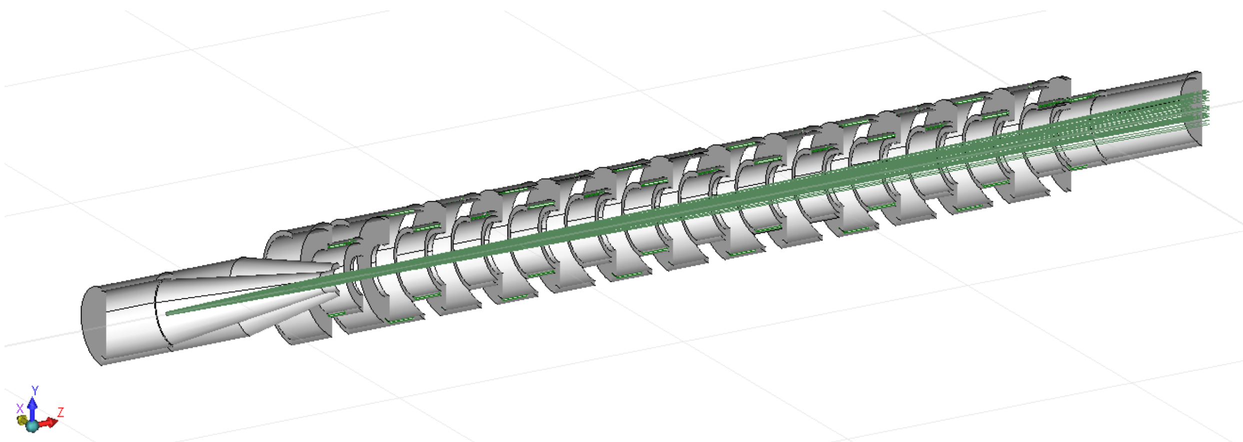

Figure 7 Beam trajectories simulation for a 1.2 MeV, 100mA proton beam using Lorentz-3D

The column has considerable vacuum pumping area throughout its length with a measured conductance in excess of 2000 L/sec for hydrogen. This high conductance, combined with the low gas load from the ECR source allows the entire system to be vacuum pumped by turbo-molecular pumps at ground potential. Eliminating vacuum pumps in the SF_6 environment at terminal potential greatly simplifies the overall system. Alumina ceramic bushings are used to further reduce the gas load to the system compared with epoxy resin bushings.

The central portion of each electrode is made of titanium with a 100 mm aperture to minimize beam strike and provide good pumping. Overlapping stainless steel stress rings with embedded samarium cobalt permanent magnets surround the central aperture and block the line of sight between the beam and the bushings to prevent coating and eventual shorting of the bushing. The embedded magnets suppress back streaming electrons in the tube by limiting the total energy gained by an electron to one or two gaps. This minimizes the bremsstrahlung radiation as well as the load on the high voltage supplies. The magnetic fields rotate 90 degrees at each stage with magnetic adjustments made at the entrance and exit such that the beam centerline remains close to the column axis throughout its length and exits on center and parallel to the axis. Electrostatic suppression is present at the exit of the column to further suppress electrons entering the column and provide a field free region beyond the column for beam neutralization.

Beam Scan System

The magnetic scan system performs two key functions. By magnetically deflecting the beam through approximately 80 degrees, unwanted species and low energy contaminants are removed from the beam prior to implant. Second, by incorporating a high speed oscillating scanner magnet, the beam is repeatedly swept across the wafers in a controlled fashion, providing very high dose uniformity for the implant(11). A set of magnetic quadrupoles control the shape of the beam spot on wafer to minimize over scan, instantaneous heating, and channeling. The magnetic scanning system is shown schematically in Figure 8.

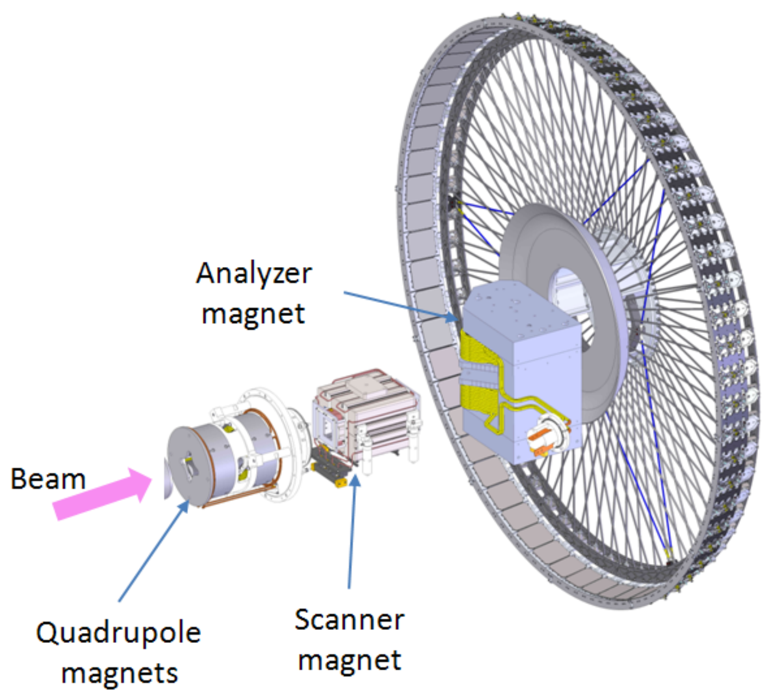

Figure 8 Magnetic scanning system

To avoid large instantaneous temperature variations on the wafer caused by the very high power beam (up to 135 kW on wafer), the scan speed can be increased up to 2 kHz, almost an order of magnitude faster than typical magnetically scanned implanters..

Process chamber and wafer drum

The silicon exfoliation process requires an implant temperature in the range 30-140°C with a temperature variation across the wafer of less than 20°C. Control of wafer temperature in this range is a formidable challenge when beam powers up to 120 kW are used. In order to reduce beam heating effects, the well known technique of beam power sharing has been adopted by implanting the wafers in large batches. In each batch 60 wafers are mounted on the inside of a 3.1m diameter, water cooled drum. The facets of the drum on which the wafers are mounted are coated with a compliant polymer of suitable thermal conductivity and the wafers are pressed against this material by the centrifugal forces generated when the drum is rotated. The total area exposed to the scanned beam is approximately 1.5E4 cm^2 and in order to maintain a temperature rise below 120°C, a thermal contact between the wafer and the drum of approximately 70 mW/cm^2 °K is required. The drum can rotate about its axis at speeds up to 400 rpm which provides radial accelerations of the wafer up to 280 Gs. The resulting clamping force of the wafer against the elastomeric coating results in the required implant temperature. The drum and the system which uniformly scans and deflects the beam onto the inside of the drum is shown schematically in Figure 1. And a photograph of the drum itself is shown in Figure 9.

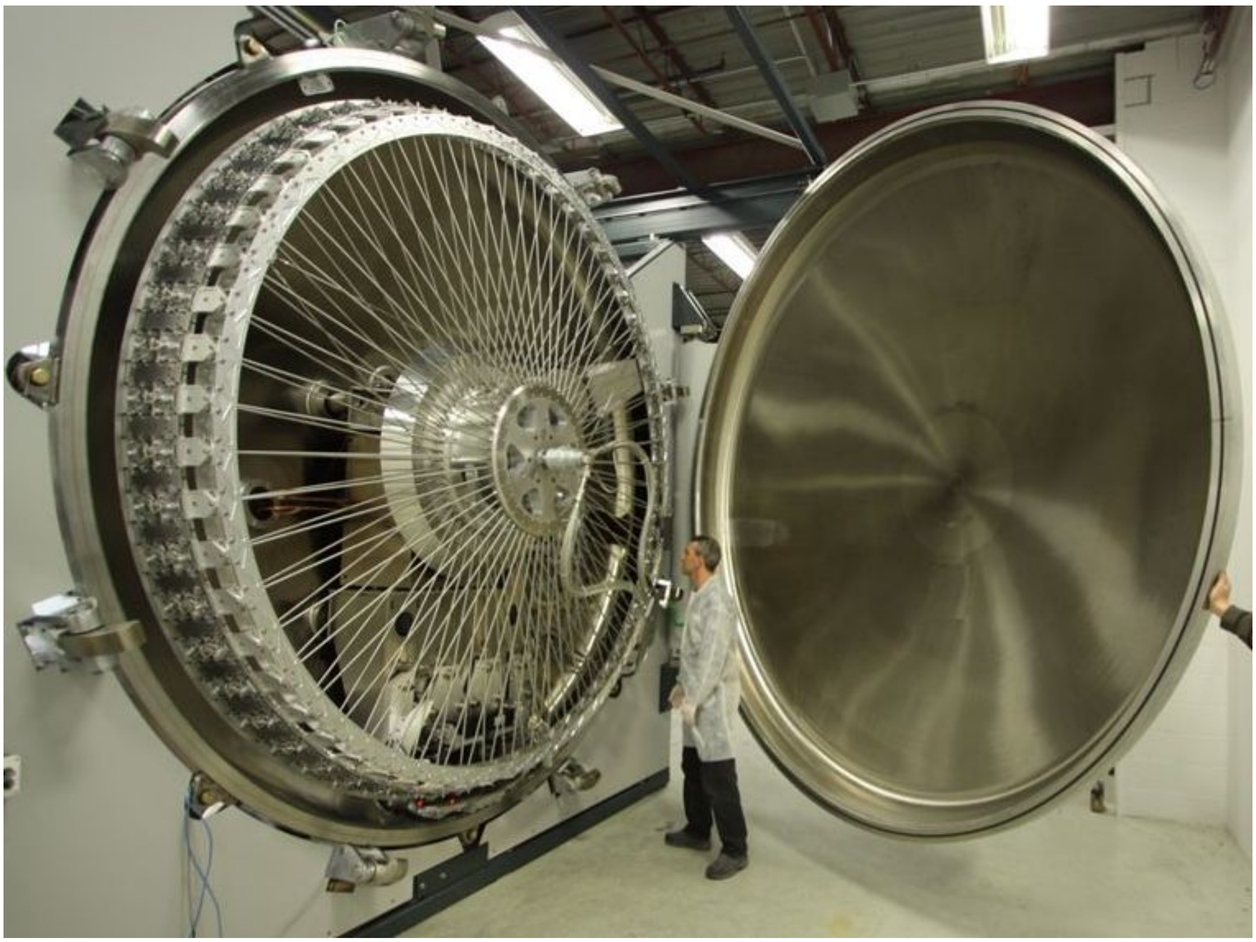

Figure 9 Photograph of the wafer drum

One complication of this arrangement is the fact that the angle at which the beam strikes each wafer varies from the edge of the wafer to the center of the wafer as a consequence of its rotation as the drum rotates. This effect (12) can result in undesirable channeling of the ions down axial or planar channels of the single crystal silicon and can occur in both rotating disk and rotating drum process stations whenever the incident ion beam axis is not parallel to the axis if rotation. It is often referred to as the 'cone angle' effect. In the system described the variation in angle is approximately ±3° and by selecting the appropriate average tilt and twist angle of the wafers with respect to the beam, all axial and planar channeling effects have been avoided.

Wafer handling

After each wafer batch has been implanted to the required dose for successful exfoliation, the wafers must be unloaded from the drum and replaced by a new batch of wafers in readiness for the next implant. During this exchange sequence the ion beam is not being used and it is therefore very desirable to minimize the time taken for any wafer handling.

To minimize wafer exchange times all wafer handling tasks are done in parallel. The system shown in Figure 10 is used to transfer implanted wafers from the drum and into a stacking elevator located in a vacuum load lock. It consists of a pick/place robot mechanism and a conveyor belt system as shown. A second system consisting of identical components is used for the reverse process whereby un-implanted wafers from a second stacking elevator located in the vacuum load lock are transferred by the conveyor system to a second pick/place robot which places them on the drum. With this arrangement, one system is dedicated to unloading implanted wafers from the drum and another system is dedicated to loading un-implanted wafers onto the drum. For this highly parallel architecture to function properly all actions must be executed with high precision. On-the-fly conveyor trajectory modification techniques and active wafer alignment mechanisms are utilized to correct any positional variability of the wafers. Sophisticated state-machine algorithms are implemented so that an action starts as soon as the right conditions are met. At the beginning of each action, sensors are utilized to ensure the software state matches the hardware. All the axes are servo-controlled; therefore any deviation from the designed trajectory is immediately detected and reported. At the end of each action, sensors are utilized to confirm successful completion. As a result, all axes work harmoniously in parallel with the state-machine generating the optimum sequence in real-time.

Finite element analysis, modal analysis, and kinematic/dynamic simulation software have been used extensively to optimize the hardware for high speed automation. Complex calculations have been done to develop advanced high speed motion control profiles for all axes.

The result is a high speed wafer handling system which reliably unloads and loads 60 pseudo-square wafers from the implant drum and transfers them into the vacuum load lock in 90 seconds.

The stacking elevators in the load lock are in turn unloaded and loaded by an external 6 axis robot(13) which can be programmed to interface with a variety of factory delivery systems.

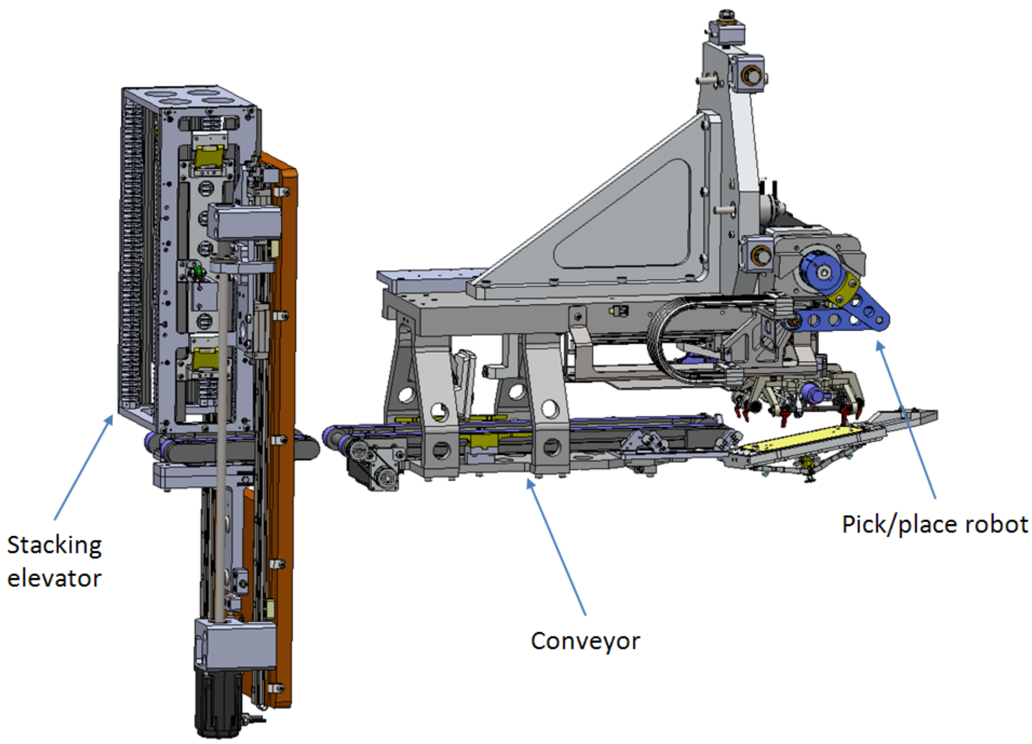

Figure 10 The three main wafer transfer mechanisms of the drum load or unload system

Performance results

The implanter described has been successfully operated with 45 mA proton beams at energies up to 800 keV. The system is now being shipped to the Twin Creeks Laminar based solar factory in Senatobia, MS.

Conclusion

A novel accelerator architecture has been demonstrated which is capable of producing high power proton beams with MeV energies and currents up to 100 mA. The system has been tested using a large area, high speed process station which is capable of maintaining wafer temperatures below 140°C at beam powers up to 120 kW. This implanter now provides a practical and unique solution for the fabrication of low cost, flexible, single crystal silicon solar cells with efficiencies ≥ 16%.

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