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Computer simulations of submicron FIB system optics

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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.

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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 compatability 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 scan e-beam lithography system as shown in Fig. 1. At each stage of the design we require experimental confirmation of the predictions of the computer code. This then guarantees that the system specifications can be met and that the hardware is not unreasonably complex.

II. DESIGN PROTOCOL

Figure 2 shows a flowchart for a typical column design and identifies the major programs used for each engineering step. After the ion species of interest are selected the ion source is mounted on an emittance measurement test stand[1] to establish the variation of beam phase space and brightness as a function of a number of source parameters. Once the range of operating conditions are determined, the emittance envelope is used as input to two first-order ray trace programs called TRANS[1] and TRANSPORT.[2] These programs have as additional input the matrix elements and approximate locations of the optical components to be used in the system.

The energy and magnification required of the system determine the lens dimensions and locations. The program ELF1[3] is then used to establish the aberration coefficients for each optical element. The program SNOW[4] 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 EDF1[5] is used to design the system's multipole deflectors. The deflectors may be used for beam centering or high-speed scanning, but must be designed to have minimal deflection distortions and aberrations.

The code RAY[6] allows us 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 $\mathbf{E}\times\mathbf{B}$ velocity selector and its fringe fields. Since the majority of the FIB systems will use an $\mathbf{E}\times\mathbf{B}$ 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.

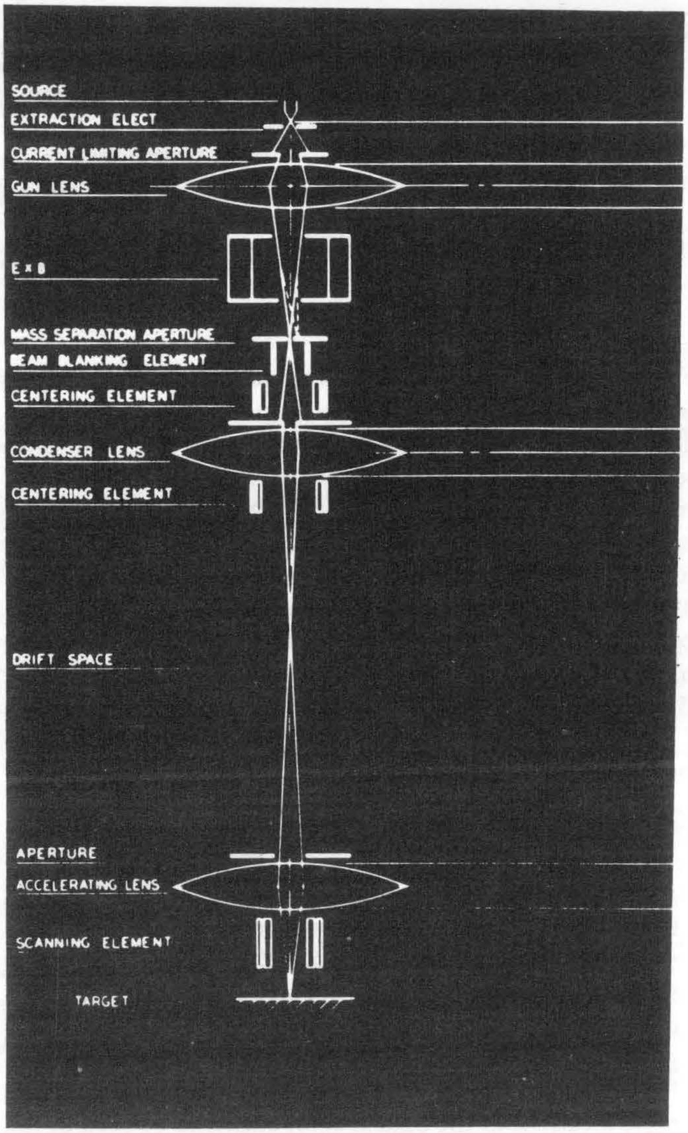

FIG. 1. Schematic of typical three lens FIB column.

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%.

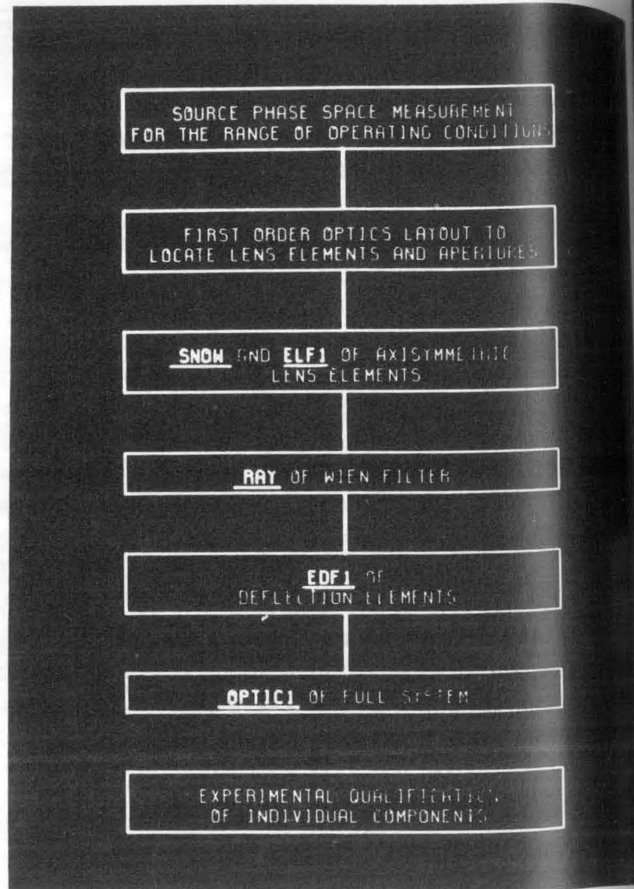

FIG. 2. Flowchart for a system design.

When more accurate representation of the trajectories and lens equipotentials is needed the programs SNOW and ELF1 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

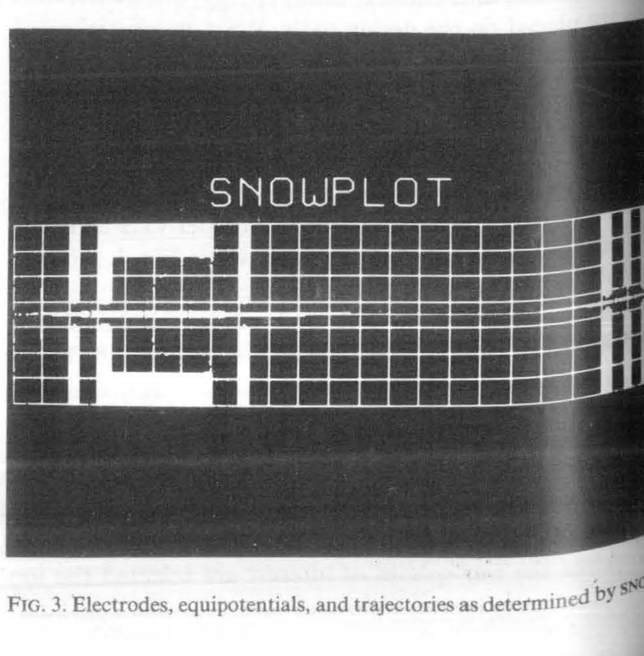

FIG. 3. Electrodes, equipotentials, and trajectories as determined by SNOW

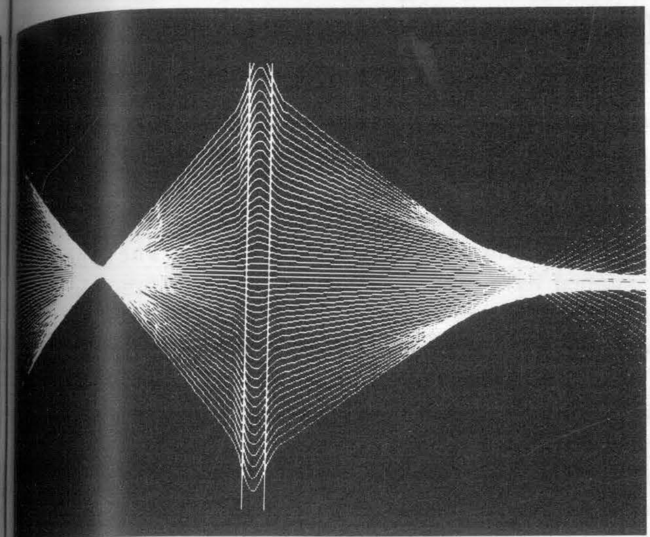

FIG. 4. Near axis trajectories as determined by SNOW for the central lens.

generated by SNOW including the electrodes, equipotentials, and ion trajectories. 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.

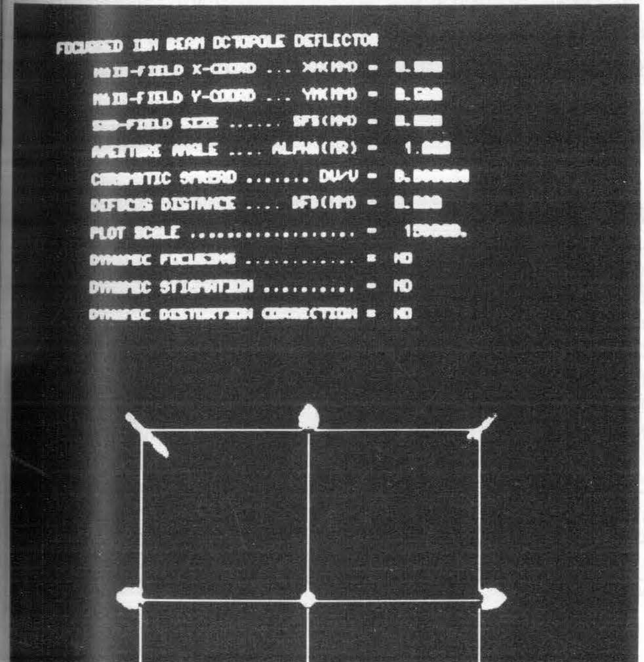

FIG. 5. Uncorrected image for a spot deflected by a postlens octupole.

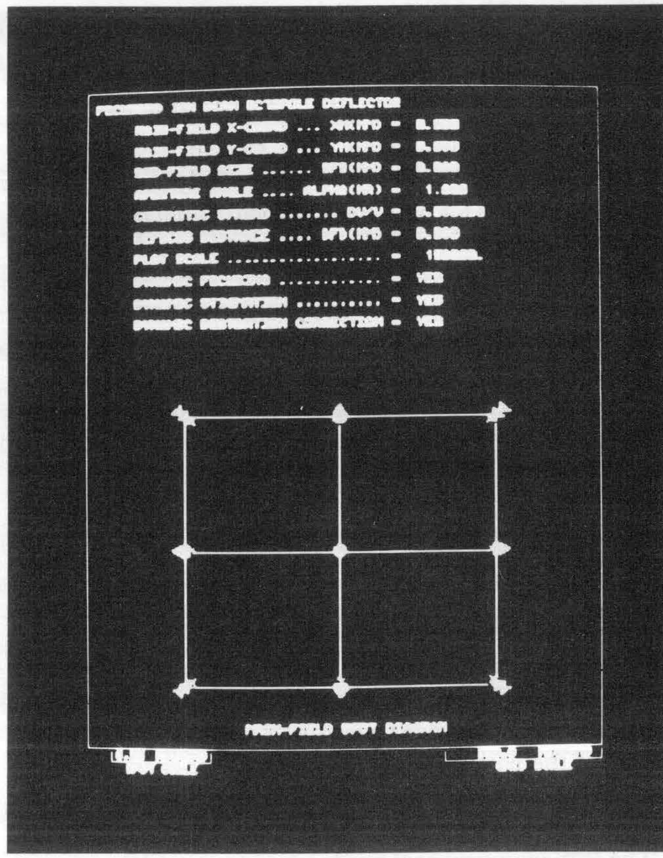

FIG. 6. Corrected image for a spot deflected by a postlens octupole deflector.

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

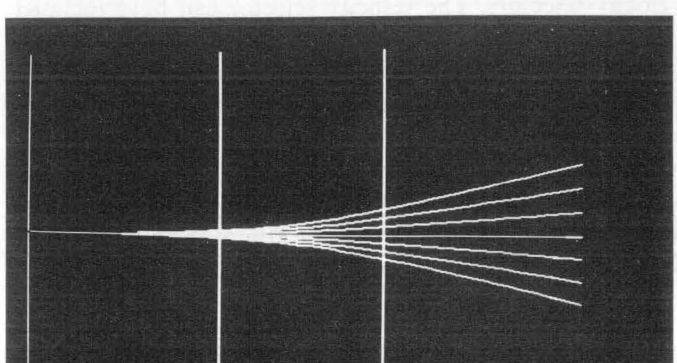

FIG. 7. Dispersion in a Wien filter as forecast by the program RAY.

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 Å 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 $\mathbf{E}\times\mathbf{B}$ filter has been done very thoroughly by Seliger *et al.*[6] It was realized, however, that to produce a truly stigmatic element with equal focal lengths in the dispersive and nondispersive planes that the effects of finite fill factor and fringe fields need to be considered. Stan Kowalski and Harald Enge[7] at MIT have developed the code RAY which has the ability to calculate ion trajectories using potential distributions expanded to fourth order of the distance from the median plane. This code models dipoles, quadrupoles, octupoles decapoles, and dodecapoles, but most importantly, it can simulate crossed electric and magnetic field velocity selectors. The velocity selector can have inclined pole pieces which are required to produce the nonzero field index necessary to accomplish stigmatic imaging.[6] The implications of realistic electric and magnetic fringe fields are also considered. Figure 7 shows the dispersive plane of the mass analyzing $\mathbf{E}\times\mathbf{B}$ filter with each ray corresponding to a single amu difference between it and its nearest neighbor. The equilibrium ray has a mass of 100 amu and rays of 1 amu difference are separated by 700 μm from their neighbor at the resolving aperture. The convergent rays in the dispersive plane have exactly the same X_1' and Y_1' for equivalent X_2' and Y_2' implying equal focal lengths in the dispersive and nondispersive planes. This system would thus be truly stigmatic. The preservation of circular symmetry can only be maintained, however, if there is complete balance between the magnetic and electric fringe fields. The implications of even the slightest imbalance are significant. The fringe fields assumed have a form defined by a Fermi function whose coefficients result from a least square fit to the results of dipole field simulation subroutine in the program Poisson.[8] When a fringe field imbalance exists the wiggle imparted to all trajectories changes their energy and this changes their velocity such that they no longer satisfy the $v_0 = \mathbf{E}/\mathbf{B}$ criteria. It is clear that the pole pieces and electrodes in this type of mass analyzer must be designed very carefully.

IV. CONCLUSION

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.

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