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Introduction to the focused ion beam system

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1.1 Introduction

The frontier of today's scientific and engineering research is undoubtedly in the realm of nanotechnology: the imaging, manipulation, fabrication, and application of systems at the nanometer scale. To maintain the momentum of current research and industrial progress, the continued development of new state of the art tools for nanotechnology is a clear necessity. In addition, knowledge and innovative application of these tools is in increasingly high demand as greater numbers of them come into use. The interdisciplinary field of materials science, in particular, perpetually seeks imaging and analysis on a smaller and smaller scale for a more complete understanding of materials structure–composition–processing–property relationships. Moreover, the ability to conduct material fabrication via precise micro- and nano-machining has become imperative to the progress of materials science and other fields relying on nanotechnology.

An important tool that has successfully met these challenges and promises to continue to meet future nanoscale demands is the focused ion beam (FIB) system. The technology offers the unsurpassed opportunities of direct micro- and nano-scale deposition or materials removal anywhere on a solid surface; this has made feasible a broad range of potential materials science and nanotechnology applications. There has naturally been great interest in exploring these applications, recently spurring the development of the two-beam FIB system, often also called DualBeam or CrossBeam, a new and more powerful tool that has advanced hand in hand with the complexity of new materials.

A focused ion beam system combines imaging capabilities similar to those of a scanning electron microscope (SEM) with a precision machining tool.

Focused Ion Beam Systems: Basics and Applications, ed. N. Yao.
Published by Cambridge University Press.

It was developed as the result of research on liquid-metal ion sources (LMIS) for use in space, conducted by Krohn in 1961 [1,2]. Liquid-metal ion sources found novel applications in the areas of semiconductors and materials science, and the FIB was commercialized in the 1980s as a tool mainly geared toward the growing semiconductor industry [3]. In the development of semiconductor fabrication, there is a constant struggle to improve the resolution and speed of the lithographic technique. The use of photoresist and masking improved the speed and reproducibility of the result, but not the resolution, due to the fundamental and practical limitations imposed by the wavelengths of the light used. Electron beam lithography was a marked improvement in this area [4], due to the much smaller wavelength of a high energy electron, often on the order of one to two hundredths of a nanometer compared to the hundreds of nanometers associated with light. However, electron beam (or e-beam) lithography is a comparatively slow process, and often has difficulty penetrating harder materials without suffering from considerable distortion effects due to local charge buildup. Electrons, though easy to produce and accelerate, simply did not have the mass to penetrate materials and remove atoms from a lattice quickly, and so e-beams have stayed primarily in the realm of imaging, except in certain very specific environments. Thus the demand for a lithographic method with the advantage of short wavelengths, allowing higher resolution, but without the drawbacks presented by the low mass of electrons, has found an answer in the use of focused ion beams.

Fundamentally, a focused ion beam system produces and directs a stream of high-energy ionized atoms of a relatively massive element, focusing them onto the sample both for the purpose of etching or milling the surface and as a method of imaging. The ions' greater mass allows them to easily expel surface atoms from their positions and produces secondary electrons from the surface, allowing the ion beam to image the sample before, during, and after the lithography process. The ion beam has a number of other uses as well, including the deposition of material from a gaseous layer above the sample. The ions in the beam strike atoms or molecules down onto the surface of the sample, where intermolecular attractions fix them, and the implantation of ions into a surface [5,6].

Today's focused ion beam system utilizes a liquid-metal ion source at the top of its column to produce ions, usually Ga^+. The ions are then pulled out and focused into a beam by an electric field. They subsequently pass through apertures and are scanned over the sample surface. The ion–atom collision is either elastic or inelastic. Whereas elastic collisions result in the excavation of surface atoms, a technique called sputtering or milling, inelastic collisions

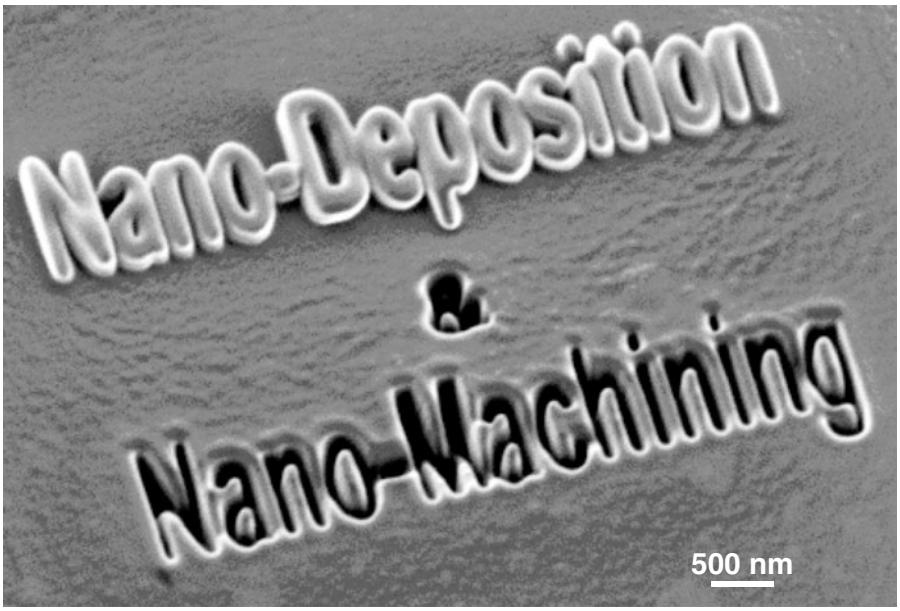

Figure 1.1 A typical SEM image showing the simultaneous milling and deposition capabilities of a two-beam FIB system. (*Courtesy of Fibics Incorporated.*)

transfer some of the ions' energy to either the surface atoms or electrons, resulting in the emission of secondary electrons (those that become excited enough to escape from their shell). Secondary ions are also emitted from the surface following the secondary electrons.

The FIB system has four basic functions: milling, deposition, implantation, and imaging; each will be discussed in detail in the following chapters. Milling is a process that allows digging into the sample surface as a result of the use of relatively heavy ions in the beam. It can also be easily converted into a deposition system simply by adding a gas delivery device that allows the application of certain materials, usually metals, to the surface of the material where the beam strikes. When combined with milling, FIB deposition can create almost any microstructure. Figure 1.1 represents a typical example of such capability. Ion implantation is another important component of surface modification that is available using the FIB. In addition to these three variations of material surface adaptation, the FIB system also has extensive imaging capabilities. The large size of the ions provides advantages that are not available with scanning electron microscopes or other imaging tools.

The FIB's unique properties allow it to isolate specific sample regions so that it only makes the necessary modifications without affecting the integrity

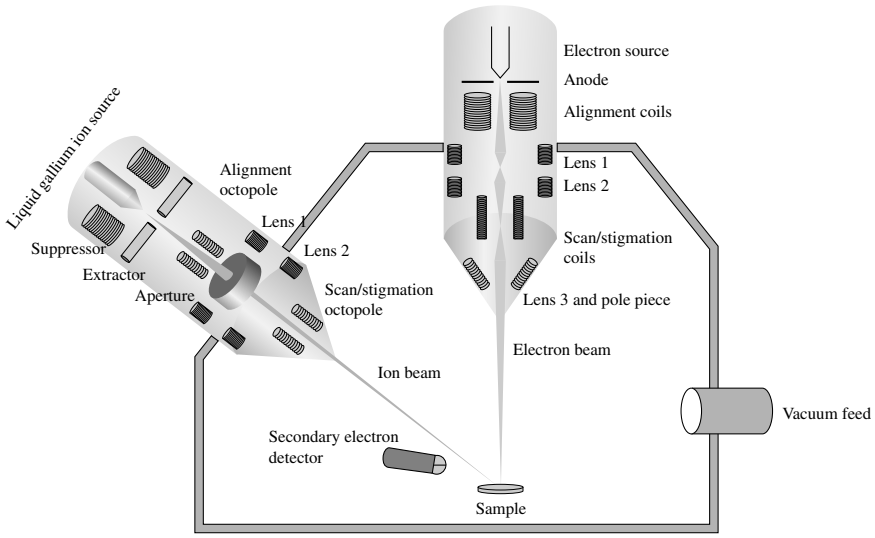

Figure 1.2 A schematic diagram showing the configuration of a two-beam focused ion beam system.

of the whole sample. With this technology the FIB can perform simple techniques such as making probe holes as well as more complicated procedures such as cutting a precise three-dimensional cross section of a sample. The FIB, with its combination of drilling and deposition capabilities, is also ideal for failure analysis and repair.

Using only an FIB system has some disadvantages, however, including that it often causes some undesired damage to the sample. Obstacles associated with the FIB, as well as the growing complexity of materials, has fueled the development of a two-beam focused ion beam system: a system that combines both electron beam and ion beam in a single microscope. Though the FIB system by itself has a wide range of functions and applications, combining the FIB's precise imaging and machining abilities with the scanning electron microscope's high resolution, nondestructive imaging leads new and invaluable applications to emerge that were previously impossible. The two-beam FIB excels at high resolution structural, chemical, and geometric analyses of cross sections of layers of material, a necessary feature for the examination of complex materials and their synthetic analogs as well as for the analysis of phenomena that may affect performance, durability, and reliability of many new materials. The combination of SEM and FIB in a two-beam system, as shown schematically in Figure 1.2, allows the electron and ion beams to work symbiotically to achieve tasks beyond the limitations of either individual system.

In this chapter, we present a basic introduction of the two-beam FIB system. Since ion beam and electron beam are the two key components of the system, we start with a discussion of them first, followed by a discussion of ion and electron sources used in the two-beam system. It is important to explain the essential differences between electrons and ions in order to understand how the properties of each affect the structure and functionality of the FIB and the SEM. Following the discussion of properties of the ion beam and electron beam and their emission sources, we will look at the ion optics and electron optics responsible for focusing ions and electrons from the source onto the sample in the column of a microscope. The detection of secondary and backscattered charged particles from the sample to form images will also be examined. Finally, we will introduce the two-beam system and discuss its advantages versus a standalone SEM or FIB platform, and how its enhanced capabilities open new channels for materials science and nanotechnology.

1.2 Ion beam versus electron beam

All emissions can be sources of information, depending on the capabilities of the instrument. The ejected signals from a focused ion beam or electron beam can be collected, amplified, and then displayed to show detailed information of the sample surface. When the ion beam is focused on one area for an extended length of time, the continuous sputtering process gives the machine another added use, that of removing surface material, which opens the door for probing and milling applications. The FIB system can also be a deposition tool by injecting an organometallic gas in the path of the ion beam, just above the sample surface. This technique allows for many kinds of material fabrication at the micro- and nano-scales.

Since ions are significantly more massive than electrons (Table 1.1), the FIB system has many more applications than a conventional imaging instrument. The collision between the large primary ions of the beam and the surface atoms causes surface alteration of various levels determined by the dosage, overlap, dwell time, and many other ion beam variables. Such surface alteration could not be achieved at the same level with electrons.

The ion beam and electron beam are based on the same principle and serve many of the same purposes. They both consist of a stream of charged particles that is focused by a series of lenses and apertures onto a sample and both employ similar methods to produce and accelerate the particles from their source. Both systems can be used to image a sample, as well as to perform etching and deposition.

Table 1.1 *Quantitative comparison of FIB ions and SEM electrons*

Particle	FIB	SEM	Ratio
Type	Ga^+ ion	Electron	
Elementary charge	+1	−1	
Particle size	0.2 nm	0.00001 nm	20 000
Mass	1.2×10^{-25} kg	9.1×10^{-31} kg	130 000
Velocity at 30 kV	2.8×10^{5} m/s	1.0×10^{8} m/s	0.0028
Velocity at 2 kV	7.3×10^{4} m/s	2.6×10^{7} m/s	0.0028
Velocity at 1 kV	5.2×10^{4} m/s	1.8×10^{7} m/s	0.0028
Momentum at 30 kV	3.4×10^{-20} kg m/s	9.1×10^{-23} kg m/s	370
Momentum at 2 kV	8.8×10^{-21} kg m/s	2.4×10^{-23} kg m/s	370
Momentum at 1 kV	6.2×10^{-21} kg m/s	1.6×10^{-23} kg m/s	370
Beam			
Size	nm range	nm range	
Energy	up to 30 kV	up to 30 kV	~
Current	pA to nA range	pA to μA range	~
Penetration depth			
In polymer at 30 kV	60 nm	12000 nm	0.005
In polymer at 2 kV	12 nm	100 nm	0.12
In iron at 30 kV	20 nm	1800 nm	0.11
In iron at 2 kV	4 nm	25 nm	0.16
Average signal per 100 particles at 20 kV			
Secondary electrons	100–200	50–75	1.33–4.0
Backscattered electron	0	30–50	0
Substrate atom	500	0	infinite
Secondary ion	30	0	infinite
X-ray	0	0.7	0

The fundamental difference between the use of an ion beam and that of an electron beam lies in their unique characteristics. The ion is much larger and more massive than the electron and can be positively charged, whereas electrons are always negatively charged. Since ions travel more slowly and require greater fields to focus and control than electrons, different methods are required to control massive ions versus electrons.

Size and mass can appreciably alter the interactions between the beam and the sample (Table 1.1). When a beam of energetic particles, whether ions or electrons, strikes a solid surface several interactions occur. Some particles are backscattered from the surface layers; others are slowed down within the solid. Unlike electrons, the relatively large ions have a hard time penetrating the surface of a sample because it is much harder for them to pass through individual atoms. Instead, their size increases their probability of interactions with atoms, causing a rapid loss of energy. As a result, atomic ionization of

the surface atoms and breaking of the chemical bonds between these atoms – both processes involving mainly surface electrons – occur as the main ion–atom interactions. Emission of secondary electrons usually accompanies these processes as well as a change in the chemical state of the material. Unlike in the case of an incident electron beam, however, the inner electrons cannot be reached or excited by an ion beam and characteristic X-rays are therefore unlikely to be generated.

The total length that the ion travels is known as its "penetration depth," a term which also applies to electrons, which often penetrate much deeper into the sample than ions (Table 1.1). Because of the statistical nature of the atomic collision, the penetration depth adheres to a symmetric Gaussian distribution around the mean value. In the process of material modification, the moving ion recoils one or more atoms in the sample, which results in the recoiling of constituent atoms, leading to the creation of atomic defects along the path of the ion beam.

The other difference between the two beam types, of course, is that the ion beam has a much greater direct effect on its target, causing localized heating and removing atoms beneath the focus, as well as implanting ions into the surface and depositing atoms located above the sample onto it. Electron beams generally cause little or no surface damage, have greater difficulty causing deposition, and generally do not change the internal structure of the sample, as the electrons left by the beam's passage dissipate through conduction [7].

Ions are many times more massive than electrons and therefore carry hundreds of times more momentum than electrons. In the ion–atom collision, this momentum is transferred to the atoms on the surface of the material, disturbing them from their aligned positions in a sputtering effect that has important milling applications. The ion beam, as a direct result of the large size and mass of the ion, surpasses the range of capabilities of the electron beam by being able to remove atoms from the surface of a material in a precise and controlled manner.

Gallium (Ga^+) ions are usually used in FIB systems for a number of reasons. First, because of its low melting point, gallium only requires limited heating and can conveniently be in liquid phase during operation; the lower operating temperature also minimizes interdiffusion with the tungsten needle substrate. Second, its mass is heavy enough to allow milling of the heavier elements, but it is not so heavy that a sample is immediately destroyed. Third, its low volatility at the melting point conserves the supply of metal and yields a long source life of about 400 μA-hours/mg. Fourth, its low vapor pressure allows Ga to be used in its pure form instead of in the form of an alloy source, which would require an E × B mass separator in the optics column.

Finally, gallium can be easily distinguished from other elements, so if implantation occurs, the gallium ions will not interfere with the analysis of the sample. Although other ions can be used, gallium has become the ion of choice for the focused ion beam system.

Ultimately, the purpose of precision engineering and attention to detail in FIB design is to produce a focused ion beam that impacts the surface at a desired point. It is important to consider the implications of this impact. A beam of light incident upon a surface causes local temperature increase, small electromagnetic fluctuations, and photoelectron emission. A beam of charged particles does all of this and more. The incident particles raise the temperature of the area they impact, although generally not to a significant degree; they change the local charge densities of the region, resulting in a temporary charge imbalance; the addition of their kinetic energy to the energy of the sample causes secondary electrons to be emitted, which can be captured and used to image the surface of the sample; they produce a degree of characteristic X-ray emission, which can be used for spectroscopy purposes; and, of course, they cause damage to the surface structure at different levels depending on the physical nature of charged particles.

The emission of secondary electrons from the surface is what gives both beam types their imaging abilities. Adding the energy of the particles in the beam to that of the electrons in the sample allows some of those electrons to escape from within the material, depending on the penetration depth of the beam and the conductivity and work function of the sample. These electrons come from a roughly spherical region around and beneath the beam spot, with increased numbers of electrons exiting from the sides of topographical features that would not have escaped from a flat surface otherwise. In addition to the secondary electrons, there is a degree of radiation produced by the rapid deceleration of the charged particles, generally in the X-ray spectrum. This radiation can later be used for X-ray spectroscopy. Between this emitted radiation and the radiation from the accelerating potentials in the sources, the chamber requires good shielding in order to preserve the safety of the operator. All the modern electron and ion instruments have handled this issue satisfactorily.

The ion beam is capable of efficiently and precisely depositing material. By creating a cloud of, for example as shown in Figure 1.3, platinum atoms above the sample, platinum can be deposited by letting the ion beam strike these atoms, imparting some kinetic energy to them and causing them to impact the surface, on which they remain, adsorbed onto the sample by Van der Waals forces. This technique can be used to deposit both conductive and resistive materials, since the type of atom in the suspended

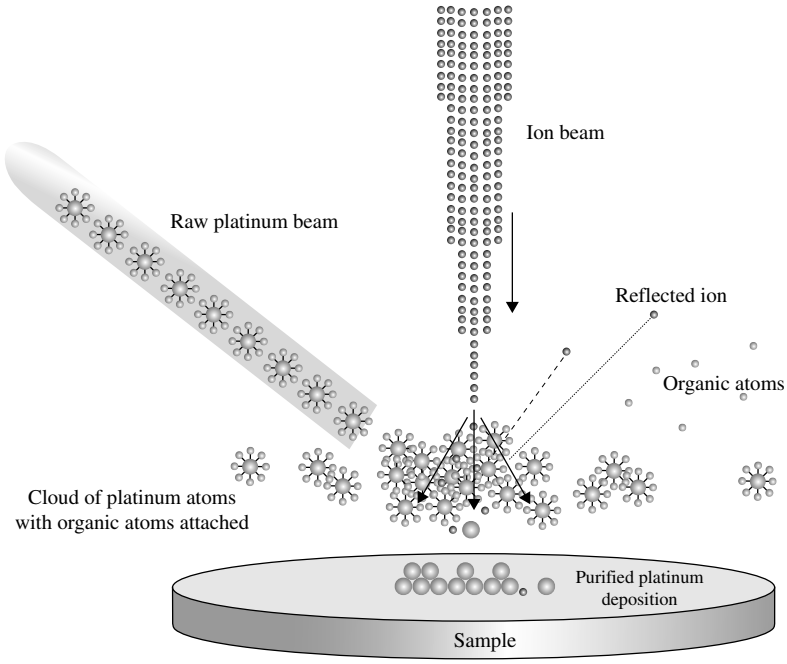

Figure 1.3 A Schematic diagram of an ion beam induced platinum deposition process.

material does not matter, making the ion beam quite useful for nano-fabrication purposes. This technique can also be used to improve electron-beam imaging, by depositing a thin layer of conductor over the surface of a feature to be imaged. Similar to sputter- or deposition-coating of a sample, this method preserves more detail at a small scale by using a precisely controlled, very thin layer of conductor to reduce charging effects and define the surface [8].

The electron beam can be used, to some degree, to perform deposition. However, due to the low mass of the electrons, the deposition occurs slowly, and it is more feasible if the beam is very intense and focused precisely, to increase the probability of electrons intersecting atoms of the deposition material. In general, electron-beam deposition is not done with the beams found in smaller scanning electron microscopes, instead requiring a larger and more powerful apparatus. Until the advent of the focused ion beam, this type of precision deposition was extremely difficult to achieve.

While the electron beam barely affects the surface, the heavy particles of the ion beam penetrate deeper within the lattice, kicking out atoms as they go and embedding them in the sample. Therefore, the lithographic abilities of

the ion beam are extremely useful. It is capable at relatively low beam currents of removing atoms from a surface in a very precise and controlled manner; it is able to make very small cuts or take large cross sections, all without changing the chemical or structural composition of the sample. Unlike traditional etching methods, it does not require masking or resist stages. The ion beam can be used to etch and mill almost any material, with little or no sample preparation. Operated at higher currents, it can achieve very high resolution etching at rapid speeds, with high reproducibility. In addition, the beam can be used to implant ions within the surface of the sample in order to tune the electronic properties of the material.

Unlike from an electron beam, collisions that result from the use of a gallium ion beam induce many secondary processes such as recoil and sputtering of constituent atoms, defect formation, electron excitation and emission, and photon emission. Thermal and radiation-induced diffusion that result from these collisions contribute to various phenomena of interdiffusion of constituent elements, phase transformation, amorphization, crystallization, track formation, permanent damage, and so on. Also, processes such as ion implantation and sputtering will change the surface morphology of the sample, possibly creating craters, facets, grooves, ridges, pyramids, blistering, exfoliation, or a spongy surface.

Because of the interrelatedness of these processes, no single phenomenon can be understood without the discussion of several others. Therefore, it is imperative that one possesses a quantitative understanding of the experimental observations as well as creativity in design so that new and more sophisticated combinations of these versatile processes can be applied in the field of nanotechnology. With it, we can aim at more advanced material modification, deposition techniques, implantation, erosion, nano-fabrication, surface analysis, and many other applications.

1.3 The ion source and electron source

In order to properly understand the focused ion beam, it is necessary to consider the source of the beam itself, as illustrated in Figure 1.4. In almost all focused ion beam systems, a reservoir of heavy-metal atoms (typically gallium for the aforementioned reasons) is heated to near evaporation, after which it flows and wets a sharp, heat-resistant tungsten needle with a tip radius of 2–5 μm. Once heated, the Ga can remain liquid for weeks without further heating due to its super-cooling properties. The Ga atoms then flow to the very end of the needle, drawn there by an annular electrode concentric with the tip of the needle and positioned close to it, called the extractor.