HIGH RESOLUTION FOCUSED ION BEAMS: FIB AND ITS APPLICATIONS

HIGH RESOLUTION FOCUSED ION BEAMS: FIB AND ITS APPLICATIONS

The Physics of Liquid Metal Ion Sources and Ion Optics and Their Application to Focused Ion Beam Technology

Jon Orloff
University of Maryland
College Park, Maryland

Mark Utlaut
University of Portland
Portland, Oregon

and

Lynwood Swanson
FIE Company
Hillsboro, Oregon

Springer Science+Business Media, LLC

Library of Congress Cataloging-in-Publication Data

High resolution focused ion beams: FIB and its applications/Jon Orloff, Lynwood W. Swanson, M. Utlaut.

p. cm.

Includes bibliographical references and index.

ISBN 978-1-4613-5229-7 ISBN 978-1-4615-0765-9 (eBook)

DOI 10.1007/978-1-4615-0765-9

1. Ion bombardment—Industrial applications. I. Orloff, Jon. II. Swanson, Lynwood W., 1934- III. Utlaut, M.

QC702.7.B65 H65 2002

621.3815'2—dc21

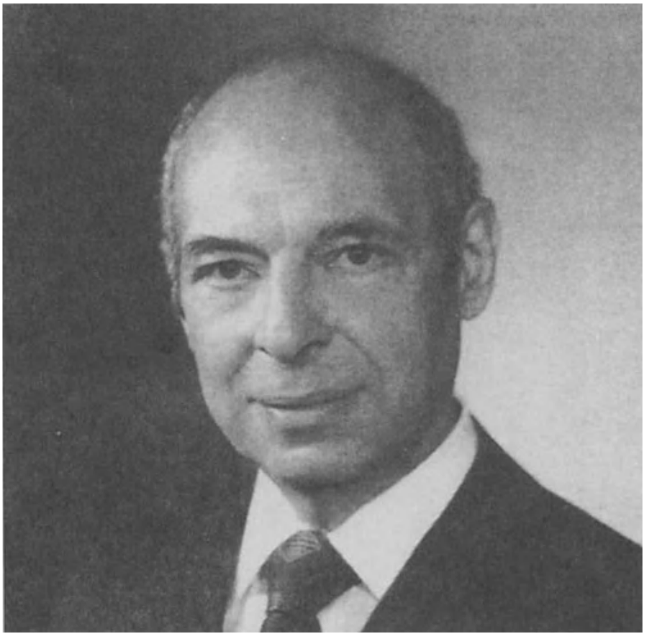
2002028661

ISBN 978-1-4613-5229-7

Originally published by Kluwer Academic / Plenum Publishers in 2003

Softcover reprint of the hardcover 1st edition 2003

To Monford Orloff, the former Chairman of FEI Company. Mr. Orloff, who passed away in February of 2000, was a well known business leader in Portland, Oregon in the period 1962–1990 and, for a period after 1985, was a Chairman of the Oregon Graduate Institute where much high resolution focused ion beam technology was developed. Mr. Orloff took an interest in FEI Company in 1985 and, although not a scientist (his training was in law), he saw clearly the potential of the focused ion beam technology being developed there. He guided the company's business development in the mid and late 1980s so that it was able to grow rapidly into the leading manufacturer of high resolution focused ion beam equipment in the world. Mr. Orloff was highly respected and regarded by the employees at FEI Company for both his business insight and for his interest in them personally.



Monford A. Orloff (1914–2000)

PREFACE

In this book we have attempted to produce a reference on FIB that will be useful for both the user and the designer of FIB instrumentation. We have included a mix of theory and applications that seemed most useful to us.

The field of high resolution focused ion beams (FIBs) has advanced rapidly since the application of the first field emission ion sources in the early 1970's. The development of the liquid metal ion source (LMIS) in the late 1960's and early 1970's and its application for FIB in the late 1970's has resulted in a powerful tool for research and for industry. There have been hundreds of papers written on many aspects of LMISs and FIBs, and a useful and informative book on these subjects was published by Phil Prewett and Graeme Mair in 1991. Because there have been so many new applications and uses found for FIBs in the last ten years we felt that it was time for another book on the subject.

We have tried to cover the essential topics needed to understand what FIB technology is, how and why it works and how it is applied. To this end we have included a chapter on the physics of the LMIS that includes a lot of practical information about these important ion sources, and two chapters that provide an introduction to ion optics and a "practical" discussion of ion optics as it is used in the FIB system today. Because FIBs are so often used to alter materials we have included a chapter on the interaction of ions with matter. The final chapter is a comprehensive coverage of FIB applications up through the year 2000.

The chapters can be read independently - the "practical optics" of chapter 5 uses chapter 3 as a reference point, but you don't have to read chapter 3 to read chapter 5: some of the material is repeated where necessary.

TABLE OF CONTENTS

INTRODUCTION

There is an old saying attributed to Confucius that is, approximately: "Theory without practice is futile; practice without theory is fatal". It is our belief that the practice of focused ion beam technology is so important that its users should know a lot about its theoretical underpinnings. The fact that the practice of focused ion beam technology is so widespread makes it easy to justify the effort spent on development of the theory of the liquid metal ion source, aside from its intrinsic interest from a scientific point of view. So, we are trying to follow the dictum of Confucius.

This book has five main topics: the gas field ionization source (Chapter 1); theory of the liquid metal ion source or LMIS (Chapter 2); optics for applying the LMIS in a focused ion beam (FIB) system (Chapters 3 and 5); interactions of ions with solids (Chapter 4); and applications of FIB (Chapter 6). Chapter 6 provides an up to date (ca. 2001) discussion of essentially all aspects of the application of high resolution FIB systems based on LMIS technology. For those who do not want to delve into the theoretical aspect of the LMIS or optics at the outset, important results from Chapters 2 and 3 are repeated in Chapter 5.

Perhaps the prime driving force in modern technology is to make objects smaller so more and more of them can be put into use in the same location. The quintessential example is the integrated circuit where all of the electronic components are microscopic, and thousands or even millions of transistors are all put into an area of a few square centimeters or less. The difficulties in building things on a microscopic scale are well known and the solutions to the many problems are often quite elaborate - lithography, with its sub-micrometer steppers and its e-beam mask writing technology, is a well known example. Other interesting technologies are the means for editing errors that occur in the design phase of an integrated circuit and for performing failure analysis on a circuit whose density of components is 10^6 cm^{-2}. In the past two decades it has been found that an effective way of building and analyzing microscopic objects is with finely focused ion beams. These can be used for observing, analyzing and modifying materials, including micro-machining. However, in order to be useful a focused ion beam (FIB) must have sub-micrometer dimensions and provide a high current density (~ 1 A cm^{-2}).

Beginning in the early 1970s a very useful class of ion sources known as field emission or "point" sources had been adapted from surface physics to become very important in a number of technological applications. These sources

J. Orloff et al., *High Resolution Focused Ion Beams: FIB and its Applications*

produce ions by means of high electric fields: by field ionization from the gas phase (gas phase field ionization sources, or GFIS) or by field evaporation from the liquid phase (liquid metal ion sources, or LMIS). Note that we will use acronyms such as FIB or LMIS in both the singular and plural sense so as to avoid ugliness such as "LMIS's". The most important property of point sources is the very small virtual source size which leads to a very high optical brightness which makes it possible to focus a (relatively) large amount of current into a very small area, thereby achieving high current densities on a target.

The purpose of this book is to describe the operation of the LMIS, to analyze the ion optics used to produce high quality focused ion beams and to describe some of the important applications. The technological significance of the LMIS is based on the ease with which it can be used to produce high intensity, high resolution focused ion beams. Therefore we feel that the optics of ion focusing columns is an important subject which should be covered along with the physics of the source itself in order to understand how it can be applied. Field emission sources for charged particles (ions and electrons) were developed many years ago but it has only been recently that they have been successfully employed in probe forming instrumentation. The optical performance; i.e., the brightness of field emission sources is so superior to that of conventional sources that at first glance it seems surprising that their successful application took so long. But on examination of the history of electron and ion probes, the reasons are clear. The transmission electron microscope (TEM) was invented in the early 1930s, and the scanning electron microscope (SEM) a little later, nearly contemporaneously with television. Zworykin and co-workers[1] described the attempted application of a cold field emission cathode in an SEM in 1942, but concluded that the vacuum technology of the day made them impractical: their SEM had to be bakeable and it took a long time to exchange specimens. Despite their much poorer brightness, thermionic cathodes requiring only modest vacuum levels were used instead. The cold field emission cathode was not widely and successfully used in the SEM until Crewe demonstrated how it could be done in the 1960s, when researchers wanted to achieve high spatial resolution (< 10 nm) and high beam current (tens of picoamperes). In the 1980s field emission became essential for CD-SEM and defect review - metrology tasks during integrated circuit manufacturing processes where low beam energies (~ 1 keV) and rapid information gathering are required. During the 1970s a competitive point source cathode, the Schottky emitter, was developed that is capable of similar performance in the SEM. Present very high performance SEM's use one or the other of these cathodes.

In the case of field emission ion sources, there was no compelling need for the high resolution, high intensity performance that point sources make possible until the invention of the large scale integrated circuit. When it was demonstrated in the 1980s that failure analysis and integrated circuit

---

1 Zworykin, V.K., Hillier, J. and Snyder, R.L., "A scanning electron microscope", ASTM Bull. 117 (1942) 1.

modification could be done with focused ion beams (FIBs) utilizing liquid metal ion sources, the resulting technological "push" for high performance caused the rapid development of new ion beam instrumentation. Among other applications, FIBs are now used for research lithography, direct implantation (using alloy metal ion sources with ion species including As, B, Si and Be), lithographic mask repair and a wide variety of micro-machining uses.

In this introduction we consider some of the important developments in field emission based ion sources along with a brief discussion of some of the important properties of the sources. The physics of the LMIS will be considered in detail in the next chapter, followed by a chapter on ion optics and ending with a chapter on applications. We begin chronologically, with a discussion of GFIS, because their operation is somewhat easier to understand than that of the LMIS.

1

FIELD IONIZATION SOURCES

1.1. GAS FIELD IONIZATION SOURCES

The possibility of applying a field emission ion source to produce a focused ion beam was first demonstrated in the early 1970's by Levi-Setti et al. [Escovitz, 1975a,b, Levi-Setti, 1974] and by Orloff and Swanson [Orloff, 1975, 1977, 1978]. Both these groups used a gas field ionization source of the sort invented by Müller in 1951[Müller, 1951, 1956, 1957] and which has been widely used for surface studies in the field ion microscope (FIM). FIMs are well known surface analytical tools capable of atomic imaging (for a thorough discussion of the FIM and principles of operation, see the monographs by Müller and Tsong [Müller, 1969] and Gomer [Gomer, 1961]). A GFIS developed by Orloff and Swanson for focused beam work is shown in Figure 1.1.

The significance of the FIM for focused beam work can be understood as follows. The FIM allows the atomic structure of the specimen to be imaged with sub-nanometer spatial resolution. A FIM consists of a specimen in the form of a very sharp needle called a field emitter, which is kept at cryogenic temperatures and maintained at a high positive potential relative to earth. The field emitter is placed near a grounded counter electrode and a few centimeters from a viewing screen or channel electron multiplier/viewing screen combination. A small amount of gas to be ionized, such as He, Ne or H_2 is admitted into the FIM at low temperature. In effect, the specimen in a FIM is viewed by projecting an image of its surface onto the viewing screen with ions generated at the specimen surface. Ions are created in the high electric field at the approximately hemispherical field emitter endpoint (the endpoint has a radius of ~ 100 nm). The ions, which have a negligible deBroglie wavelength, follow nearly radial paths from the field emitter to the viewing screen and appear to originate from a virtual source ~ 1 nm in diameter located some hundreds of nm behind the emitter surface. The process is analogous to the projection of an image contained in a photographic slide onto a large viewing screen (see Figure 1.2). The fact that the image contains information with atomic resolution implies the virtual source size δ must be less than a nanometer (the virtual source size can be determined by projecting the tangents to the ion trajectories at some distance

J. Orloff et al., *High Resolution Focused Ion Beams: FIB and its Applications*

from the field emitting source back to the location where they form a waist. See Figure 1.3). It is this feature of the gas field ionization source (GFIS) which is of interest from an ion optical point of view, since source brightness depends on the virtual source size, and the amount of ion current that can be focused in a given size spot depends on the brightness. The reason for the small source size can be understood from the emission mechanism

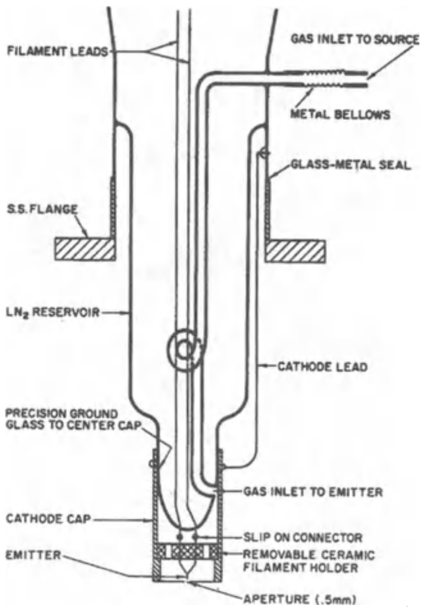


Figure 1.1. A field ionization gun designed for microprobe work in 1978 [Orloff, J. and Swanson, L.W., "Angular intensity of a gas-phase field ionization source," J. Appl. Phys. 50 (1979) 6026]

of the ions. The field ionization process is a quantum mechanical tunneling process in which an electron tunnels from an atom or molecule through a highly distorted Coulomb potential, the distortion being due to the very high electric field. The tunneling process can be explained in a quantitative way by a WKB analysis and the rate of ion production is found to depend primarily on two factors: the probability of ionization D, which is strongly field dependent and which is the subject of the WKB analysis, and the supply of material to be ionized, which is also field dependent.

The probability of ionization calculated by the WKB method is approximately given by $D \sim \exp(-c\,[I - \phi]/F)$ where I is the ionization potential of the gas, ϕ the work function of the field emitter, F the applied electric field and c is a constant. An electric field with a strength $F \sim 10^{10}$ V/M can be produced by application of a modest voltage $V \sim 10$ kV to a field emitter with an end radius ~ 100 nm. The need for an end radius $R \sim 100$ nm is because to