Ion Sources For Commercial Ion Implanter Applications

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Abstract

Ion sources for implantation have changed considerably since implantation was first used commercially. Dramatic increases in beam output have been sustained with each new generation of ion implanters. In addition to the drive for improved beam currents, the need of the implant users for reliable long life operation has driven much of the new development in implanter ion sources. In addition, the opportunity to achieve new capabilities, such as buried oxide layers, has sparked novel ion source designs to answer the demand. This paper will review some of the history as well as recent developments in the implanter ion source field.

1. INTRODUCTION

During the past twenty years, ion implantation has evolved from a laboratory curiosity to a highly productive tool in the fabrication process of integrated circuits. Latest generation BICMOS devices can require fifteen or more distinct implant steps in the full process sequence. As the spectrum of applications for ion implantation grew, a parallel increase occurred in the level of performance demanded from ion sources. The principal new capability required was for ever higher beam currents to address more of the high dose applications such as those for source/drain (MOS) and emitter/subcollector (BIPOLAR), and more recently for buried insulators. Simultaneously, the progressive requirements of the production environment were imposing additional demands for longer source life, ease of maintenance, reproducible operation source-to-source, limited costs for spare parts, etc. Thus while the demands for new capabilities has sparked novel ion source designs in response, only a limited variety of ion sources have been proliferated commercially in any significant number.

2. HISTORICAL REVIEW

Commercial ion implantation equipment used in the production of semiconductor devices has been on the market since the early seventies. Since that time ion implanters have evolved from fairly simple low current machines, with ion beam currents of the order of 100 μA, to complex automated and computer-controlled machines with beam currents approaching 100 mA. The energy range of commercial implanters has remained fairly constant, with the great majority of production machines having been designed to cover energies up to 200 keV for singly charged ions, although both low energy and high energy special purpose machines have also been produced. An increase in available beam current by about three orders of magnitude has been made possible by development of ion sources capable of stably and reliably producing these ever increasing levels of output of the different ion species required for semiconductor manufacturing. Several detailed discussions of implanter ion sources have been published [1, 2, 3].

The early low current implanters typically used cold cathode ion sources of the Penning or PIG (Penning ionization gauge) type, such as Western Electric's ERC source [4], and Extrion's PD-75 source [5] depicted in Figure 1. In the PIG source the discharge region is formed by a cylindrical anode and two electrodes at cathode potential at the ends of the anode. The dopant gas or vapor is admitted through an aperture in one cathode and the ion beam is extracted from an axial aperture in the other. The discharge is maintained by a potential of 1-2 kV between the anode and cathodes. Efficient electron confinement is achieved by means of a strong solenoidal magnetic field which inhibits radial drift of the electrons and the reflecting potential of the cathodes which prevents axial losses. This source had the virtues of simplicity and long life, but was difficult to control, because of several modes of operation, and also tended to produce a hashy discharge. It was still used in Varian's high energy implanter as recently as five years ago.

Low current implanters were supplanted by the so-called medium current type. These machines were typically equipped with hot filament Freeman-type ion

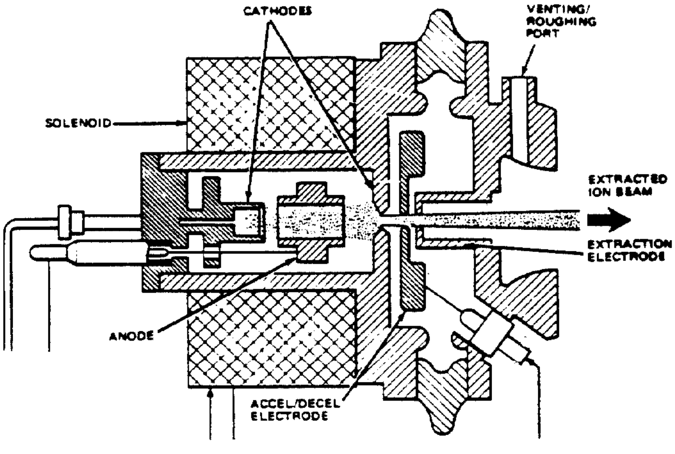

Figure 1. Cold Cathode Ion Source (Extrion PD-75).

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sources [6,7] and offered DC beam currents of the order of 1 mA. The Freeman source has proved immensely successful in this application and is still the most widely used source in the implanter industry, although other types of sources have started to appear in higher current applications. The Freeman source in its generally used embodiment is shown in schematic form in Figure 2. The discharge chamber is at anode potential; a straight axially disposed tungsten filament at cathode potential is located near a lateral beam extraction slit. Dopant gas or vapor is admitted through a penetration in one of the chamber walls. In a manner similar to the PIG source, an axial magnetic field of about 100 G inhibits radial electron drift and small reflector electrodes at filament potential reduce electron loss to the ends of the discharge chamber. The source produces a ribbon beam, and maximum current density near the extraction slit is 20 to 40 mA/cm^2. This type of source operates stably and efficiently with a variety of gaseous and vaporized dopant materials. With the advent of high current implanters which typically deliver beam currents of 10 to 30 mA, the Freeman source was scaled up to meet these increased demands with no great difficulty. An inconveniently short filament life remains the only major shortcoming of this source.

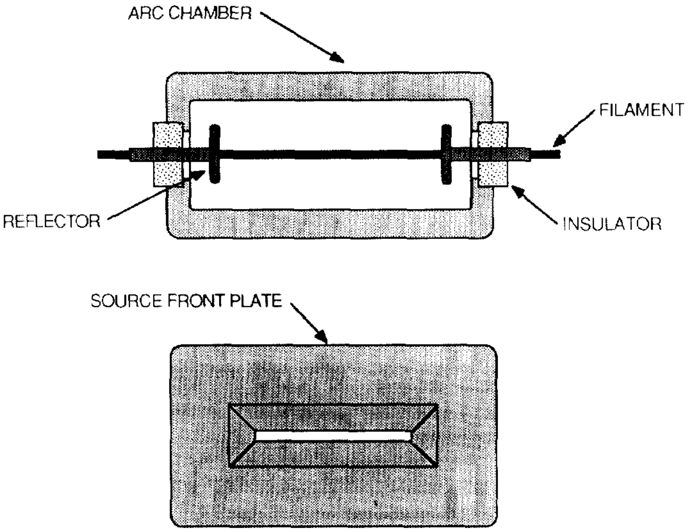

Figure 2. Freeman source configuration.

3. CURRENT ION SOURCE VARIATIONS

A. Freeman Ion Source Variants

The basic Freeman geometry has remained relatively unchanged for three decades. One exception is the SKM variant used by Eaton [8] and shown schematically in Figure 3. This source uses two electrically connected floating electrodes to replace the two sections of the anode through which the filament passes. These floating electrodes acquire a potential close to that of the filament and serve to confine the electrons. This modification has resulted in a substantial improvement in boron and multiply charged ion output and in better uniformity of the extracted current density. Source lifetime is also improved due to the increased efficiency. The configuration has the drawback of being substantially more complex.

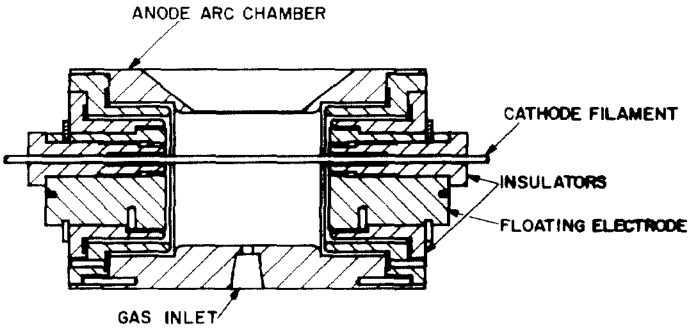

Figure 3. A schematic drawing of the SKM Freeman source.

As an alternative to hardware changes, modifications in operating procedure and automation software have made great improvements in source life for the Freeman possible. Reducing arc voltage will substantially increase the source life, as is well known, however if the discharge power is maintained by increasing the arc current, the source life is increased with no performance penalty. As an example, reducing the arc voltage from 120 V (standard) to 60-80 V for a BF_3 discharge increased source life from about 13 hours to over 50 hours for the case of a 5 mA, 100 keV $^{11}B^+$ beam on a Varian 160XP implanter [9]. Similar operational changes for other species are also effective, and this tactic is generally applicable to all hot cathode ion sources.

B. Bernas Ion Source

A successful variation on the Freeman source, which was used by IBM [10], and more recently has found application in Eaton implanters [2], is the Bernas configuration, Figure 4, in which the axial Freeman filament is replaced by a helical filament placed near one end of the arc chamber. A reflector electrode at cathode potential at the other end again provides the Penning type of electron confinement. The axial magnetic field had to be increased by a factor of two to three over that of the Freeman source. The operating characteristics of the Bernas source are similar to those of the Freeman, but filament life tends to be significantly longer. The higher magnetic field results in increased deflection of the beam emerging from the source, which must be compensated by the beam steering features of the extraction system.

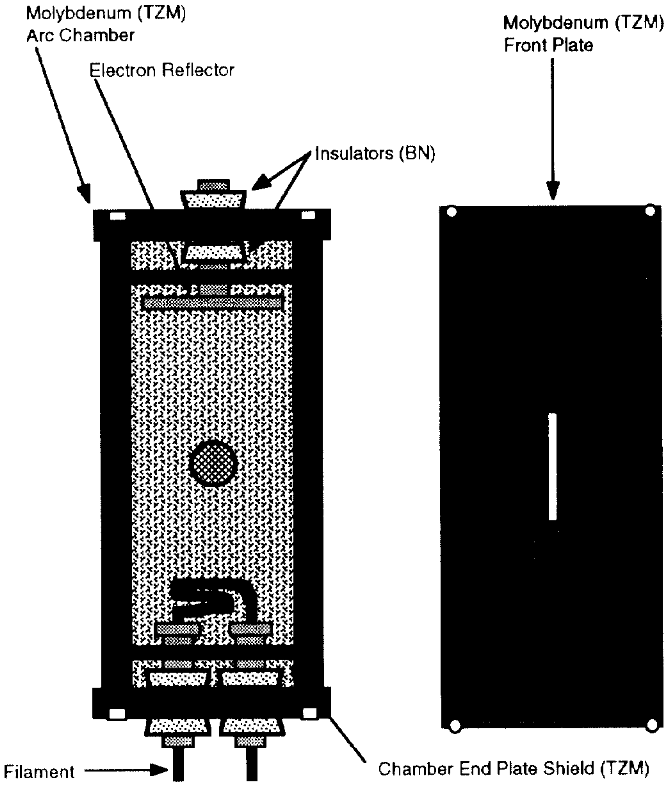

Figure 4. Bernas Source Configuration.

4. RECENT DEVELOPMENTS

A. Microwave Ion Sources

There has always been a strong motivation to develop ion sources that do not require a hot filament for operation in order to increase source life. The filament has been the shortest lifetime component in the ion source. With the advent of the microwave oven and the availability of cheap power at 2.45 GHz, there has been a great deal of work on microwave generated plasmas. Much of the work relevant to conventional implantation has been done at Hitachi [11,12,13]. The difficulty in applying this technology to commercial implanters is caused by the problems associated with reactive dopant gases such as BF_3 [14].

The Hitachi microwave source, shown in Figure 5, has undergone the most extensive development as an implanter source. The magnetic field is provided by a solenoid at ground potential outside the source. This axial field is somewhat stronger than that producing electron cyclotron resonance (ECR), and extends throughout the length of the source. Microwave power passes from a rectangular waveguide, through the dielectric window, into a tapered ridged waveguide with two iron blocks at the periphery. The discharge region has a small rectangular cross section, for slit beam extraction, with the remaining space in the waveguide filled with boron nitride as a dielectric. When used on an implanter, a beam of 40 mA can be extracted from the 2x40 mm^2 slit. This results in available implant currents of 10 mA for P^+ and As^+, and 4 mA for B^+. With phosphorus and arsenic, source lifetimes of 100-200 hours have been achieved for 10 mA beam currents. The longevity of this source is significantly better than the Freeman, while the performance is almost as good.

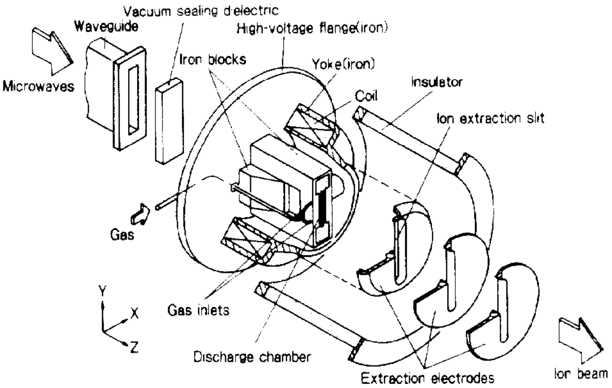

Figure 5. The Hitachi microwave ion source.

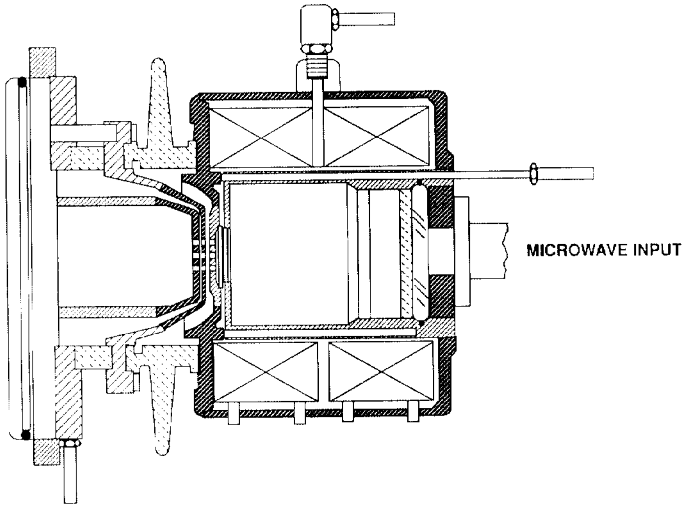

Figure 6. The Eaton microwave oxygen ion source.

For oxygen implantation (SIMOX), currents of the order of 100 mA are needed. This has resulted in the development of dedicated oxygen implanters. Microwave ion sources are perfectly suited to the application and have rapidly taken over as the technology of choice [15,16]. The Eaton microwave oxygen source, shown in Figure 6, was developed as an alternative to the duopigatron source originally used. An external solenoid produces the ECR field inside the cylindrical source, which has a diameter of 28 cm and a length of 29 cm. Microwave power is fed through a triple layer dielectric window for improved power transmission. The microwave source produces the same beam current at reduced extracted current as the duopigatron, while source life is greatly improved. Some notable features of this source include the high current density of about 150 mA/cm^2 and the use of multiple circular apertures for ion extraction.

A different type of microwave ion source has been developed at Varian for conventional implanter applications. This source uses permanent magnets to produce an axial field greater than the ECR value (about 875 G for 2.45 GHz) in a rectangular geometry with a size comparable to the standard Freeman ion source. Microwave transmission is greater than 95% with the use of an external tuner. This prototype source is undergoing preliminary testing as a replacement for the Freeman source in existing implanters. As in the previous cases, improvements in source lifetime are driving development rather than performance increases.

B. Single Ring Cusp Ion Source.

The most recent Varian high current implanter, the E-1000, which delivers beam currents of the order of 30 mA to the target chamber, makes use of a hot filament ion source with a ring-shaped magnetic cusp field. This type of source, shown in Figure 7, was described by Brainard [17] who developed it to produce a 200-mA deuterium beam. The Varian cusp source has been optimized to operate efficiently with the dopant materials needed for implantation [18,19]. The discharge chamber of the source is cylindrical with a ring-shaped anode and a heated semicircular tungsten cathode. A slit-shaped extraction aperture in the front plate allows extraction of a ribbon beam. Electron confinement is achieved by use of a reflector plate at cathode potential located between the cathode and the back wall of the chamber, and by means of a circular magnetic cusp field which reduces electron loss to the anode. The source operates at a current density of up to 40 mA/cm^2.

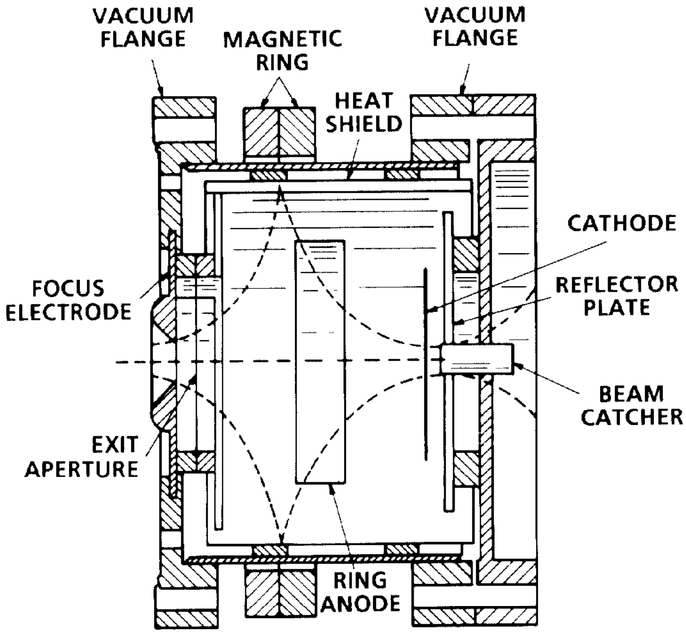

Figure 7. Circular cusp source.

C. Multicusp Ion Sources

The multicusp or bucket source has been extensively developed for neutral beam heating applications [20,21,22] as well as plasma processing [23] and general ion source work [24]. It is noted for its ability to generate large volumes of high density quiescent plasma. The multicusp design uses permanent magnets of alternating polarity to create magnetic cusp lines at the ion source periphery. This field arrangement provides electron confinement with strong fields at the walls, and only weak fields (less than 50 G) in the central plasma volume. The source geometry is either cylindrical or rectangular, and is very scalable, with dimensions ranging from a couple of centimeters to a meter. The plasma is usually generated by one or more filaments at cathode potential located anywhere within the central magnetic "field free" volume. The rest of the arc chamber is typically the anode, similar to the Freeman source. There has also been successful work with RF plasma generation in the multicusp source [25]. In this case, an antenna coil of several turns replaces the filaments. A small "starter" filament may be momentarily used to initiate the plasma. Microwave sources using a multicusp geometry have also been developed, mainly for plasma processing applications.

A filament driven multicusp source, shown in Figure 8, has been tested at Lawrence Berkeley Laboratory (LBL) with BF_3 [26]. It was found that this geometry can produce a high current density $^{11}B^+$ ion beam. LBL uses a magnetic filter to achieve a higher boron fraction in the extracted beam. This filter is simply a local transverse magnetic field near the extraction aperture. Work is progressing at Varian on a multicusp source adaptable to commercial high current ion implanters. Such a source must improve source life and reduce con-

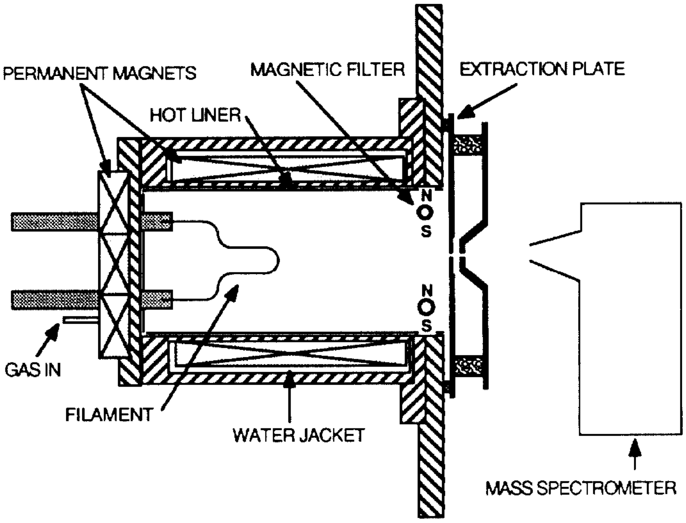

Figure 8. A schematic drawing of the LBL multicusp source.

tamination in the ion beam, while maintaining the level of performance of the ion implanter. The advantage of this type of source for implantation is in flexibility of plasma generation and the scalability of the source output for high current applications.

4. SUMMARY

Ion source technology has made a great deal of progress since ion implantation equipment became a commercial tool for semiconductor fabrication. In the past this progress has been defined by increase in usable beam current, but this is no longer the sole measure of improvement. Source performance criteria now also include lifetime, freedom from metallic contamination, reliability and ease of maintenance. The development of new ion sources is therefore directed toward achieving gains in all these areas. Source types which do not have the inherent problem of limited filament life are receiving particular attention.

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