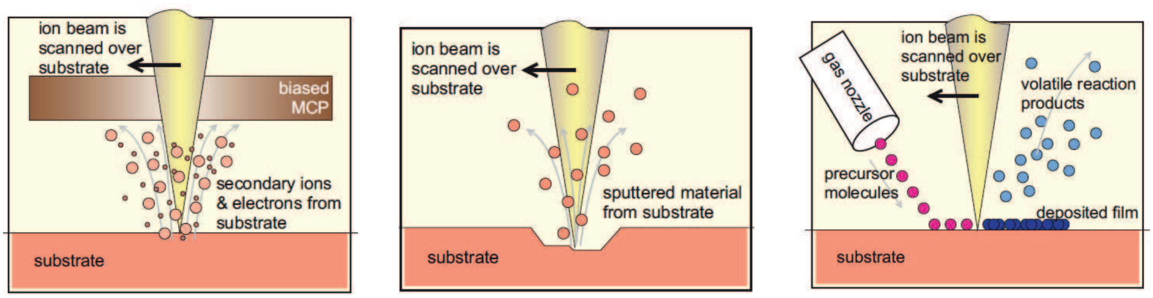
Introduction

Abstract. The work in this thesis covers the research on two kinds of ion source for focused ion beam (FIB) applications. An ion source is an apparatus capable of providing ions on demand. This section summarizes the applications of FIB and gives an overview over the existing ion sources. The reduced brightness and the emittance are useful figures of merit used to characterize an ion source and a definition is here given. Those definitions are used through the chapters to compare the performances of the sources. Finally, an outline of this thesis is given at the end of this chapter.

1. Overview over focused ion beam applications

Miniaturization is the central theme in modern fabrication technology and many of the components used in modern products are becoming smaller and smaller [1]. Nanotechnology tools have to keep up with this trend improving minimum achievable resolution. FIB systems have in common high-brightness ion sources capable of producing high current density beams [2, 3]. Those machines can create structures with few nanometer precision, remove or add material through ion bombardment or beam-induced chemistry. Imaging is also possible, although damages are dominant at the smallest scales. Figure 1, shows three examples of the most common applications of FIBs.



(a) Imaging (b) Milling (c) Deposition

Figure 1. Applications of FIBs [4].

A focused ion beam microscope operates along the same principle as the scanning electron microscope (SEM), in that a beam of charged particles is scanned across a specimen, and the resultant signals at each raster position are plotted to form an image. The signal comes from a multichannel plate detector (MCP), see figure 1a. However, in FIBs the charged particle beam consists not of electrons, but rather of ions, which are typically positive charged. Because of the short wavelength of the ions, FIBs have achieved spatial resolution rivaling that of the standard scanning electron microscope. Today's state-of-the-art FIBs are capable of imaging with a few nm spatial resolution, using secondary ions or electrons, i.e. secondary ion mass spectrometry (SIMS). Figure 2 shows a typical schematic of a FIB ion column.

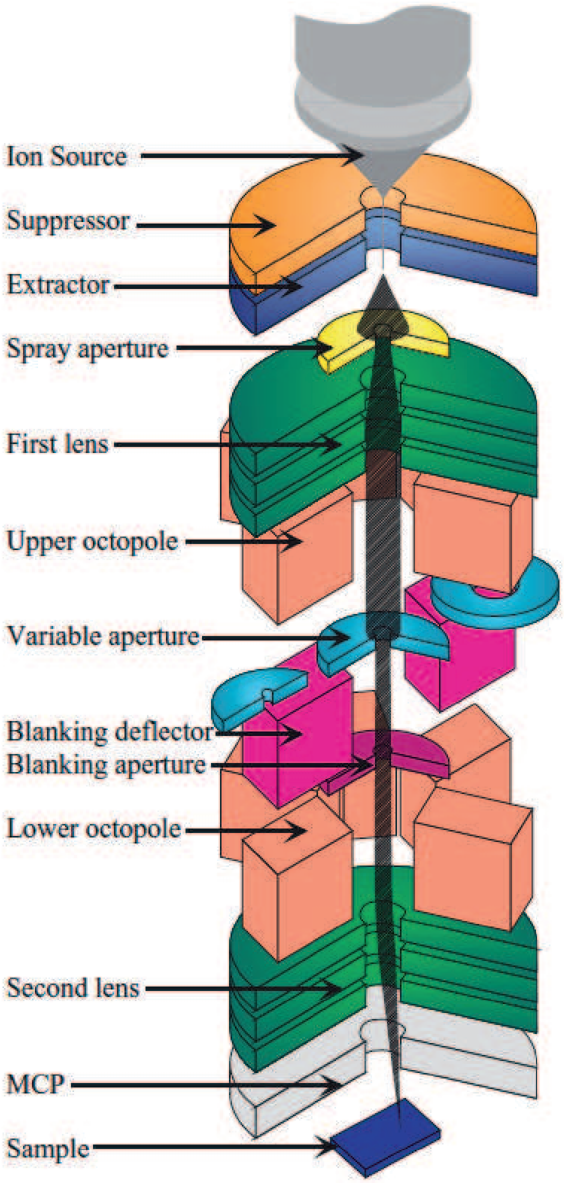


Figure 2. Schematic drawing of a FIB column [4].

The use of FIBs as precision sectioning tools down to sub-micron scale, creating a precise cut or cross-section from a few tens of nm with positional placement accuracy on the order of 20 nm is well exploited in the industry, see figure 1b. FIB has recently become a popular tool in making high-quality microdevices or high-precision microstructures [10]. Also, their ability to deposit metals and insulators on a micron scale, introducing several different gases into the vacuum chamber to either deposit a range of materials up to tens of micrometers thickness over areas ranging from the submicrometers to tens of thousands of square micrometers or selectively etch one material rapidly, see figure 1c.

Moreover, FIB have been adopted into the product cycle of semiconductor manufacturer in the late 1980s. In 1986, the number of FIB fabrication systems totaled about 35; in 1998, the number has increased 15-25 times [5]. FIBs are highly exploited in device modification, mask repair, process control and failure analysis [6, 7, 8].

Even more, the preparation of specimens for transmission electron microscopy (TEM) is an important application [9].

2. Overview of the existing ion sources for FIBs

In the past few years, the interest on focused ion beams has seen another significant increase also because of the development of few distinct ion sources, which can expand the capabilities of these instruments. FIB system based on high-brightness [11] gallium liquid-metal ion source (LMIS) became commercially available in the late 1980s. The LMIS [3] is still currently the most used one in commercial instruments. The current is extracted from an extremely sharp tip (of the diameter of few atoms) by applying high electric fields. Gallium is the most used element in the LMIS and this is also an important limitation for these sources. Expanding the choices of atomic spacier beyond gallium opens up FIBs to new applications on the market. The gas field ionization source (GFIS) [12] replaces the heavy Ga^+ ions with much lighter He^+ ions, enabling a very high resolution imaging and with limiting the damage to the sample. Long lifetime and high brightness operation are its most important features. In order to improve the milling application, an inductive-coupled plasma source is being developed [13]. This source uses Ar^+ and Xe^+ ion beams that can remove material almost contamination-free.

Laser-cooled ion sources as the ultracold ion source (UCIS) [14] and the magneto-optical trap ion source (MOTIS) [15], promises to expand the choice of ions available for FIB applications. These sources can in principle be configured to produce ions of over twenty different elements [16]. Those sources aim to high brightness starting the very low transversal temperature (a few hundreds of millikelvin) of the ions, rather than extracting the ions from a "point source". Having an extensive source is advantageous for the energy spread (space charge forces are less strong) and the probe is far less sensitive to vibrations and instabilities, one typically experiences with point sources. Sub-micrometer focus-ability has been demonstrated [16]. The energy spread have been measured down to 20 meV [17]. Time-dependent manipulation of ion bunches have been shown in references [18, 19] and is successfully used for the measurement presented in chapter 3.

To avoid disorder-induced heating of the UCIS [20] and the MOTIS [21], another laser-cooled source with a much higher particle flux is proposed in chapter 6.

Finally, laser-cooled sources have been successful in the production of bright electron beams for ultrafast electron diffraction [22, 23].

3. Source characterization: useful figures of merit

When characterizing an ion source, only two figures of merit are of most importance: the brightness and the longitudinal energy spread.

The reduced (transversal) brightness B_r [24] is the current density per unit of solid angle and beam energy and is a in Lorentz-invariant. In units of [A/m^2 sr eV], the reduced brightness is defined as

$$B_r = \frac{2I}{4\pi^2 mc^2 \epsilon_n^x \epsilon_n^y}, \tag{1}$$

where I is the current and ϵ_n^x and ϵ_n^y are the normalized *rms*-emittance of the beam in the x and y direction (in this thesis, the ions always propagate along the z-axis). In the previous equation, a factor e (the elementary charge) is removed in order to express the unit of brightness in eV instead of V. The normalized *rms*-emittance ϵ_n^x is defined as

$$\epsilon_n^x = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2} = \frac{1}{c}\sqrt{\langle x^2\rangle\langle v_x^2\rangle - \langle xv_x\rangle^2}. \tag{2}$$

where c is the speed of light, x is the position of a particle and the notation $\langle\ \rangle$ implies an average over a set of particles. In the previous equation, the substitution of the non-relativistic momentum $p_x = mv_x$ is used (ions at energies up to 15 keV are non-relativistic). The normalized *rms* emittance ϵ_y^n is defined similarly.
Filling equation (2) in equation (1), the reduced brightness can be rewritten as

$$B_r = \frac{I}{4\pi^2 \epsilon_r^x \epsilon_r^y}, \tag{3}$$

where the reduced emittance in the x-direction ϵ_r^x is given by

$$\epsilon_r^x = \sqrt{\frac{m}{2}}\sqrt{\langle x^2\rangle\langle v_x^2\rangle - \langle xv_x\rangle^2}. \tag{4}$$

A similar equation holds for the quantity ϵ_r^y.

The *rms* energy spread σ_U is an intrinsic property of the source. It is proportional to the accelerating field E_0 and the ionization laser *rms* radius σ_i as

$$\sigma_U = eE_0\sigma_i. \tag{5}$$

The attainable spot size d in a FIB [25], for a chromatic aberration limited source, is connected to the energy spread and the brightness as

$$d = \left(\frac{I\ C_C^2\ \sigma_U^2}{B_r\ V_p^3}\right)^{1/4}, \tag{6}$$

where C_C is the chromatic aberration coefficient of the focusing system, I is the ion beam current and V_p is the voltage applied to accelerate the ions. Typically, $C_C = 20$ mm and $V_p = 30$ kV for FIB columns [20].

4. This thesis

This thesis is mainly made up as a collection of three scientific papers, already published or submitted for publication (chapters 3, 4 and 5). In chapter 2, the experimental setup is presented, focusing on some details that were not covered in the publications. Chapter 3 and 4 are based on experimental measurement of the UCIS. Chapter 3 goes over the measurement of the source temperature. An upper limit of the emittance is there obtained and this chapter introduced a new technique used to focus an ion beam with the use of time-dependent electric fields. In chapter 4, a model of the source is presented and validated with measurements. Then, the current of the UCIS is measured and finally simulations of disorder induced heating are presented. The general conclusion is that the UCIS can not increase the brightness and at the same time decrease the longitudinal energy spread of the LMIS: one of the two quantities need to be sacrified respect to the other one. Chapter 5 presents a new kind of source, also based on laser-cooling, and summarize a series of simulations where it is shown that even with taking into account the disorder induced heating, the source performs better than the LMIS. Finally, chapter 6 summarizes the main conclusions of the thesis and gives an outlook for the future of laser-cooled ion sources for FIBs.

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