Chapter 1. Introduction

The development of focused ion beam (FIB) technology has resulted in many different areas of technology, e.g., the manufacture of semiconductor devices, surface analysis, ion milling, ion microscopy and some areas of nanotechnology. These developments have been due primarily to the exploitation of field emission ion sources, particularly the liquid-metal ion source (LMIS) and the gas field ion source (GFIS). The LMIS produces a beam size of about 100 nm with a current of pA range (Melngailis, 1993, Wolf, 1995, Orloff, 1996). Operation is based on the formation of a liquid metal cone at the apex of the needle or capillary tube in high electric field. The GFIS (Orloff, 1993, Melngailis, 1993) is much more efficient producing about 1 nm beam size with a current in the nA range and smaller in ion energy spread. GFIS results in a 1 eV energy spread compare to 5 eV spread with LMIS. Both ion sources could be said to be "point sources". In contrast, volume sources, such as plasma sources, are less suitable for the creation of bright and narrow beams (Orloff, 1993,1996).

One of the important applications of FIB is scanning ion microscopy (SIM). SIM is analogous to scanning electron microscopy (SEM), in which ions replace electrons although the contrast mechanisms are somewhat different. Spatial resolution is lower and the ion beam has a destructive nature (Itakura et al, 1985; Kasahara et al, 1988; Orloff, 1993). A new development in FIB application is ion milling. Ion milling has a meaning of cascade collisions of an incident beam transfering sufficient momentum to form a sputtering of a material. Orloff (1993) and Vasile et al, (1994) reported micron-size cutting using heavy ions. However, both the LMIS and the GFIS ion sources can not provide sufficient intensity for this new kind of application to be useful. For example the sputter yield for Si is 0.27 μm^3/nC, so that for an incident beam current of 1 nA, the sputter rate is 0.27 μm^3/s. To mil a 5 μm square hole 5 μm deep will take 7.7 min with a conventional FIB. A new high intensity FIB ion source is needed. An FIB application such as ion milling on a micron scale with a short processing time have been reported by Kalbitzer (1996) and Gamo (1997). They employ a high current ion beam in the range of mAs. The possibility of developing a volume plasma source has been discussed by Leung et al (1993) for a system which would produce a micron-size focused ion beam with ion current up to 10 mA (Holmes, 1979; Cavennago et al, 1991; Beker et al 1992; Ovsyannikova, 1996).

An inductively coupled radiofrequency (rf) driven ion source has the advantage of low energy spread (about 5 eV) and high discharge efficiency, especially, when used with a multicusp magnetic field (Leung et al, 1991; Yamauchi et al, 1993; Nakamura et al, 1995). A multicusp plasma source using permanent magnets was first reported by Limpaecher and MacKenzie (1973). Leung *et al* (1975) report an optimal geometry of permanent magnets and found that the full line cusp gave optimum plasma density. Characteristics of a steady-state dc discharge multipole ion source were subsequently reported by Leung et al (1978).

In recent years, an rf driven ion source has been shown to have simpler structure, longer operational lifetime and cleaner plasma discharge than a filament-discharge (Leung et al, 1990). One disadvantage of an rf driven source is the large energy spread on both longitudinal and transverse spaces due to an rf coupling to the extracting grid voltage (Zakhary, 1995; Sarstedt et al, 1996). An inductively coupled rf discharge in multipole fields demonstrates a uniform large volume plasma at very low neutral pressure (Shirakawa et al, 1990; Suanpoot et al, 1998). This type of discharge is competitive with both magnetron and ECR-type plasmas for low pressure etching or deposition processes. In the interest of plasma applications, several rf inductively modeling studies (Lister et al, 1991; Piejak et al, 1992; Keller, 1996; Kolobov et al, 1997; Suzuki et al, 1998; You et al, 1999; Zorat et al, 2000; Gudmundsson, 2001) have been made on frequency, skin depth, gas type, internal and external discharge and E-H mode jump with reasonably good agreement among experimental data.

The so-called rf driven source, has been studied extensively by a group at the Lawrence Berkeley National Laboratory (Lee et al, 1997; 1998) and elsewhere (Boonyawan et al, 1999; Bruenger et al, 1999; Lee et al, 1999) . Lee *et al* (1997) operated their 10 cm diameter and 10 cm long rf driven multicusp ion source with a maximum output power of 2.5 kW. Their rf antenna was made of copper tubing and coated with a thin layer of porcelain. The external surface of the source chamber was surrounded by 20 columns of $Sm\text{-}Co_5$ permanent magnets. They measured the axial ion energy spread to be approximately 3.2 eV and found that the extractable beam current was comparable to that of a filament discharge source. They were able to reduce the axial energy spread considerably by installing the rf power supply on the high voltage platform and shielding the leads between the matching network, antenna and the connecting capacitors for the source chamber to ground. Wutte *et al* (1998) reported the development of a similar type of ion source for radioactive ion beam (RIB) applications. Their ion sources showed promising features for RIB production with a gas efficiency of up to 60 % for Argon and up to 80 % for Xenon and a relatively low axial energy spread of 4-7 eV for the rf driven source. More recently, filament-discharge multicusp ion sources have been investigated for application in ion projection lithography (IPL) (Bruenger et al, 1999; Lee et al, 1999) and focused ion beam (Scipioni et al, 2000) with an important reason of having very low ion temperature (0.1 eV).

The purpose of this study is to develop a high-intensity multicusp ion source for a FIB system using rf-discharge technique from Argon gas for application in micron-size ion-milling. By taking advantage of its high density and uniformity, it is suitable for multi-beam formation (Lee et al, 1999). In addition, rf discharge can provide the most desired ion beam properties to the dc-discharge source with the use of fewer power supplies. Also, it is necessary to investigate a proper beam extracting and focusing system for beam transport in order to gain optimum beam brightness from this rf plasma source. The last objective is to develop a micron-size beam profile monitor of the extracted beam.

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