STUDY OF POSSIBILITY OF INDUSTRIAL APPLICATION OF ION INJECTOR I-3

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Abstract

Ion injector I-3 of the ITEP-TWAC accelerator complex consists of a buncher, two-gap accelerating cavity and a beam transport line. Laser ion source is used to generate ions for the injector. Possibility of application of the injector to dope semiconductor materials with variable energy ions is considered. Results of beam parameters optimization by numerical simulation to produce uniform distribution of particles density and required energy spread on the target are presented.

INTRODUCTION

Layout of the ion injector [1] is shown on Fig. 1. A solid-state target is placed at the target chamber of Laser Ion Source (LIS). The chamber is under potential of 50 kV. Laser pulse focused on the target produces plasma. The ion beam is formed at the extractor then is focused by means of electrostatic lenses, passes through the buncher and accelerated in the two gap resonator at the voltage of up to 2 MV per gap. Resulting beam energy is up to 4 MV per charge. It is possible to accelerate ions with A/Z from 2 to 5. The injector is able to produce ions of carbon, aluminium, silicon, iron and silver with intensity up to 5×10^{11} particles per pulse and repetition rate of 1 Hz.

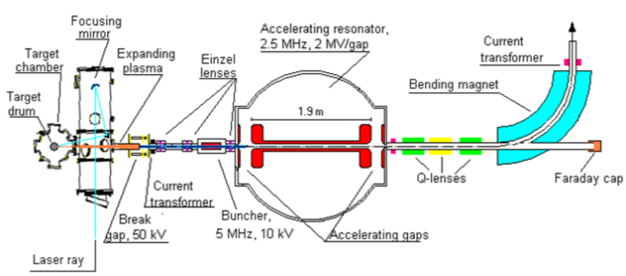

Figure 1: Layout of I-3.

Parameters of the accelerator allow considering it for industrial application in the area of doping of semiconductor materials [2]. Energies of ions in range of hundreds keV to units of MeV allows to provide a deep or a mid-deep ion implantation.

One of the possibilities of such application is production of buffer zone of Soft Punch Through (SPT) IGBT [3]. Fig. 2 shows the cross section of such SPT IGBT and concentration of the doping which should be produced to provide required electric field distribution inside the wafer [4]. Different technologies require different thickness of the buffer layer. To create the buffer layer some n-type particles, such as Phosphorus, should be implanted with a dose higher then 5×10^{12} cm^{-2}. Required particles energy is up to 2÷4 MeV per nucleus, or even more. Silicon wafers have diameter of 150±1 mm and base slice of 57±2 mm and thickness of 120÷700 um. Deviation of irradiation dose over the surface should not exceed 20%.

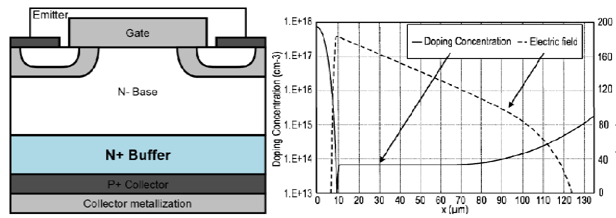

Figure 2: Structure of SPT IGBT.

SOURCE OF IONS

LIS generates ions of different charge states at the same time. These ions are presented in the accelerated beam in different concentrations depending on configuration of the ion source and the accelerator.

An experiment on production of phosphorus ions on LIS is in the beginning stage. Fig. 3 shows structure of silicon beam on the outlet of the accelerator that was produced by LIS with L-100 laser in 2011 [5].

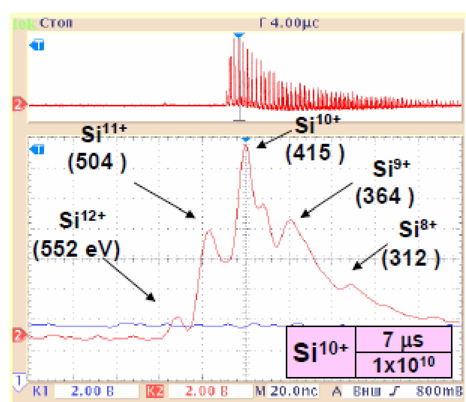

Figure 3: Structure of Si-beam produced by L-100.

Closeness of silicon and phosphorus atoms and similarity of their ionization potentials [6] allows assuming that the structure of phosphorus beam produced by L-100 will include ions of charge 8, 9, 10 and even 11, produced by L-20 - from 4 to 8.

By means of laser's power tuning and positioning of the target it is possible to achieve domination of the particles with required value of ion charge in the beam.

THE SIMULATION

While the accelerator is used as an injector of synchrotron it typically operates at maximum possible energy of ions. But in case of doping of semiconductor

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materials exactly required energy distribution and maximum intensity of the beam should be provided.

Simple mathematical model of an accelerating gap which assumes constant amplitude of acceleration field was used for the simulation, but values of the amplitudes and geometry of the buncher and the accelerator was chosen by approximation of accelerating field calculated by solving of Poisson equations [7]. The model was tested on different types of ions and the results are in good agreement with the experimental data available.

It should be noted that beam loss results listed below were obtained considering only phase motion of particles and they are not involve space charge effects which are dominant prior to the first accelerating gap of the resonator. It was shown in work [7] space charge effects causes beam losses of about 70% of 50 mA and about 80% of 100 mA.

Fig. 4 shows dependence of the transfer factor and the beam energy from the phase of the buncher for different ion charges of phosphorus.

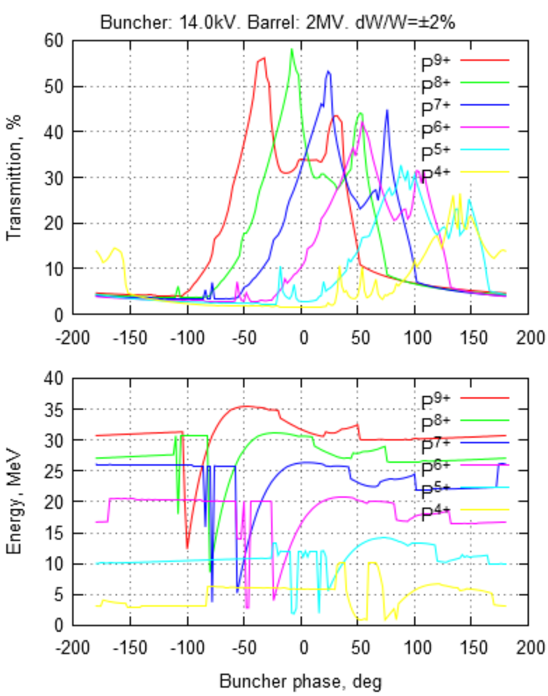
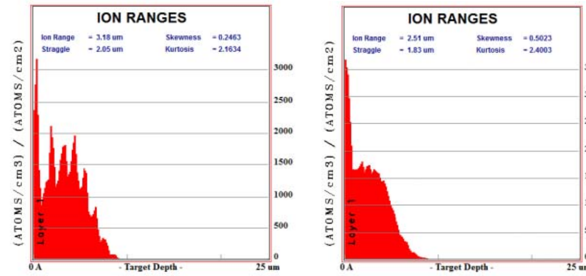


Figure 4: Transferring of phosphorus.

Acceleration efficiency of low charge ions is not high but the energies are in the required range for the implantation. Using of ions with different charge without separation by the energy allows providing smooth variation of doping concentration. Fig. 5a shows the results of the simulation of irradiation of silicon target by the beam composed of phosphorus ions of various charge state. The simulation was performed by SRIM [8] software.

Irregularity of the distribution may be simply eliminated by varying of accelerating voltage during of irradiation (Fig. 5b).



a b

Figure 5: Irradiation of Si-target by P-beam at 1 MV (a), 0.8÷1 MV (b).

More complicated variations of beam parameters that are besides may occur spontaneously during long irradiation process will allow providing high quality of the distribution.

Simulation of longitudinal motion in the accelerator I-3 shows that it is possible to vary the energy of the beam by varying accelerating voltage of the resonator in a wide range. Fig. 6 shows dependence of the beam energy from the accelerating voltage.

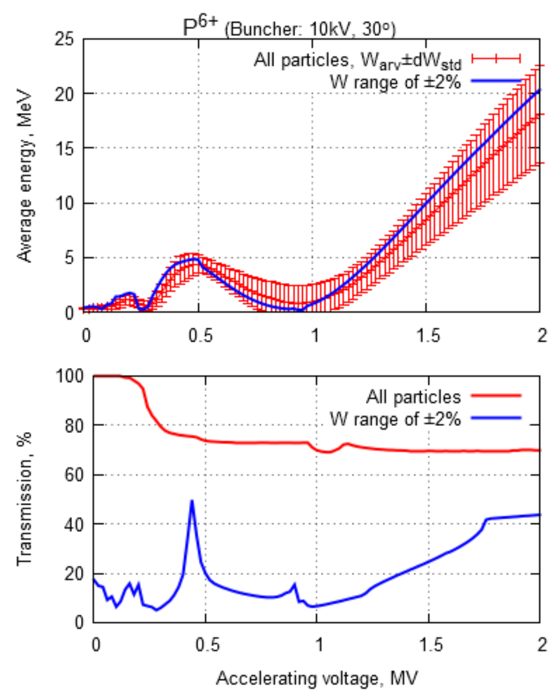


Figure 6: P^{6+} beam energy and transmission factor vs. accelerating voltage.

Transverse motion

Space charge effects are dominant in the transverse motion of particles before the acceleration begins. These effects are not considered in this work. So, transverse motion was simulated only after the acceleration while initial data for the simulation was extracted from [7] where space charge effects were involved.

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Triplet of the quadruples in the beamline allows focusing the beam on the target. If necessary, the analyzing magnet may be used to select required energy of particles.

SCANNING OF THE WAFER

Technology of scanning of the wafer by the beam should be used to produce uniform particles density on the surface. Technical details of this task are out of this work. Only the method of varying of beam coordinates relative to the target to provide uniform dose and minimize time of the irradiation is described.

In case of using I-3 with present parameters to provide required particles density on the target of mentioned size thousands of pulses should be performed. Uniform density distribution may be achieved by simple regular shifting of the beam along the target. The beam should be focused to reduce particle losses on the edges of the target.

In case of increased beam intensity the distribution of the particles inside the beam becomes important. It looks a good idea to use triangular mesh for positioning the beam along the wafer (or vise versa). Minimal number of pulses that provide irradiation of round wafer of radius R with the beam of $\boldsymbol{\eta}$ particles to produce a dose of $\boldsymbol{\rho}$ may be written as (1).

$$n_{\min} = \frac{\pi \cdot R^2 \cdot \rho}{\eta} \quad (1)$$

Allowable number of nodes of the concentric triangle mesh is defined by expression (2).

$$3k^2 + 3k + 1, \quad (2)$$

where k - is the number of concentric hexagonal layers forming the mesh. Equating expressions (1) and (2) we get the expression for the number of layers (3).

$$K = \left[\sqrt{\frac{4n_{\min} - 1}{12}} - \frac{1}{2}\right] \approx \left[R\sqrt{\frac{\rho}{\eta}}\right] \quad (3)$$

Therefore step of the mesh may be expressed by (4).

$$a = \frac{R}{K} \approx \sqrt{\frac{\eta}{\rho}} \quad (4)$$

Using these expressions we will get that to provide particles density of 5×10^{12} см$^{-1}$ by the beam with 1×10^{11} particles we need about 9 thousands pulses, the step of the mesh is about 1.4 mm and it takes about three hours. These values are acceptable for initial experiments. But to become an industrial machine we need to increase the beam intensity. If we get an order of magnitude then the irradiation of a wafer will take about 15 minutes with step of the mesh about 4.5 mm.

It should be noted that in case of transverse beam size significantly exceeds the step of the mesh additional pulses must be provided outside of the wafer to compensate particles losses on the edges of the wafer. Total number of layers needed may be expressed as (5).

$$K_T \approx \left[(R + r)\sqrt{\frac{\rho}{\eta}}\right], \quad (5)$$

where r - is the radius of the beam. Taking into account (5) it is reasonable to provide good focusing of the beam.

CONCLUSION

The investigation shows that application of ion linac I-3 as independent industrial device may be reasonable. The accelerator may be tested as a machine for doping semiconductor devices particularly for implantation of phosphorus ions in accordance with SPT technology.

Main trouble on the way of industrial application of the accelerator is relatively low intensity of the beam generated by the laser ion source and as the result long irradiation time and low productivity. The way to solve this problem is to optimize parameters of the laser ion source (this work is in progress now) or to use an alternate source of ions such as ECR.

REFERENCES

[1] N.N. Alexeev et al., “Upgrade concept of multipurpose ITEP-TWAC accelerator complex”, in Proc. of AccApp’2013, Bruges, Belgium
[2] S.B. Felch et al., “Ion implantation for semiconductor devices: the largest use of industrial accelerators”, in Proc. of PAC’2013, Pasadena, CA, USA
[3] A. Wintrich et al., “Application Manual Power Semiconductors”, ISBN 978-3-938843-66-6, SEMIKRON International (2011)
[4] M. Rahimo et al., Patent № WO2011058035 A3 “Punch-through semiconductor device and method for producing same”, 2011
[5] N.N. Alexeev et al., “ITEP-TWAC Progress Report”, in Proc. of IPAC’2011, Kursaal, San Sebastian, Spain
[6] A. Kramida et al., “NIST Atomic Spectra Database”, National Institute of Standards and Technology, Gaithersburg, MD, http://physics.nist.gov/asd
[7] A. Balabin et al., “Numerical Study of Beam Current Limit in the I-3 Ion Injector”, these proceedings, TUPSA08, RuPAC’2014, Obninsk, Russia
[8] http://www.srim.org/

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