1-1984

Computer simulations of submicron FIB system optics

W. Thompson
I. Honjo
Mark Utlaut
University of Portland, utlaut@up.edu

Follow this and additional works at: http://pilotscholars.up.edu/phy_facpubs

Part of the Plasma and Beam Physics Commons

Citation: Pilot Scholars Version (Modified MLA Style)
http://pilotscholars.up.edu/phy_facpubs/40

This Journal Article is brought to you for free and open access by the Physics at Pilot Scholars. It has been accepted for inclusion in Physics Faculty Publications and Presentations by an authorized administrator of Pilot Scholars. For more information, please contact library@up.edu.
Computer simulations of submicron FIB system optics

W. Thompson, I. Honjo, and Mark Utlaut

Varian Associates, Inc., Gloucester, Massachusetts 01930

H. Enge

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 3 June 1983; accepted 13 September 1983)

The design of the optical elements for a focused ion beam (FIB) system having a 50 nm spot size over a 1 mm square field requires extensive computational analysis. We discuss the mathematical techniques applied to the components of interest in this submicron FIB system; the electrostatic lenses, the mass analyzer, and the electrostatic deflectors. The results of ion trajectory calculations predicted for the whole FIB column by the computer code SNOW are presented. The aberration coefficients to third order and a parametric study of a stigmatic Wien filter whose design includes entrance and exit fringe field effects will be considered. We also cover our optimization algorithms for selecting lens and deflector elements which demonstrate minimal chromatic and spherical aberrations and distortions. A spot symmetry and spot location map for the final 1 mm square field and its 50 nm image constraint is shown for mixed electronic configurations of dynamic focus, dynamic distortion, and dynamic stigmation correctors. A comparison of the computer predictions to measured values of lens parameters is given for a typical liquid metal source and its extractor lens. The equipotentials in the vicinity of a representative lens is plotted with emphasis on the dielectric-conductor interface in order to demonstrate the significance of stressed electric fields to the hardware designer.

PACS numbers: 41.80.Gg

I. INTRODUCTION

A number of applications for focused ion beam systems are emerging. Some microfabrication uses include etch rate enhancement, resist exposure, and direct microbeam doping. No one ion optics design will meet all needs. The optics associated with these ion beams systems are of necessity electrostatic and require design techniques that differ significantly from those used in the design of SEM and e-beam lithography equipment. Since the majority of these systems may have the further constraints of compatibility with existing hardware and software, large deflection fields, circularly symmetric submicron images, mass analysis, accurate feature placement, and variable beam energy, additional burdens are placed on the design tools. What follows is a prescription for the design of customized ion beam systems which can be tailored to meet the needs of a specific application or which can be used to generate the evolutionary optics inevitably required by the changing goals of the semiconductor industry. Our first test of this design procedure was an ion column which would adapt to our model VLS-80 raster beam e-beam lithography system as shown in Fig. 1.

The energy and magnification required of the system determine the lens dimensions and locations. The program ELFI is then used to establish the aberration coefficients for each optical element. The program SNOW gives the equipotentials within the lenses and the trajectories of the ions throughout the system.

Since several of the codes produce similar output, where possible we cross check one program's results against another. In addition, each lens is qualified on the emittance measurement stand to determine if it is actually meeting its design goals.

The program SNOW is used to calculate the ion trajectories to fifth order in an arbitrary mix of static multipole elements which may range from dipoles to dodecapoles. It also will calculate the ion trajectories in an \( E \times B \) velocity selector and its fringe fields. Since the majority of the FIB systems will use an \( E \times B \) filter for mass analysis and these filters are typically not aberration free, we are designing a low aberration stigmatic Wien filter as our mass analyzer with the program RAY.
III. DESCRIPTION OF THE COMPUTER CODES AND THEIR RESULTS

The program EMITTN\(^1\) used for gathering beam profile and phase space data steps a pair of slits across the beam envelope just downstream of the ion source or optical element being evaluated. The beam current for different \(X\) and \(X'\) or \(Y\) and \(Y'\) values is stored and presented as a current contoured emittance diagram. These measurements made by EMITTN define the angular distribution and current density variation of the beam from the liquid metal sources used for most FIB systems. One can also determine the amount of spherical aberration introduced by a lens at different operating potentials.

The programs TRANS and TRANSPORT use as input the phase space information gathered by EMITTN. They assume a first-order matrix representation for each optical element in the system and translate the phase space through these elements and the drift space between them. From TRANS one can obtain a value for all \(X\) and \(X'\) and \(Y\) and \(Y'\) for selected trajectories within the beam phase space. From this information an estimate of the dimension of the full beam envelope without apertures and the system magnification can be made. The results of both TRANS and SLAC's TRANSPORT agree with each other to within 2%.

When more accurate representation of the trajectories and lens equipotentials is needed the programs SNOW and ELFI calculate the interelectrode potentials to third order and solve the Lorentz force equation for the particle trajectories. Figure 3 shows a complete representation of a FIB column as

FIG. 1. Schematic of typical three lens FIB column.

FIG. 2. Flowchart for a system design.

FIG. 3. Electrodes, equipotentials, and trajectories as determined by SNOW.
Near axis trajectories as determined by SNOW for the central lens.

Figure 4 gives a closeup of the trajectories near the einzel lens. Both SNOW and ELF1 have the ability to accurately represent the equipotentials in the vicinity of a lens electrode. Thus, the designer can know what field strengths exist and how close to a breakdown condition it is. The program SNOW also has the additional ability to produce beam profile and emittance diagrams from the trajectory plot files. It is, therefore, possible to determine the current and power density anticipated at spray and blanking apertures.

By varying the central electrode potential of the einzel lens, one can see the variation in image location produced by focusing with it. SNOW also will calculate the equipotentials at a vacuum, dielectric, electrode interface which makes it a powerful tool for locating regions of stressed electric fields.

Although SNOW considers the particle charge distribution...
in its solving of Poisson's equation, we have not used SNOW for LMI source region analysis. In order to do a SNOW simulation of the source region, we would have to add variable mesh capability to the finite element algorithm and have a better model for the Taylor cone emitter geometry. Although SNOW has been used to successfully design the extractor electrodes for both Freeman and duoplasmatron ion sources, we feel that it is unwise to model an LMI source with it.

The programs of Eric Munro, ELF1 and EDF1, are used after SNOW to determine the chromatic and spherical aberration coefficients of each of the electrostatic lenses. They are also used to forcast the deflection distortion and aberrations associated with large fields and small spot sizes. It is, therefore, possible to predict exactly what electronic corrections may be necessary to reduce the deflector distortions and aberrations. Figure 5 shows a representative EDF1 output giving the spot size and position change for a 500 Â spot deflected over a 1 mm field by an electrostatic octopole deflector without any electronic corrections. Figure 6 shows the effects of making dynamic corrections to the focus, stigmator, and distortion. With a color terminal, color coding can be added so that each trajectory is coded to represent the energy of the particle, with red being a low-energy particle and blue being a high-energy particle, for example. The significance of axial and deflection aberrations is evident.

The last analytical tool needed to design a FIB system is one which models the trajectories of particles in the crossed fields of a Wien filter mass analyzer. The first-order treatment of our $E \times B$ filter has been done very thoroughly by Seliger et al. It was realized, however, that to produce a truly stigmatic element with equal focal lengths in the dispersive and nondispersive planes of the mass analyzing EXB filter with each ray corresponding to a single amu difference between it and its nearest neighbor, we feel that it is unwise to model an LMI source with it.

The programs of Eric Munro, ELF1 and EDF1, are used after SNOW to determine the chromatic and spherical aberration coefficients of each of the electrostatic lenses. They are also used to forcast the deflection distortion and aberrations associated with large fields and small spot sizes. It is, therefore, possible to predict exactly what electronic corrections may be necessary to reduce the deflector distortions and aberrations. Figure 5 shows a representative EDF1 output giving the spot size and position change for a 500 Â spot deflected over a 1 mm field by an electrostatic octopole deflector without any electronic corrections. Figure 6 shows the effects of making dynamic corrections to the focus, stigmator, and distortion. With a color terminal, color coding can be added so that each trajectory is coded to represent the energy of the particle, with red being a low-energy particle and blue being a high-energy particle, for example. The significance of axial and deflection aberrations is evident.

ACKNOWLEDGMENTS

The authors would like to thank Stan Kowalski of MIT and Dana Gould of Varian Associates, Inc., for their assistance with the computer simulations and the graphics. We would also like to acknowledge the effort of the original authors of the computer models we used. It is they who did the real work and deserve the credit.

We have adopted the simulation tools of a broad range of charged particle designers and applied them to a focused ion beam system. From our own experience in the design of other ion optical and electron lithography systems and from the success others have had with those computer models, we feel confident of their results. Wherever possible, experimental configurations are made of our theoretical predictions.