DESIGN STUDY OF HIGH-ENERGY, HIGH-CURRENT RF ACCELERATORS FOR ION IMPLANTATION

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Abstract

Ion implantation is of great importance in semiconductor device fabrication. Due to the increasing interest of the microelectronic industry in the implantation of ions in the MeV-energy range, high energy beams are required. Furthermore, for several applications the implanted dose is as high as some 10^{18} ions/cm^2, which implies that high currents are needed also.

For both requirements the RF linac is well suited. The presented design studies are based on new linac structures (RFQ, MEQALAC, Spiral Loaded Cavity), which fulfil the specific demands of various applications. The discussed systems cover a current range from 1 to 150 mA and an energy range from 0.3 to 6 MeV for ion masses between 10 and 133.

Introduction

Since the 70's ion implantation became increasingly important in microelectronic industry as localized doping technique. The trend is on one hand towards lower ion energies due to the fact that with the lateral device dimensions also the vertical dimensions are decreased (miniaturizaton). On the other hand, increasing ion energy is needed to substitute the traditional thermal diffusion steps by deep ion implantation in order to reduce the 'Thermal Budget' in device fabrication[1].

This evolution was driven by the development of high current machines that allow to move from implant doses of 10^{13} ions/cm^2, used in earlier applications, to doses of 10^{16} ions/cm^2 that are currently used in recent low energy applications. There is a general agreement that the evolution towards even higher currents will go on, in fact SIMOX processes involve implant doses up to some 10^{18} ions/cm^2. The latter application requires ion currents in the mA range to keep the irradiation time in economical limits. Note that for a dose of 10^{18} ions/cm^2 and an ion current density of 1 mA/cm^2 the required implantation time for one cm^2 is 2.5 minutes. Furthermore, high voltage insulation requires a layer depth of several µm and an according ion energy in the MeV range. Both requirements - high ion current and high energy - can hardly fulfiled simultaneously by static machines. Modern RF linacs combine strong radial focusing with efficient acceleration, which allows for high currents and high transmission. Further advantages of RF acceleration in comparison to the commonly used DC acceleration are:

- Only ions with one particular value M/Q (number of nucleons/charge state of ions) are accelerated; a discrimination against impurity ions takes place.

- The highest voltages present are those on the ion source extraction grid and in the RF gaps (~ 40 - 250 kV), independent of the final ion energy. Consequently voltage hold-off, radiation, and SF$_6$ - handling problems are absent or reduced.

In this paper we present design studies of RF accelerators which are well suited for high energy, high current ion implantation.

Theoretical Background

A time-dependent electric field is present in the accelerating gaps of a linear accelerator. The distance between the gaps (cell length) has to match the particle velocity in such a way that the phase of the RF field changes by 180° during the time the particle takes to travel this distance. This implies that an accelerator containing a large number of gaps acts as an velocity filter. When the center of the beam bunch enters a gap during those periods when the RF field is positive and increasing in value longitudinal stability is obtained, because particles in front of the bunch are accelerated less and particles lagging behind are accelerated more.

Radial beam stability is achieved by transverse periodic focusing elements, which exert forces on the particles in each cell such that, averaged over the cell length, a net force remains, driving them back to their equilibrium position (focusing by alternating gradient).

The beam space charge decreases the focusing force. Beside that, it strongly couples the particle motion in the different planes. The latter makes it difficult to describe the particle motion analytically. Nevertheless, several authors [2,3,4,5] have derived an approximate solution for the limiting current in periodic channels. These formulae have been used for a first rough estimate of the current transport capability of the accelerators. Further detailed investigations are carried out with simulation programs (PARMTEQ, PARMILA), in which particle trajectories are calculated in three dimensions including space charge effects.

In general, an RF accelerator is designed for one maximum value of M/Q. For this ratio the design gap voltage has to be applied to the electrodes, which is for reasons of accelerator length and loss power consumption as high as possible. But each particle species with a smaller M/Q can be accelerated in this structure to the same end velocity (same energy in keV/M) with lower electrode voltage.

Acceleration Structures

MEQALAC

In the Multiple Electrostatic Quadrupole Array Linear ACcelerator (MEQALAC, invented by Maschke 6]) , the ion [beam is devided into a number of parallel beamlets, which are simultaneously accelerated. A scheme of this concept is shown in fig. 1. RF voltages are applied to a (large) number of accelerating gaps. In each gap a fixed amount of energy

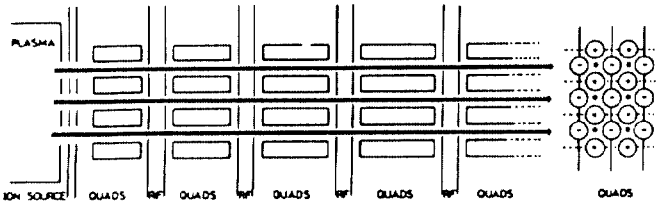

Fig. 1. The MEQALAC concept. A number of ion beams is injected into a RF gap/electrostatic quadrupole structure and subsequently accelerated. The arrangement of the quadrupole elements makes it possible to stack many beams within a small area.

is gained by the particles. Electrostatic quadrupole lenses are placed in the field-free drift regions between the gaps to provide radial stability. This configuration allows for an independent adjustment of the longitudinal and transverse focusing strength. The total accelerated current can be increased by increasing the numbers of channels. In a cooperation between the FOM-Institute and the IAP of the University of Frankfurt a proof-of-principle MEQALAC has been built and tested at Amsterdam. Four He^+ ion beams have been accelerated from 40 to 120 keV with a total current of 8 mA. The resonance frequency of the accelerator was 40 MHz [7]. In a second stage of the project a MEQALAC with variable resonance frequency for the acceleration of N^+ ions has been developed and built [8]. The 4 beam-line accelerator is designed for a maximum end energy of 1 MeV and a total current of 6 mA. First beam experiments are expected for summer 1988.

Four-rod RFQ

In contrast to the MEQALAC, the RFQ makes use of the concept of spatial homogeneous focusing [9]. In this device, four modulated metal rods or vanes are placed in a resonator cavity. The RF power coupled into the resonator is converted into an electric field between the electrodes, which has both a transverse and a longitudinal component. These serve to focus and accelerate the ions, respectively. The RFQ is studied in many laboratories [10].

The 4-rod RFQ, developed at Frankfurt University [11] applies cylindrical rods with conical varying diameter as electrodes. The resonator basic cell consists of two oscillators excited in the transversal π-mode to give the proper quadrupole field distribution between the electrodes. The accelerating structure consists of a chain of these cells operating in the longitudinal 0-mode. Fig. 2 shows a scheme of two cells of this structure and the electrode configuration. Prototypes have been built and operated in order to optimize shuntimpedance and particle dynamics. Several 4-rod RFQ's for light ions have been designed and built to prove its attractive properties. Comparison with the commonly used 4-vane RFQ has been carried out at Hamburg [12]. These measurements have shown that the 4-rod RFQ is equivalent to the 4-vane RFQ concerning the beam properties.. In both accelerators an H^--ion current of 40 mA, which is two times the design current, has been accelerated from 18 to 750 keV without optimization of the experiment. The advantages of the 4-rod RFQ compared to the 4-vane RFQ is easier manufacturing, easier tuning, higher RF stability, smaller weight and price, respectively.

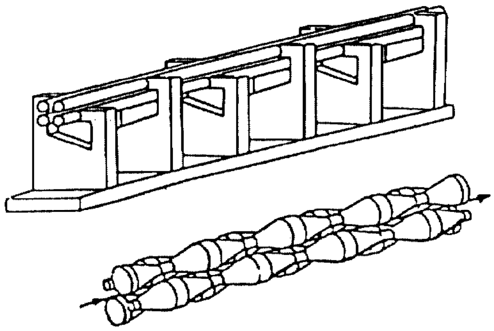

Fig. 2. Scheme of a two cell 4-rod RFQ. In the lower part the electrode configuration is shown; cylindrical rods with conical varying diameter.

Spiral Loaded Cavity

The Spiral Loaded Cavity (S.L.C.) [13] is a short and compact RF structure giving high voltage gain (500 kV, 60 kW). It consists of a spiral $\lambda/4$-resonator connected at one end over a common leg with the cylindrical outer tank, and is equipped with a drift tube at the free end (fig. 3). The tank is terminated by end plates, each carrying a drift tube at the center and thus forming the two acceleration gaps. Due to its large energy acceptance it is well suited for the post acceleration or deceleration of ions. In many laboratories the S.L.C. is used for upgrading of Van de Graaff or tandem generators as well as for buncher and debuncher cavities in the frequency range from 27 to 250 MHz. In the next section designs will be presented in which S.L.C. will be used behind RFQ's to allow for an energy variation of the proposed implanter systems.

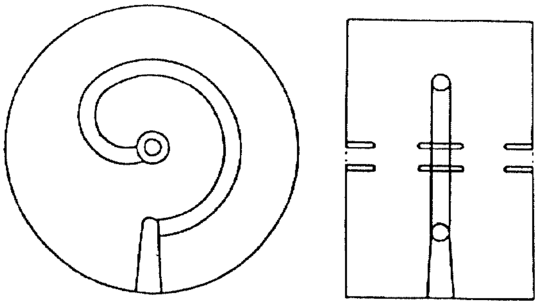

Fig. 3. Schematic drawing of the Spiral Loaded Cavity.

Implantation Systems

Fig. 4 shows a scheme of an implantation system, which consists of an ion source, a matching section, a 4-rod RFQ, a Spiral Loaded Cavity, and an implantation chamber. Such a system could be used e.g. for the economical production of deep buried SiO_2 layers. Oxygen ions are accelerated in the RFQ from the source potential (80 kV) to 3.2 MeV. By means of the S.L.C. the end energy of the ions can be varied between 2.7 and 3.7 MeV for an adjustment of the layer thickness. The maximum current amounts to 10 mA at a transmission of the order of 90 %. The current can be easily decreased by decreasing the duty cycle of the accelerators. The length of the complete system is estimated to 7 m. The total RF-power consumption, including beam loading, is of the order of 250 kW. Further informations are given in Tab. 1, column RFQ I and S.L.C.

In this table three other RFQ designs are listed, which are meant for the acceleration of ions with $M/Q \leq 4$, e.g. He^+ from 30 keV to 3 MeV (RFQ II), of ions with $M/Q \leq 30$, e.g. P^+ from 80 keV to 3.1 MeV (RFQ III), and of ions with $M/Q \leq 60$, e.g. Sb^{2+} from 120 keV to 6 MeV (RFQ IV), respectively. All these accelerators can be combined with one or more S.L.C.'s each giving an energy variation of +/- 500 keV. One possible option is to use the different accelerators in a radial arranged production line with one endstation at the center. In this case the power supplies and RF transmitters will be used alternately, thus reducing the overall investment cost drastically. An overall advantage of the proposed production line is its flexibility to different applications. The possibility of a modular set-up allows an easy increase in particle energy by additional sections. The most expensive ion source and RF amplifier can be used for modified accelerators with which other ion species are accelerated to different end energies. In many cases only an exchange of the cheap inner part of the accelerator is sufficient.

A scheme of another accelerator design for even higher current is shown in fig. 5. Two coupled MEQALAC's accelerate Nitrogen ions from 90 keV to 3 MeV at a resonance frequency of 30 MHz in the first resonator, which is doubled to 60 MHz in the second resonator. This design is based on experiments done at the FOM-Institute (8). By increasing the injection energy to 90 keV and the number of channels to 49, the maximum current is increased to 150 mA. The overall beam dimensions are 100 cm^2 at an aperture radius of 3 mm. The total length of the two resonators is to 4 m. The RF power loss for the maximum gap voltage of 64 kV amounts to 150 kW. This accelerator should be used for large size applications due to the total beam power of 450 kW.

Conclusion

The applicability of RF accelerators for ion implantation systems has been shown by several examples. With RFQ and MEQALAC two different systems are presented which both have the capability of high energy, high current acceleration. The MEQALAC featured the multi-channel acceleration for special large-size implantation applications. The single beam RFQ is a sophisticated and cheap accelerator. Combination of an RFQ with an S.L.C. leads to an efficient energy variable implanter system.

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TABLE 1. Parameters of 4 different 4-rod RFQ's. M/Q: design particle mass to charge ratio; f_0: resonance frequency; T_{in}: injection energy; T_{out}: exit energy; ΔT: absolute energy spread; I: accelerated ion current; V_{max}: design electrode voltage; r_a: minimum aperture radius; L: cavity length; D: cavity diameter; Rp: resonance parallel resistance; P_{max}: RF loss power for design voltage.

	RFQ I	S.L.C.	RFQ II	RFQ III	RFQ IV	DIM
M/Z	16	16	4	31	60	
f_0	108	108	108	36	36	MHz
T_{in}	5.0	200	7.5	2.5	1.0	keV/amu
T_{out}	200	170-230	750	100	50	keV/amu
ΔT	<1	<2	<1	<1	<1	%
I	10	10	40	8	5	mA
TR	>90	>95	>95	>90	>85	%
V_{max}	80	250	70	80	90	kV
r_a	3.2	10	3.0	3.1	3.5	mm
L	3.5	0.4	4.5	5.5	3.5	m
D	35	60	35	60	60	cm
Rp	43	6000	33	80	130	kΩ
P_{max}	150	50	150	90	65	kW

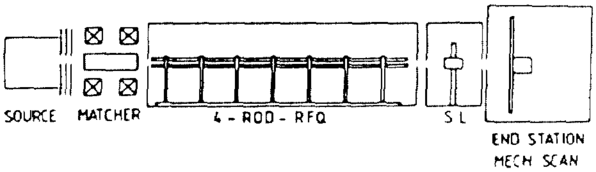

Fig. 4. Concept of a high energy, high current ion implanter. A high-current beam is extracted from the ion source and matched to the 4-rod RFQ by means of the matching section. The RFQ accelerates the ions to high energies. Via an S.L.C. the end energy of the ions can be varied. Subsequently the beam is injected into the implantation chamber.

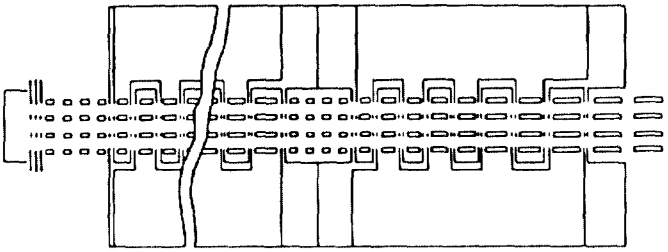

Fig. 5. Scheme of a MEQALAC implanter. The ion beams are extracted from the source and matched to the accelerator, which consists of two resonators. The beams are focused and transported by electrostatic quadrupole elements.