PREVAIL—Electron projection technology approach for next-generation lithography

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This paper is an overview of work in the IBM Microelectronics Division to extend electron-beam lithography technology to the projection level for use in next-generation lithography. The approach being explored—Projection Reduction Exposure with Variable Axis Immersion Lenses (PREVAIL)—combines the high exposure efficiency of massively parallel pixel projection with scanning-probe-forming systems to dynamically correct for aberrations. In contrast to optical lithography systems, electron-beam lithography systems are not diffraction-limited, and their ultimate attainable resolution is, for practical purposes, unlimited. However, their throughput has been—and continues to be—the major challenge in electron-beam lithography. The work described here, currently continuing, has been undertaken to address that challenge. Novel electron optical methods have been used and their feasibility ascertained by means of a Proof-Of-Concept (POC) system containing a Curvilinear Variable Axis Lens (CVAL) for achieving large-distance (>20 mm at a reticle) beam scanning at a resolution of <100 nm, and a high-emittance electron source for achieving uniform illumination of a 1-mm^2 section of the reticle. A production-level prototype PREVAIL system, an "alpha" system, for the 100-nm node has been under development jointly with the Nikon Corporation. At the writing of this paper, its electron-optics subsystem had been brought up to basic operation and was being prepared for integration with its mechanical and vacuum subsystem, under development at Nikon facilities.

Introduction

Feature size reduction has been the most important factor in the productivity improvement attained by the semiconductor industry since its inception. Extensions of optical lithography using ever shorter wavelength

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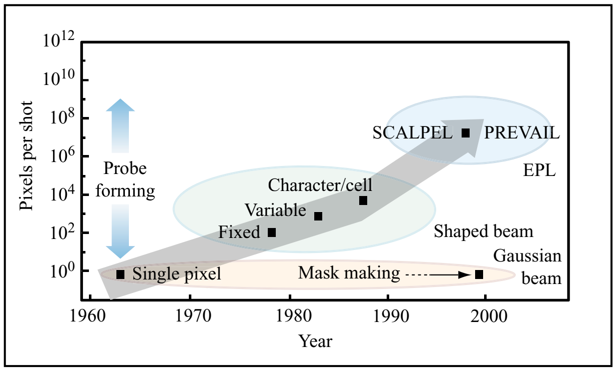

Figure 1

Evolution of electron-beam lithography.

radiation and various ingenious resolution-enhancement techniques are expected to come to an end around 2004 at the 100-nm minimum feature size. For technology nodes of sub-100-nm feature sizes, the International Technology Roadmap for Semiconductors (ITRS) identifies next-generation lithography (NGL) techniques employing both photons of significantly shorter wavelength and charged particles. PREVAIL is IBM's electron-based approach for NGL.

PREVAIL has its antecedents in a long and distinguished history at IBM. **Figure 1** illustrates the evolution of electron-beam lithography from the early scanning-electron-microscopy-type systems which expose integrated-circuit (IC) patterns one pixel at a time to massively parallel projection of pixels in electron projection lithography (EPL) systems targeted at exposing ten million pixels per shot. IBM has been at the forefront of this evolution from its beginnings [1]. During the 1970s, IBM pioneered the concept of shaped beams [2] and led the industry in the development and application of high-throughput e-beam direct-write systems [3]. The IBM EL-1 system generation with a fixed shaped beam achieved a record throughput of 22 57-mm wafers per hour in the quick-turnaround-time (QTAT) manufacturing facility of the IBM Microelectronics Division at East Fishkill [4]. By the 1980s, IBM had installed 30 additional EL-3 variable shaped-beam systems [5] worldwide in its semiconductor fabrication lines to manage large numbers of bipolar logic chip designs through maskless writing of their interconnect personalization layers, which determined the part numbers of high-performance gate-array chips. These systems exposed up to several hundred pixels per shot. The shift from bipolar to CMOS-based chip designs at IBM in the early 1990s reduced the required part numbers by several orders of magnitude and made the use of e-beam "direct write" unnecessary and impractical. This brought to an end the first and only large-scale industrial application of e-beam lithography for wafer exposure which had exploited the maskless pattern-generation capability of probe-forming systems rather than their superior resolution.

Attempts to increase the throughput of direct-write shaped electron beams (e.g., by character and cell projection) could not keep pace with the relentless pixel growth dictated by Moore's law. Consequently, electron-beam lithography has been relegated to the limited but important role of the tool of choice for mask-making in the industry, where again its pattern-generation capability more than its superior resolution drives its use.

It has long been recognized that the revival of electron-beam lithography for high-resolution, high-throughput wafer exposure of next-generation IC chip designs would require a quantum leap in exposure parallelism. Early attempts to improve throughput with "full-chip" e-beam projection systems (e.g., [6]) failed, because the systems suffered from large off-axis aberrations of the electron optics, which severely restricted the useful field size. A combination of full-chip projection optics with sequential illumination of the mask by a scanning shaped beam, proposed by Koops in 1988 [7], provided some capability to reduce field aberrations through dynamic corrections, but it was not sufficient. Eventually the inventions of SCALPEL** [8] at Lucent Technologies and PREVAIL [9] at IBM brought EPL within range of use in IC production. Both concepts involve the projection of sections of a chip pattern, or "subfields," small compared to the size of a chip, but large compared to pattern features, on a 4× mask onto a wafer; the complete IC chip pattern is then generated through accurate stitching of the subfields.

The SCALPEL proof-of-concept system [10] was the first to implement sequential illumination of the mask in an e-beam reduction projection system by mechanical scanning of reticle and wafer at a 4:1 speed ratio underneath a stationary beam. PREVAIL carries this concept further by combining electronic beam scanning with continuous stage motions. This approach provides the significantly larger effective field size needed to achieve commercially viable throughput levels.

As a consequence of beam scanning, off-axis aberrations are generated. However, these aberrations are drastically reduced through a system of variable-axis lenses, which electronically shift the electron optical axis simultaneously with the deflected beam so that the beam effectively remains on-axis. IBM laid the foundation for this technology with the development of the variable-axis lens (VAL) [11] for the EL series of e-beam lithography systems during the 1980s. In the EL-3 e-beam lithography system, field sizes of 10 mm × 10 mm containing 10^{10} pixels were achieved [12] with the VAL technique. For

PREVAIL this still-unparalleled state-of-the-art performance had to be further improved, because larger scan ranges are required for the illumination and projection of the 4× reticle, and because the pattern subfield chosen—although small (~250 mm)—is two orders of magnitude larger than the size of a shaped beam (~2 mm).

This paper is an overview of the PREVAIL technology, with reference to numerous previous publications addressing individual aspects. First described are the novel electron-optical concepts and their feasibility demonstration, which has established an advanced state-of-the-art performance for electron-beam projection systems. Then, the implementation of the technology in a production-level alpha system, currently being developed jointly with the Nikon Corporation, is described in largely conceptual terms. The contractual agreement governing the joint effort restricts dissemination of associated technical information, necessitating the omission of details of implementation.

Column concept

Electron-optical systems can project only relatively small pattern sections (<1 mm^2) in a single exposure or "shot" [13], to be stitched together on a wafer with high accuracy. If only mechanical positioning of reticle and wafer were to be used, subfield stitching would be limited by stage acceleration and speed, and would result in prohibitively low throughput. By introducing high-speed electronic beam scanning, the PREVAIL approach alleviates the burden on the mechanical system for the benefit of dramatically increased throughput with little or no loss of optical performance; the price paid is significantly increased system complexity. **Figure 2** indicates the projected throughput potential of a PREVAIL-type system for 200-mm-diameter wafers; a complementary stencil reticle is assumed to be used at the indicated exposure conditions. In the figure, I denotes beam current, S sensitivity, and V_{ret} reticle speed. For the stages, state-of-the-art performance was assumed, representing the limiting factor only at field sizes <3 mm. The electron-beam column consists of the following building blocks:

- An electron source or gun.
- A first lens system to generate a square-shaped beam.
- A second lens system to provide illumination of the individual square subfields of the reticle with the square beam of essentially the same size.
- A means to scan the beam over multiple subfields with minimal loss of image quality and to control exposure timing.
- A third lens system to project the reticle subfields, reduced in size, onto the wafer—including means to maintain image quality and accurate stitching.

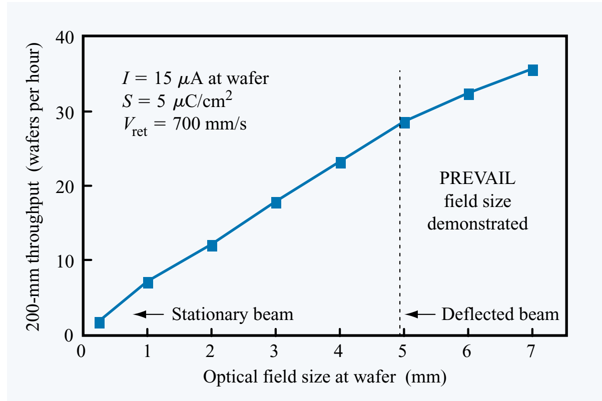

Figure 2

Projected PREVAIL-based system throughput potential for 200-mm-diameter wafers. Adapted from References [9(c)] and [17], with permission.

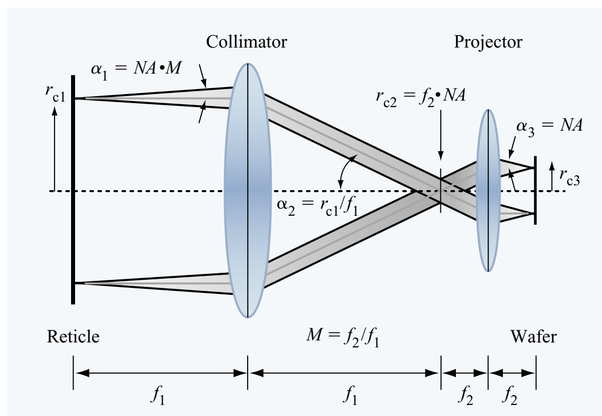

Figure 3

Telecentric antisymmetric doublet (TAD) lens system having a numerical aperture NA and a magnification M. From References [25] and [26], with permission.

The lens systems are telecentric antisymmetric doublets (TADs, **Figure 3**) known to inherently have a minimum of geometric aberrations [6]. Lenses, deflectors, and correctors all use magnetic fields to shape and position the beam, whereas the exposure is controlled with high-speed electric deflectors moving the beam on and off a beam stop with a pass-through aperture. Located between illumination and imaging section is the reticle, mounted on a precision movable stage in a chamber; the wafer is mounted on a similar stage below the imaging section. The column and stage chambers are, of course, under vacuum, requiring appropriate reticle and wafer load/unload systems to

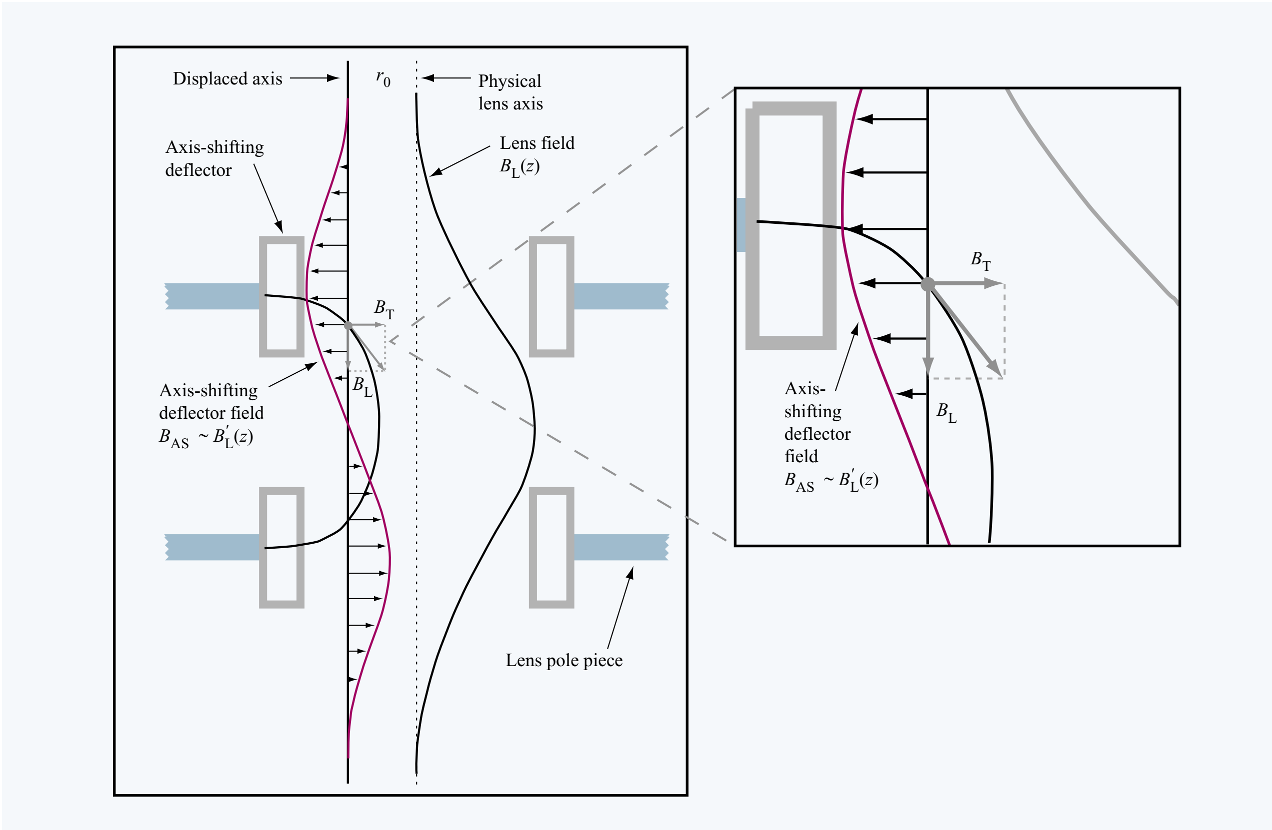

Figure 4

Variable-axis lens (VAL) principle: superposition of lens and axis-shifting deflection fields.

connect to the outside. Except for the vacuum requirements, the column and mechanical system resemble optical scanners in widespread use today. Their control systems, however, are much more extensive, and are discussed later.

Electron optics

In view of the foregoing, to achieve an acceptable throughput, the key design goals for the PREVAIL optics were a) to achieve a beam scan range as large as possible to minimize the number of stage reversals or stripes per chip; b) to maximize the size of each subfield to project as many pixels per shot as possible; and c) to maximize the beam current to keep the exposure times as low as possible for a given resist sensitivity. These goals had to be met while maintaining resolution and shape integrity (distortion) of features and subfields commensurate with the CD specifications at all positions. In addition, the large scan range requires advanced electronic control capabilities in terms of range, speed, and accuracy.

The large scan range is realized by application of the VAL principle. **Figure 4** illustrates how lateral shifting of the lens axis is accomplished through superposition of deflector fields over the lens field. A magnetic lens has a field, which is cylindrically symmetric about an axis (conventionally, the *z*-direction), at which the radial components vanish. This is also its mechanical symmetry axis, as well as that of the entire column.

To move the axis to a shifted position, where the magnetic field normally has radial components, a magnetic compensating field equal and opposite to the radial component is superimposed for cancellation, re-establishing the axial field at this position off (the mechanical lens) axis. This axis-shifting field B_{AS} is proportional to the distance of displacement r_0 and to the first derivative of the axial lens field B_L; it must satisfy the VAL condition $B_{AS}(z) = ½\, r_0\, dB_L(z)/dz$ [11]. In this case, the shifted axis is as straight as the central axis.

In PREVAIL the principle of VAL must be extended: Not one lens, but a doublet of VALs is used; hence, the axis of the object-side lens must be shifted to the position of the beam entering it, and that of the image-side lens to the point at which the beam is supposed to exit it (at a different location off the system axis, commensurate with the image reduction of the electron optics). Furthermore, additional deflectors are needed to connect these two shifted axes, or, more specifically, to deflect the electron beam to keep traveling along these axes. In order to maintain straight shifted axes, the system must be long enough to avoid overlap between the fields of the axis-connecting deflectors with the lens fields, as well as overlap of the lens fields themselves. Extensive calculations, however, have shown that disregarding these constraints and also the distinction, conceptually as well as physically, between axis-shifting and axis-connecting/beam-positioning deflectors results in greatly improved performance [14] (see below). Then the optimal beam axis is curved everywhere and within the lens field, as illustrated in **Figure 5**. The curved beam path is referred to as the curvilinear variable axis (CVA) and the corresponding lens system as a CVAL, representing a significant extension of the VAL concept.

The z-dependency in the VAL equation is now obviously more intricate: For each point along the curvilinear axis, a specific value of the axis-shifting field must be applied. In principle, separate deflection fields are needed to shift the beam in synchronism with the shifted axis, so that it remains on the chosen curvilinear axis along the column and for every deflection position throughout the effective optical field. Since axis-shifting fields are oriented in the direction of deflection, and beam-deflection fields are—as a result of the Lorentz force vector—orthogonal to this beam deflection, both fields can be generated by deflectors each having sets of orthogonal x and y coils on the same yoke.

To acquire a better understanding of the properties of the advanced optics as well as to ascertain the practicality of the CVA, a proof-of-concept (POC) system, described below, was developed [15]. The CVA was designed to follow a specific path in a meridianal plane. For the column of the alpha system, computer simulation software[1] was used to find the CVAL with optimum performance and minimum design constraints. The results predicted for the POC configuration [16] and achieved in POC [9(c), 17] were a satisfactory demonstration of the viability of the PREVAIL approach. The optimization effort for the column of the alpha system resulted in a differently curved, nonplanar, and substantially higher-performing CVAL, adequate to meet the requirements of the 100-nm circuit design node.

Optical performance characterized by the term *image quality* is defined by two factors: feature edge blur and pattern distortion. The former is the inverse of resolution, and its variation over the subfield as well as the scan field has a major impact on the critical dimension (CD) control. The latter has three components: feature shape distortion (blur), feature placement errors within the subfield (subfield distortion), and placement errors of the subfield (scan field distortion), all affecting CD control and pattern overlay.

[1]Munro's Electron Beam Software (MEBS) Ltd., London, England.

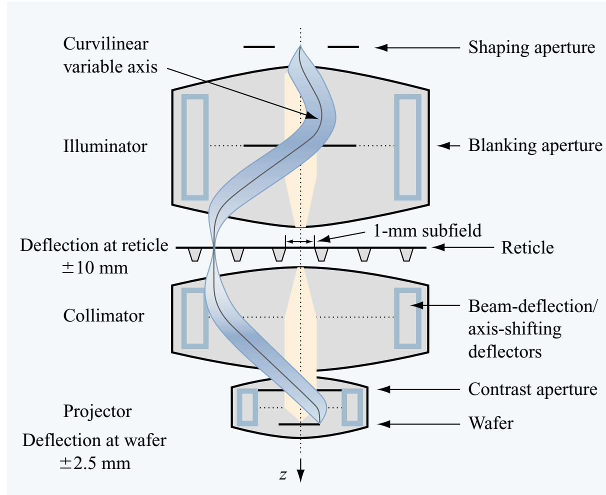

Figure 5

Curvilinear variable-axis lenses (CVALs) of PREVAIL electron optics. Adapted from References [9(c)], [14], and [17], with permission.

There are two classes of image quality detractors: optical aberrations and interactions between the beam electrons. They cause deviations of the individual electron trajectories from the ideal ones determined by the laws of Gaussian optics.

The optical aberrations are a consequence of the shape of the (in the present context, primarily magnetic) fields of the optical elements, lenses, and deflectors. These fields are in turn determined by the physical configurations and materials used for the optical elements, and therefore the aberrations are also referred to as "geometric."

The Coulomb force between beam electrons has two consequences:

1. A macroscopic effect properly referred to as the (bulk) *space-charge effect*, for which the stream of electrons is treated as a fluid under internal pressure. This effect manifests itself optically as an extended lens with associated aberrations analogous to the geometric ones. It should be recognized that the space-charge distribution depends on the beam geometry, determined not only by the (first-order or Gaussian) optics, but also by the specific pattern in the subfield projected.

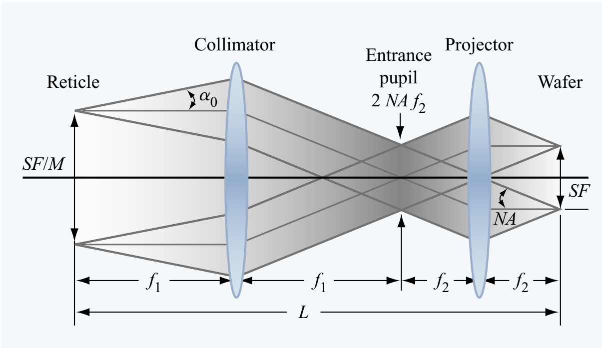

Figure 6

Coulomb interactions envelope in the lens doublet; shading illustrates interaction intensity. Image blur increases with increasing perveance and decreasing beam envelope and entrance pupil. Adapted from References [9(c)] and [17], with permission.

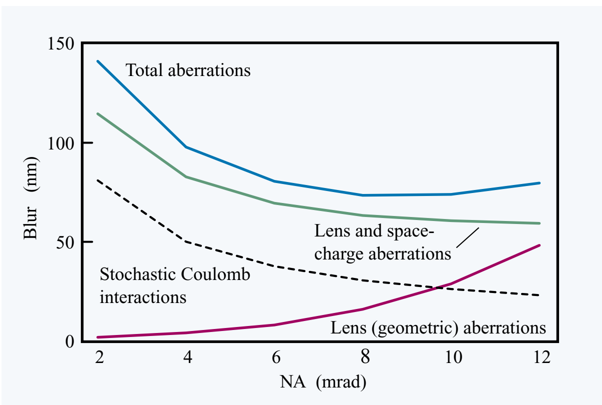

Figure 7

Calculated geometric aberrations and Coulomb interactions blur as a function of numerical aperture—at a beam current of 15 μA, voltage of 100 kV, reticle-to-wafer distance of 600 mm, and wafer subfield of 0.25 mm.

2. A microscopic effect arising from collisions between individual beam electrons, which is treated statistically and correctly referred to as the *stochastic interaction effect*.

Both effects increase with the total number of electrons or beam current, and also with the current density. Both effects are determined in part by the size of the subfield and by the time available for interaction, increasing with the system length, but inversely with the traveling speed or beam energy. The effects are depicted in **Figure 6**; the image blur increases with increasing perveance, $I/V^{3/2}$, where I is the beam current and V is the accelerating potential. In the figure, SF denotes the size of the subfield or projected image.

The requirements for the sub-100-nm nodes force the optics design to be accurate up to at least the fifth order in the (Taylor expansion of the) aberrations. The projection (relative to traditional probe-forming e-beam systems) of large objects over large distances off the central system or lens symmetry axis leads to several hundred geometric aberrations, classified as *axial*, *deflection*, and *hybrid*. The axial aberrations are determined by the design of the lenses. The deflection and hybrid aberrations are minimized, as described, by proper design of the CVAL: Lens and deflector field shapes are constructed to fulfill the condition of axiality along the entire beam path. However, even if the field shapes are perfectly matched, they do so only in a plane through the central system axis, the azimuthal orientation of which is given by the direction of the deflector field. Electrons not exactly on the shifted axis are still affected by residual radial-field components asymmetrically distributed around the axis, the distribution varying with the distance of the shifted axis from the central axis. Those electrons still experience aberrations, which fortunately can be compensated by corrector elements. Since the excitation of these correctors must be changed in synchronism with the deflection, these elements are therefore designated as *dynamic correctors*. Specifically, some of the correctors comprise additional lenses, usually referred to as *focus coils*, since they are not encased in ferromagnetic material, which would impair their dynamic response. Others are quadrupoles to compensate astigmatism, and are therefore referred to as *stigmators*.

Since in general the subfields sequentially exposed contain pattern segments of varying density and (in)homogeneity, the impact of the space-charge lens also varies from subfield to subfield, therefore requiring modified or additional dynamic corrections if the same correctors are used to compensate both types of aberrations. Geometric aberrations as well as interactions depend on a multitude of configuration and operation parameters, most of them common for both, but with different trends. Consequently, they must be chosen such that the combined effect on image quality is minimized. One key parameter is the numerical aperture (NA) of the system, i.e., the half-angle of the cone, which contains all electrons converging at the same image point on the wafer. Lens aberrations increase, but space-charge lens aberrations and interaction blur decrease with NA. This is demonstrated in **Figure 7**, where optical and space-charge lens aberrations are added linearly, but the stochastic blur is included by rms summation. These dependencies were derived from computer simulations [18]. Both components of interactions, however, increase with the beam current. Consequently, for currents in the range of 15–20 μA, required for viable throughput, the minimum image blur occurs at an NA of 8–10 mrad. These are rather large values, which, in combination with the large subfield size to be illuminated uniformly within <1%, required a new type of electron gun to be developed specifically for the PREVAIL system [19]. The product of beam (or subfield) size and NA is denoted as the *emittance*, which is ideally conserved along the entire beam path, starting at the source. Therefore, the "high-emittance gun" has an emitter or cathode of several mm diameter, quite in contrast to conventional guns typically with pointed cathodes. A key achievement demonstrated with the POC system was an illumination uniformity over the 1-mm^2 reticle subfield of ~3% at an NA of 8 mrad. In order to obtain this and better results, significant effort went into the design of the gun, in particular into the provisions for extremely uniform heating of its large disk cathode.

The requirement of a large beam current—more than an order of magnitude above typical currents of traditional e-beam lithography systems—for engineering reasons calls for best utilization of the current emitted by the large cathode. Accordingly, the concept of "critical Koehler" illumination [20] was implemented. In that type of illumination, the emitter surface is imaged into the object—in a first stage into a diaphragm with a square "shaping" aperture opening, and in a second stage into the reticle subfield at the appropriate size. Simultaneously the apparent origin of the electrons, a virtual *crossover* behind the emitter, is imaged in several steps into the *entrance pupil* of the imaging doublet, which is located at the coincidence of the lens focal points of the imaging TAD (see Figure 3). This plane is also the location of the *contrast* aperture, the purpose of which is explained in the following section.

Reticle

Because electrons cannot penetrate bulk solid material, reticles such as the chrome-on-glass masks used in optical lithography are not feasible for use as e-beam masks. Probe-forming systems of the shaped-beam type in essence have used primitive and small (<0.5-mm) stencil masks, with some of the beam electrons passing through one or a few more openings, others being absorbed in the material surrounding the openings. Extending this principle to EPL, with its much higher beam current and the reticle now containing an entire chip pattern, at least four times larger than the chip on the wafer and several cm in size, is not possible. The reticle would have to absorb 50% to almost 100% of the beam current per subfield of 50 to 100 μA, depending on the pattern density; the energy absorbed would heat up the reticle to cause uncorrectable distortion even within subfields, not to mention the effect on the entire chip.

The heating problem is circumvented if the reticle is a membrane thin enough for most of the electrons to pass through it as well as its openings. Electrons traversing the membrane are scattered into a cone with a much larger angle than that of the unscattered beam passing through its openings. An aperture, appropriately placed (see above), is used to absorb the widely scattered electrons representing the opaque parts of the pattern before they reach the wafer, thus converting scattering into intensity contrast in the resist. The SCALPEL team at Lucent Technologies first proposed and exploited the idea [8], but developed a different type of reticle with a contiguous membrane of material having a low atomic weight, covered with a patterned layer of metal having a high atomic weight, which scatters electrons into an even wider cone than the membrane material. The contrast aperture then separates *weakly* from *strongly* scattered electrons, leading to the choice of the acronym for the technique: SCALPEL, or SCattering with Angular Limitation Projection Electron Lithography. **Figure 8** shows calculated [21] and measured transparencies for SiC membranes of various thicknesses. The contrast apertures had diameter equal to that of the unscattered electron beam. To permit the use of membranes thick enough to be stable over the entire reticle, several cm in size, a high beam energy of 100 kV had to be chosen for penetration. However, stabilizing struts in the form of a grillage between individual or rows of subfields are still needed. In addition, each subfield is surrounded by a small "skirt" of contiguous membrane for several reasons, primarily to account for the fact that the illuminating beam (the shaping aperture image) is not sharply defined, but has a finite gradient at the edge of the intensity distribution, as is shown below. Accordingly, the shaped beam must be slightly larger than the patterned subfield area.

As a consequence, the separated subfields must be stitched together by the scanning beam and proper stage

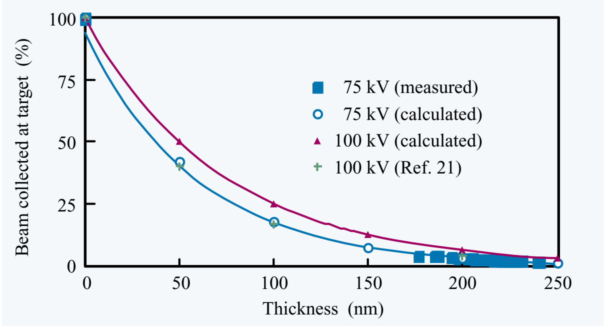

Figure 8

Transmission of a beam of electrons through SiC membranes differing in thickness.

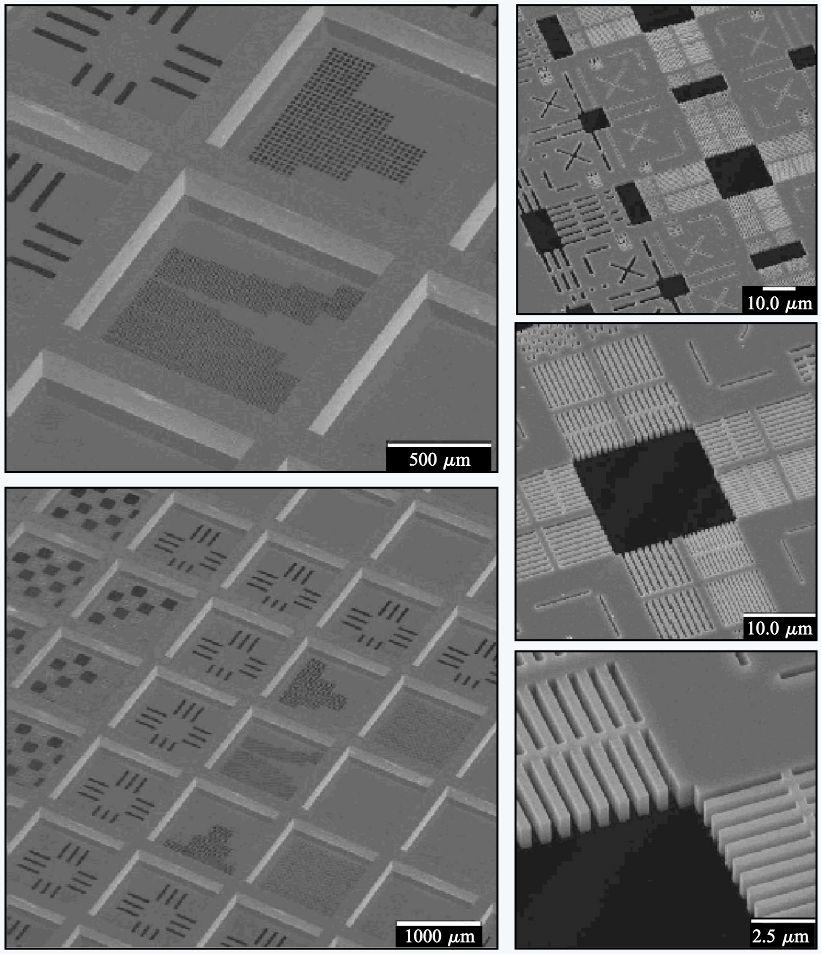

Figure 9

Micrographs of sections of a boron-doped Si test reticle for use in an EPL system. Counterclockwise starting with the lower left, the scales indicated on the micrographs are 1000, 500, 10, 10, and 2.5 μm. Adapted with permission from *J. Vac. Sci. Technol. B* **19**, No. 6 (2001, in press).

positioning. From Figure 8, it follows that the SCALPEL membrane must be thinner than ~100 nm to contain the loss of electrons at the contrast aperture, even those representing transparent pattern elements. The stencil/scatter reticle described above, developed by the PREVAIL team with support from other groups within and outside IBM, permits the use of membrane thicknesses of ≥1000 nm. **Figure 9** presents examples of such a reticle, fabricated from boron-doped Si, with various test patterns and a close-up view of a line/space pattern, demonstrating the quality achieved [22]. Both SCALPEL and PREVAIL reticles have advantages and disadvantages not further discussed here. The projection tools can easily be adapted to operate with either type.

Proof Of Concept

The Proof-Of-Concept (POC) system was fabricated to determine the viability of the PREVAIL electron optics concept. Specifically, the two key features of the system had to be practically implemented: a) Large-area-reduction projection optics with beam scanning (LARPOS) utilizing the CVAL concept; b) a gun capable of providing uniform illumination at the high emittance required. As already mentioned, the POC system implemented the predetermined planar curvilinear axis, which follows the real part r_b of the off-axis fundamental imaging ray w_b [23] of the lens doublet without deflectors (see the dotted curve in Figure 21, shown later). For safety reasons, most of the experiments were carried out

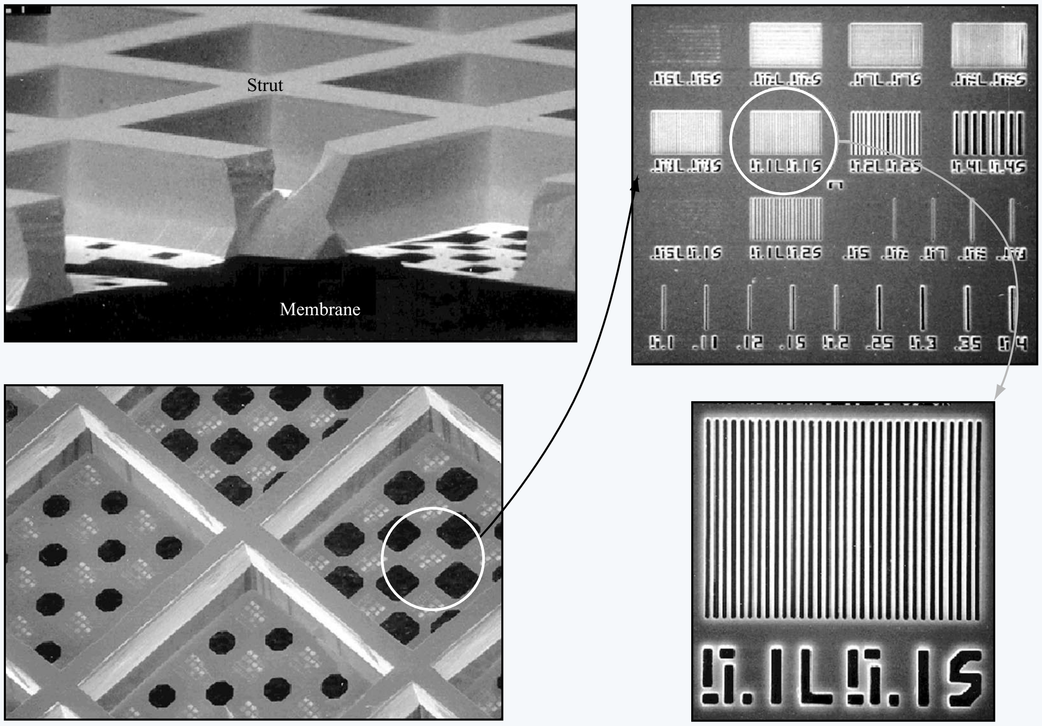

Figure 10

POC system test reticle containing patterns for resolution measurement. From Reference [9(c)], and adapted from Reference [17], with permission.

at a beam voltage of 75 kV. Reticle and wafer handling was done with simple lead-screw-driven stages with encoders equipped with load-lock chambers. Test patterns fabricated on stencil/scatter reticles with 4× features were used to assess the resolution of the POC system as a function of beam current and deflection. **Figure 10** shows a test reticle with subfields of 1 mm^2 containing isolated lines and line/space (L/S) patterns down to 50 nm in width, as well as openings of varying sizes for resolution evaluation at different beam currents.

Illumination

The subfield illumination uniformity achieved with the high-emittance gun developed for the POC system is indicated in **Figure 11**. The figure shows area and line scans obtained by scanning the unpatterned subfield image across an (8-μm) pinhole in the wafer plane with a current detector underneath.

CVAL adjustment and performance

Twenty-four magnetic deflectors, placed in close proximity throughout the illumination and imaging sections, were used to generate the smoothly varying magnetic fields required to emulate the r_b-CVA, which denotes the CVA following the r_b trajectory. As an aid to adjusting the planar curvilinear axis, a stack of slit apertures, oriented in parallel and having widths which varied according to the r_b curvature at full amplitude, was temporarily installed (**Figure 12**). The adjustment procedure using these apertures is semiautomated [15]. The beam is scanned in both lateral (x and y) axes by the deflector immediately above an individual aperture; at the same time, the beam is also offset by all of the deflectors above this aperture alternately in the positive and negative directions and the currents are adjusted, with guidance from the theory [16], until eventually the beam passes through all apertures at the same distance from their edges. **Figure 13** shows illustrative resist cross-section micrographs of 100- and 80-nm-wide lines and spaces for the undeflected and deflected beam of the POC system, at low beam current to minimize interference of Coulomb interactions with the evaluation of the optical performance. The image quality of the beam deflected 10 mm at the reticle and 2.5 mm at the wafer is nearly identical to that in the undeflected case.

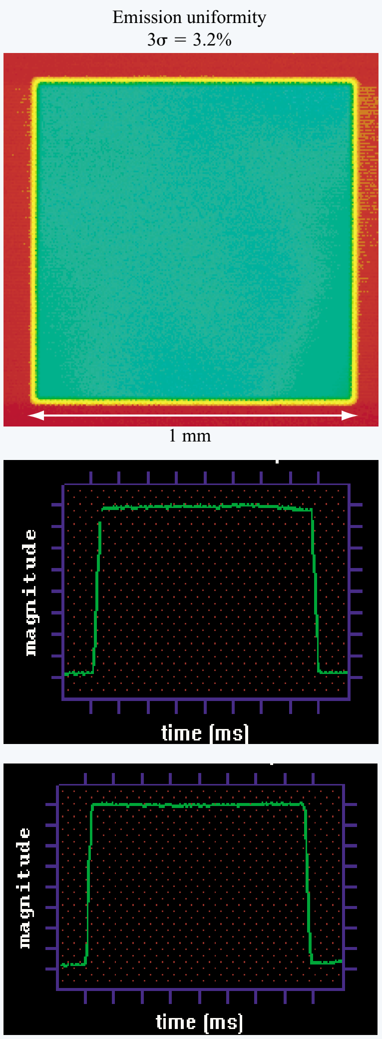

Figure 11

Reticle subfield illumination uniformity achieved with high-emittance electron gun of POC system. From Reference [17], with permission.

Subfield distortion control

Besides the capability to resolve features ≤ 100 nm across the 5-mm scanning field at the wafer, the POC system had to demonstrate equivalent control over the subfield shape in order to meet associated placement (overlay and stitching) requirements. For that purpose, the POC system contained a plurality of dynamic correction elements in its imaging section between reticle and wafer. With a pair of properly positioned magnetic double quadrupoles (for any direction in the x, y plane) known as *stigmators*, nearly independent control of feature astigmatism, resulting in feature blur, and shape astigmatism, a form of linear subfield distortion, was demonstrated.

Subfield distortion was measured using a stencil reticle with subfields containing a regular array of 9 × 9 L-shaped features. After exposure, the resulting placement of the features on wafers was measured with a NIKON 3i metrology tool. The 81 data points for each subfield were fit for translation, rigid-body rotation, and isotropic magnification (resulting from factors other than astigmatism).

The technique used to adjust the pair of stigmators to reduce the subfield distortion has been described in detail elsewhere [24(a)]. First, one of them is adjusted to compensate feature astigmatism of the undeflected beam. **Figure 14** shows the subfield distortion for the POC system, before and after adjustment of the second stigmator for a beam current, again low enough not to produce a noticeable Coulomb interaction effect. As shown on the left, the distortion of the undeflected subfield is within the precision of the metrology tool. The arrows indicate the deviations from the nominal positions. Deflecting the beam leads to substantial subfield distortion, as indicated in the center of the figure. With proper adjustment of the second stigmator, the distortion is reduced to the level shown on the right, well within the POC system specifications. The residual distortion can be attributed to deviations of the deflector coil windings from their ideal positions, which disturb the field rotational symmetry, causing so-called fourfold aberrations [23]. The design of these deflectors was the same as that used in previous shaped-beam applications. The results of the POC system experiments instigated an innovative new design implemented in the alpha tool discussed below.

Subfield magnification and rotation control

In addition to the stigmators, the set of dynamic correctors encompasses three focus coils to independently control the axial image position or *focus*, the image size or subfield *magnification*, and the image orientation or subfield *rotation*. Using an inverted-sensitivity matrix approach [24(a)], independent control of subfield magnification, rotation, and focus has also been demonstrated.

Resolution vs. beam current

Figure 15 shows [24(b)] micrographs of resolution patterns produced in 300-nm-thick KRS resist at two beam currents. A degradation of resolution with increased current is noticeable, but the 80-nm-wide and 100-nm-wide lines and spaces are still clearly resolved. The loss of resolution due to increased Coulomb interactions is consistent with modeling results, which also predict that the result shown here at 7.5 μA and 75 kV is equivalent to that obtained at 12.8 μA and 100 kV [25].

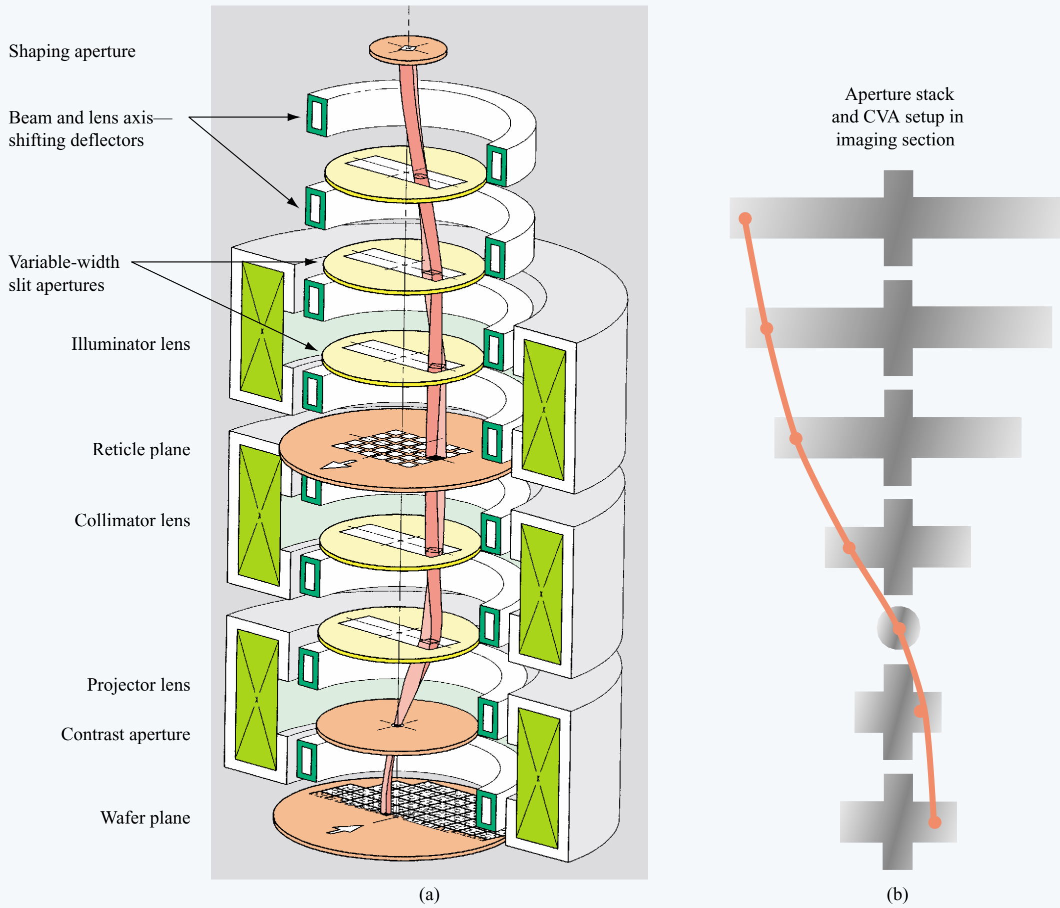

Figure 12

Configuration of CVAL adjustment aids (aperture stack) in POC system (not to scale). Part (a) adapted from Reference [9(c)], part (b) adapted from Reference [15], both with permission.

Electron-optics subsystem (EOS) of alpha system

Having accepted the results achieved with the POC system as the practical demonstration of feasibility of the PREVAIL electron-optics technology, IBM and Nikon have proceeded with the development and fabrication of a prototype PREVAIL-based system, the alpha system, for determining the applicability of the PREVAIL approach to IC production.

Figure 16 depicts the building blocks of the alpha system and their interactions. The lightly shaded units depict the EOS, discussed next. **Figure 17** is a view of the subsystem installed in the Semiconductor Research and Development Center (SRDC) of the IBM Microelectronics Division. The racks of the electronic control are seen in the foreground on the left, and the column on the test stand in the background. The unit on the right is a prototype thermal control system from Nikon to provide thermal stabilization for both column and high-power electronics.

Column optics

Advancing from the POC column to the alpha column, the electron-optical design objectives were improved imaging performance as well as a) physical compatibility with reticle and wafer stages; b) electrical compatibility with the high-bandwidth electronic control systems that are needed; c) good thermal control of all lenses and correctors; d) system simplification; and e) drastic shortening of the illumination section of the column. The length reduction was accomplished by more compact design of the optical elements, and by combining in the same section the two dynamic operations—beam scanning for illumination of reticle subfields at various positions off

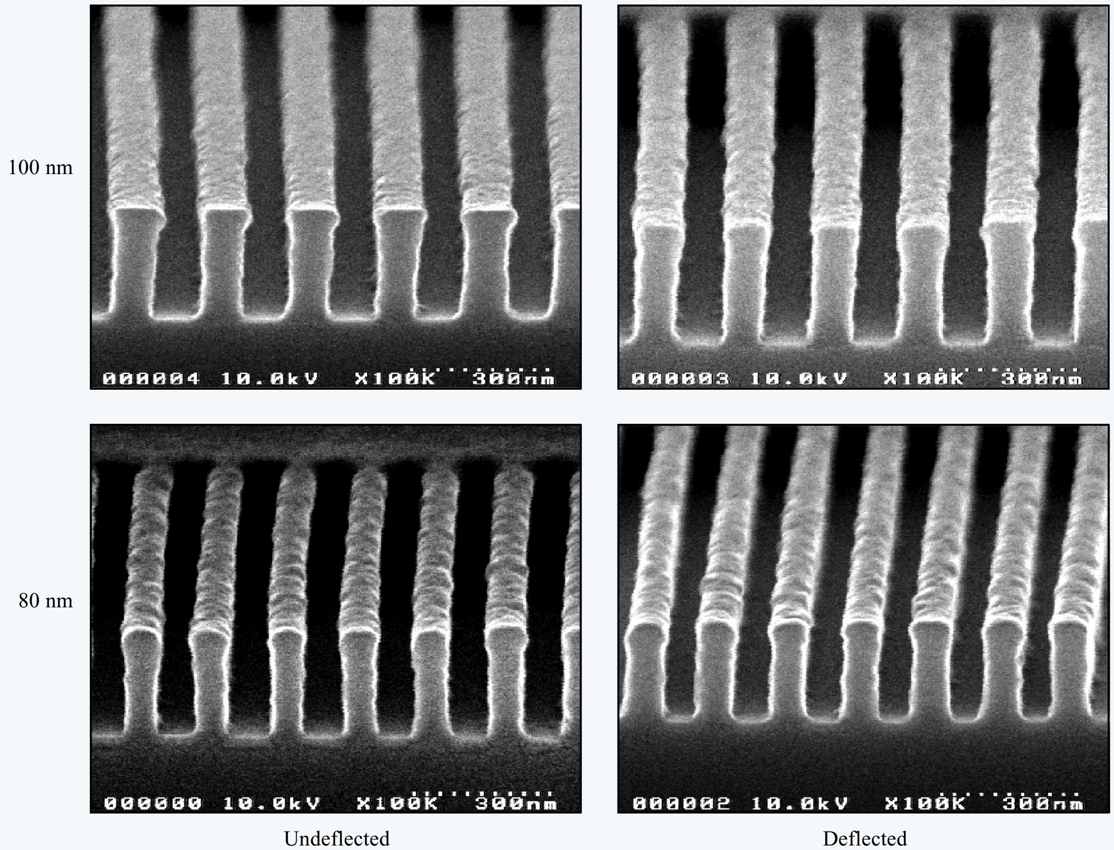

Figure 13

Patterns having lines and spaces of equal widths, exposed in POC system at 75 kV and <1 μA, undeflected and deflected (10 mm at reticle and 2.5 mm at wafer). Adapted from References [9(c)] and [17], with permission.

the central axis, and exposure control by beam blanking (executed in separate sections in the POC system). Thus, the blanking was superimposed over the magnetic scan deflection in the illuminator TAD, requiring the pivot point of the CVA to be placed at the aperture between the two doublet lenses (see also Figure 5). The photographs of **Figure 18** show the comparative appearance of the POC (a) and alpha (b) columns. Various electrical and cooling circuit connections required to execute and stabilize their operation are also shown.

Figure 19 is a schematic cross section of the alpha column. Its first-order optics are depicted by the two linked beam tracings of Koehler illumination, with the illumination rays originating from the aforementioned virtual source or crossover and the imaging rays from the emitter surface.

Figure 20 depicts the CVAL of the illuminator doublet of the alpha system, as optimized by computer simulation. Since the reticle stage moves continuously in, e.g., the *y* direction, while the beam is moving in the scanning (*xz*) plane, a *y*-deflection component must be added in the direction perpendicular to ("off") the scanning plane to follow the stage. The path represents a variant of the CVAL concept to accommodate, as mentioned, the superimposed beam blanking. The program provides the deflector currents required as input for the column setup by an operator of this nontrivial variable optic axis. Predicted blur and distortion are well within the 10-μm specifications of the skirt allowed for the illumination intensity gradient at the edge of the beam.

Figure 21 shows the optimized curvilinear variable axis of the imaging section of the alpha system together with its r_b-CVA. As the comparison demonstrates, the

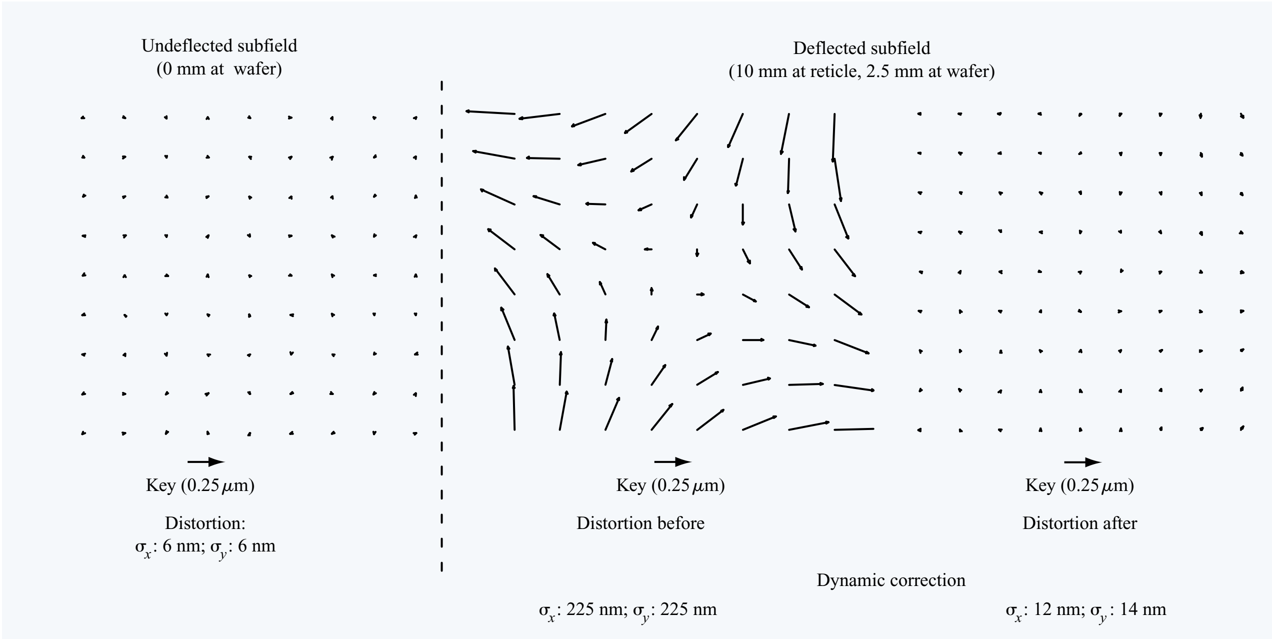

Figure 14

Subfield distortion control in POC system: Deviations from nominal placement of L-marks measured with Nikon 3i metrology tool. Left, on-axis, feature astigmatism compensated; center, off-axis, feature astigmatism compensated only; right, off-axis, feature and subfield shape astigmatism compensated. From Reference [9(c)], and adapted from Reference [17], with permission.

optimization of the actual variable trajectory has led to a shallower CVA, which also deviates from planarity, though only slightly. This trend has been shown on a generalized scale as fundamental [26].

Figure 22 shows the resulting imaging performance of the CVAL doublet, using the worst-case theoretical prediction. The total blur was derived in accordance with Figure 7.

Mechanical aspects of the column

The primary advantage of electron beams for use in lithography besides their inherent resolution capability—their controllability with static as well as dynamically varying electromagnetic fields—is also their Achilles heel and significantly complicates the mechanical design of a column: The beam must be protected from unwanted interferences of internal as well as external origin. First and foremost, an excellent vacuum is needed, requiring optimum airflow conductivity and the use of materials which do not emanate volatile components and which expose a minimum of surface area to adsorbents; i.e., they must be highly polished. The second category of interference to be avoided comes from undesired sources, such as magnetic material in locations not required for lenses and deflectors; bulk conductive material in the vicinity of changing electromagnetic fields leading to eddy currents, which in turn cause dynamic field distortions; nonconductive material leading to repulsive charge accumulation; and external static magnetic fields and electromagnetic radiation which can introduce positional noise in the beam. A third category includes mechanical and thermal interferences, such as self-generated and external vibrations, which must be minimized through the use of rigid components and passive or active dynamic compensation; and heat generated by the gun and the beam at aperture stops and by power consumption of the coils generating the magnetic fields. Both types of interference cause distortion of components and changes in properties such as magnetic permeability. Good thermal stability requires the use of materials having low expansion coefficients, low heat dissipation by radiation, bulk conductivity, and forced and unforced gas and liquid convection effects. Finally, for most optics components, a high degree of machining and assembly accuracy and precision is essential, in particular rotational symmetry and axial alignment. Also, serviceability is important, primarily with respect to components exposed to the beam and containing the vacuum.

Column test stand

The mechanical subsystem (MS) of the alpha tool has been under development by Nikon. However, to facilitate testing of the EOS prior to integration with the MS, a test

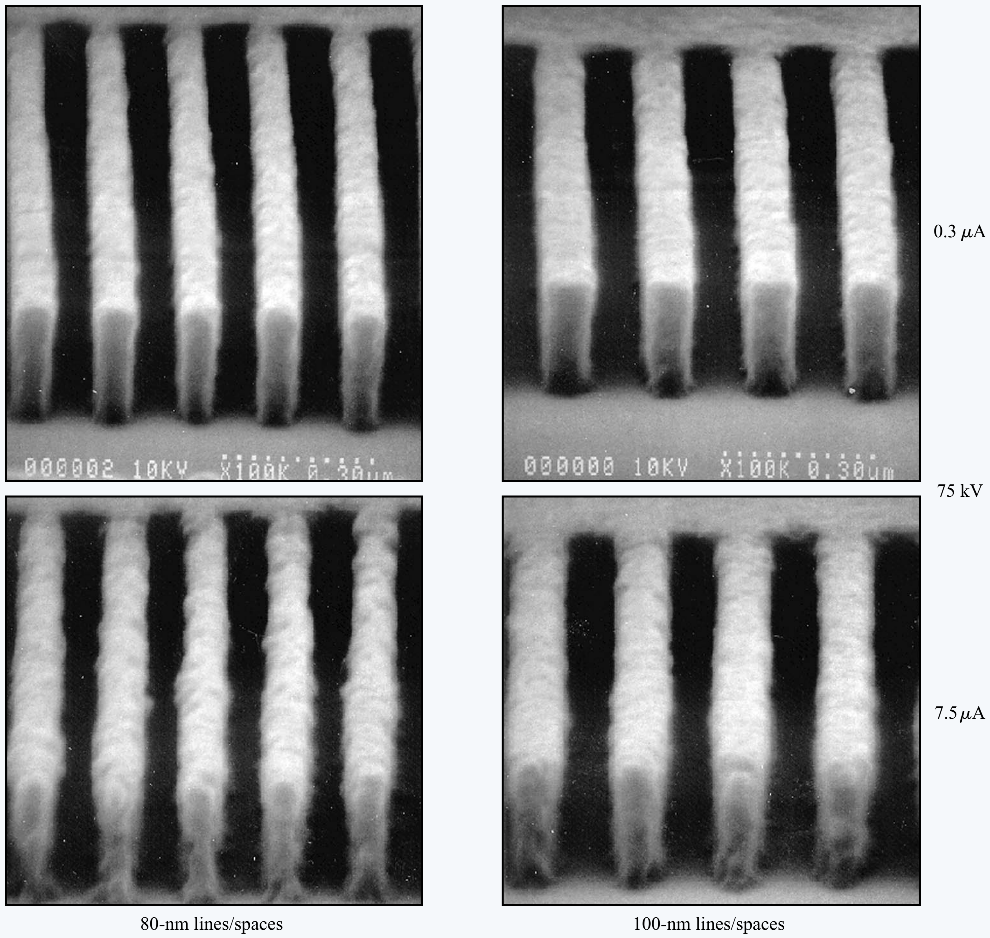

Figure 15

Micrographs of POC system resolution patterns produced in 300-nm-thick KRS resist.

stand was designed and built to provide a full-function, high-vacuum, vibration-isolated test environment at the SRDC. It consists of a rigid, air-cushioned mounting structure for the column and identical load-locked reticle and wafer-stage chamber assemblies, which have separate vacuum systems to enable the exchange of reticles and wafers for test exposures without affecting the column vacuum. Peripheral features include a capacitance wafer height sensing system used for automatic focus adjustment, a scintillator/photomultiplier tube detector used to observe transmission images, and various stage-mounted targets used for beam setup and calibration. **Figure 23** shows the test stand at a factory of the Nikon Corporation in Japan.

The stages are driven with dc servo motors mounted to the outside of each chamber. Encoders attached to the motor shafts enable the stages to function at a maximum resolution of 1 μm. Ferrofluidic feedthroughs are used to transmit the rotary motion of the motor into the vacuum chamber. Two linear-motion feedthroughs are also mounted on each stage chamber to permit external alignment of the reticle and wafer stages housed within the chambers.

The stage assemblies are of a stacked *x–y* design with recirculating ball linear bearing guides for each axis, driven by leadscrews; *x*-axis travel range is 600 mm, *y*-axis 127 mm. Flexible ribbon cables transmit electrical signals within the stage assembly. Attached to each *x–y* stage is a cantilevered paddle to position the reticle/wafer carriers. The portion of the paddle which moves within the magnetic lens field of the column is fabricated from ceramic to avoid disturbance of the beam by the magnetic

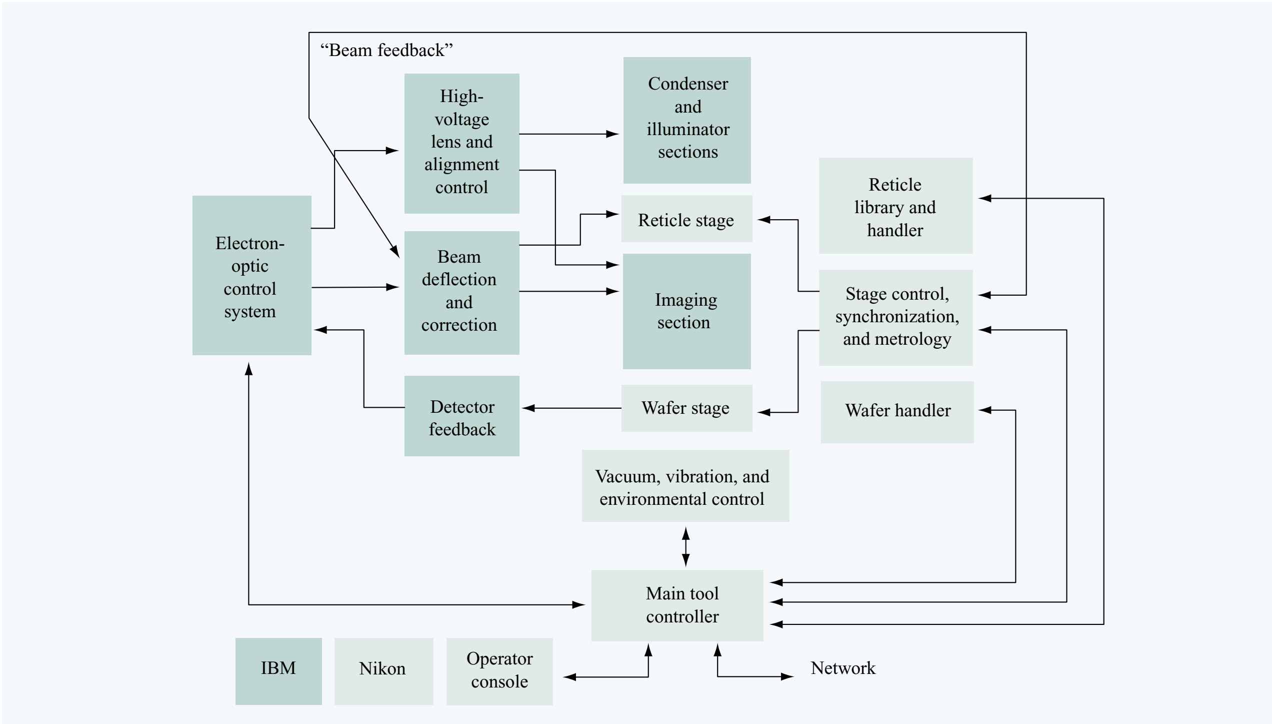

Figure 16

PREVAIL alpha system block diagram. The light and dark portions pertain to aspects being addressed in IBM and Nikon, respectively. Adapted from Reference [18], with permission.

fields of eddy currents. The reticle and wafer carriers are positioned on the paddle via a three-groove kinematic coupling containing ceramic balls. All of the hardware used on the carriers and ceramic portions of the stage paddle is nonmagnetic and fabricated from 6AL-4V titanium or beryllium copper. Vacuum is provided by four identical, independent 700-l/s turbomolecular-drag pumps, backed up by dry rough pumps to provide oil-free evacuation. The controls are interlocked for safety with the high-voltage electronics, stage position sensors, and vacuum isolation valves. Dry nitrogen is used to purge the stage chambers after venting to minimize the amount of atmospheric moisture which would otherwise enter the system during carrier exchanges.

The vibration isolation for the test stand plus supported column, weighing a total of almost two tons, is provided by four passive air mounts to dampen facility vibrations. Each turbo pump is individually isolated to minimize induced vibrations.

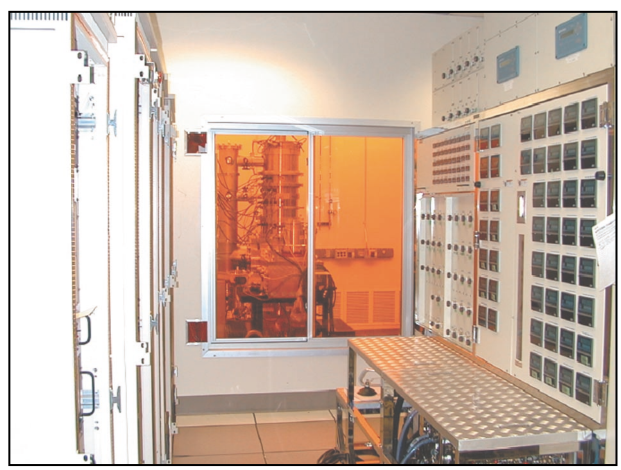

Figure 17

EOS of alpha system; column in background mounted on test stand.

Writing strategy

Figure 24 describes the motions of beam and stages during exposure of each chip on the wafer. Each chip is exposed by stitching together 0.25-mm × 0.25-mm subfields. These subfields are stepped by the CVAL magnetic deflection into scan fields that are 20 subfields long and cover an area of 5 mm × 0.25 mm. The fields are stacked into stripes formed by the mechanically moving reticle and

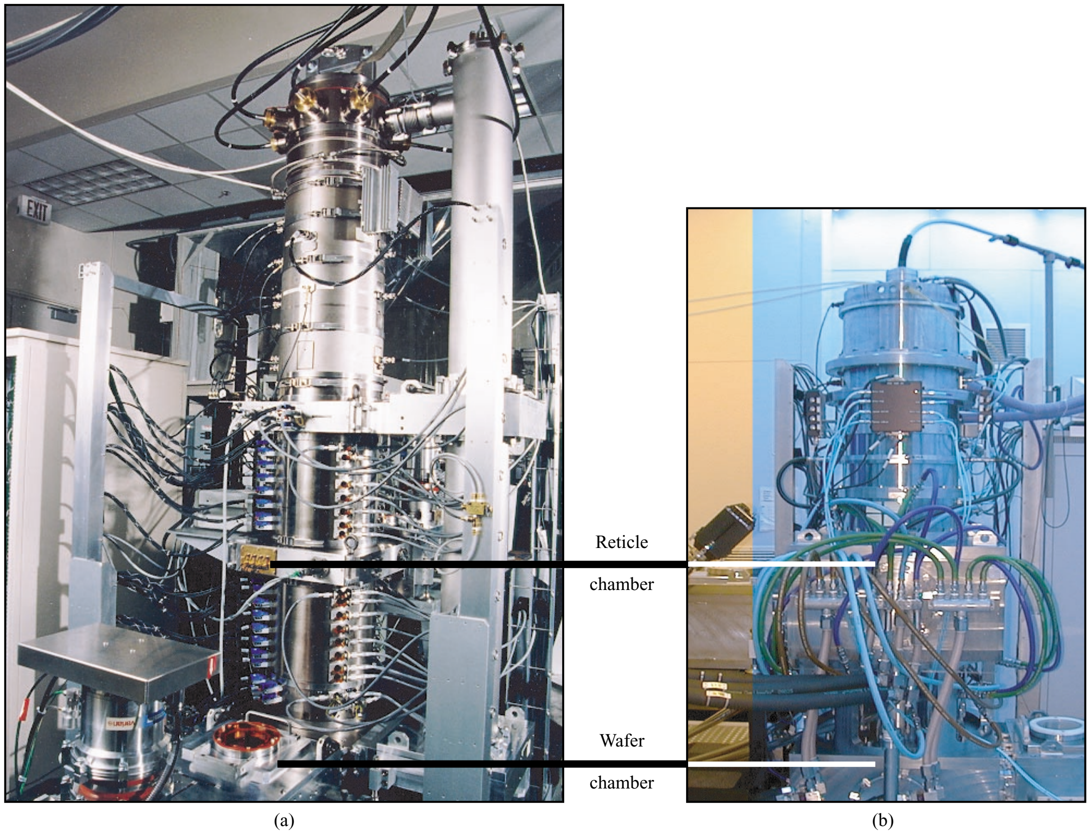

Figure 18

Comparison of columns of POC (a) and alpha (b) systems. Part (a) adapted from References [9(c)] and [17], with permission.

wafer stages. Multiple 5-mm-wide stripes are written to assemble each chip. As can be seen in the figure, the subfields are written sequentially in a "serpentine" fashion from left to right, while the reticle and wafer are moved under the beam in the orthogonal direction.

The alpha tool system uses a stepping technique as opposed to a continuous scan of the field to move rapidly from one subfield to the next and maintain position over the subfield to be exposed. Since the reticle and wafer stages move continuously under the beam, the deflection system must track this motion during exposure to keep the beam stationary over the subfield at both reticle and wafer. This results in a "staircase" deflection pattern.

Stepping rather than continuously moving the beam from subfield to subfield has many advantages. It allows precise image quality adjustment for the different deflection subfields, of which there are a relatively small number (typically 40; 20 scanned from left to right and 20 from right to left). The adjustment parameters, collected in a "deflection list," include the basic calibration of deflection position and the dynamic corrections of subfield shape distortion and feature blur caused by geometric aberrations [27]. The repetitive sequence of subfield exposures permits the arrangement of data structures that define the characteristics of all of the subfields on the wafer subfield units, or "events." In addition to the deflection list, the tool then is run with "event lists," allowing for individual adjustments to each subfield to correct for distortions other than those caused by the column optics. The latter can arise from Coulomb interaction effects due to varying pattern density, errors in the reticle, and distortions of previous layers on the wafer. Once a reticle has been fabricated, it can be measured for accuracy on a metrology tool. Thus, an "error" file is created for use with the reticle that describes its deviations from nominal, such as subfield placement errors and magnification and rotation errors. The data then is used as input to the data-preparation system. The software

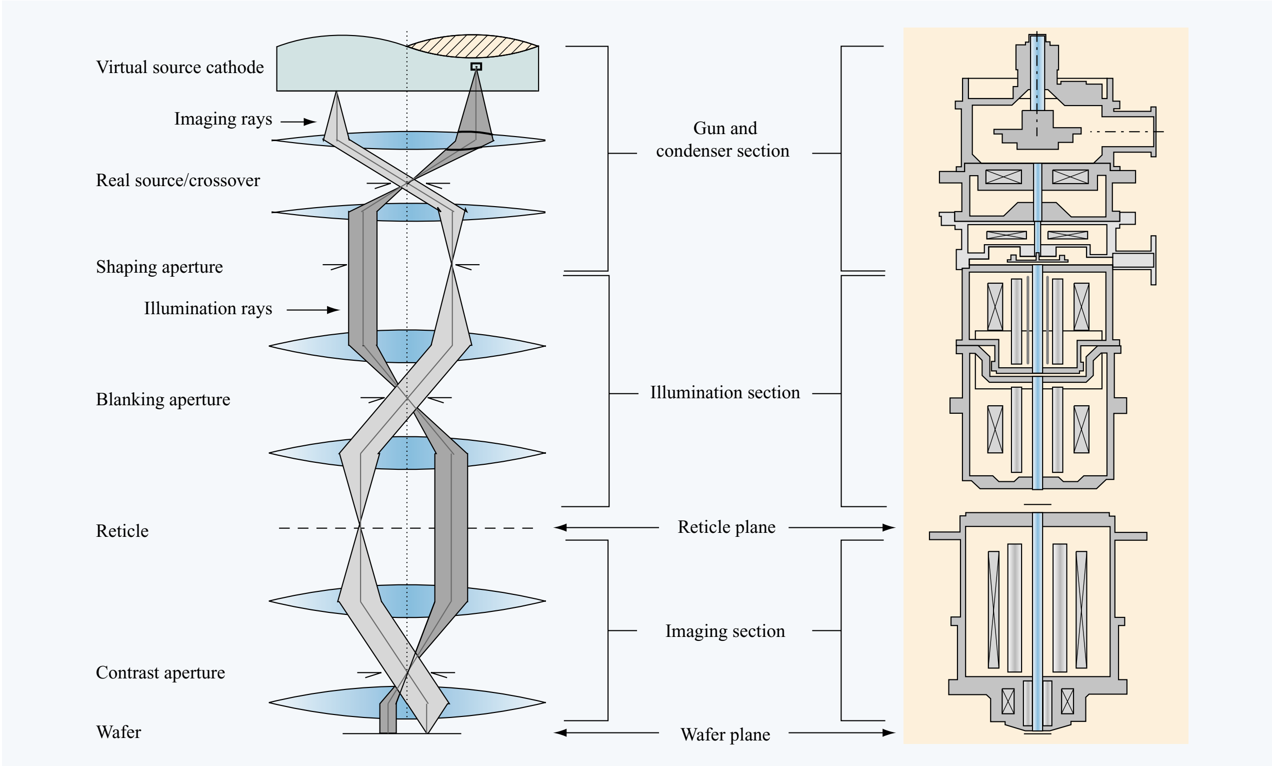

Figure 19

Schematic cross section of alpha system column and its first-order optics. Adapted with permission from Reference [18] and from *J. Vac. Sci. Technol. B* **19**, No. 6 (2001, in press).

combines the reticle design data and error file with the chip placement information and any measured wafer error data to incorporate it into an event list. Thus, the tool can effectively "improve" on the reticle as well as on preceding lithography tool performance. This is particularly advantageous for "mix-and-match" lithography.

Electronics aspects

The control of an electron beam requires analog (voltage or current) signals. Although PREVAIL is not a pattern generator in the traditional sense, where the circuit pattern resides in the memory of a computer and not in a mask, operation of the analog electronics nevertheless requires digital signal processors and microprocessors and associated software, including automatically invoked as well as user-initiated routines. To avoid or suppress noise interference, PREVAIL electronics have been designed following the standard practice of (electrically) separating the analog circuitry from the digital front end by the use of commercially available fiber-optical signal transmission technology.

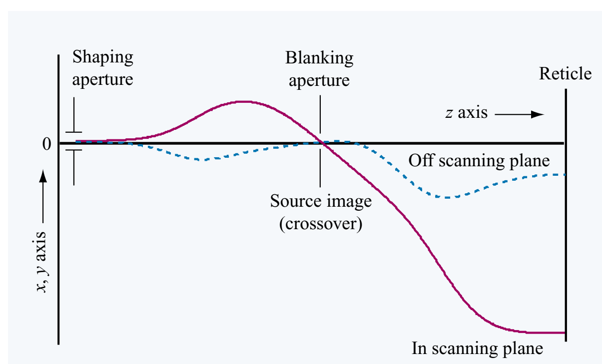

Figure 20

CVAL of illuminator section of alpha system.

Analog electronics

The analog electronics required present special challenges. The stability, speed, and accuracy requirements push the state of the art in many areas.

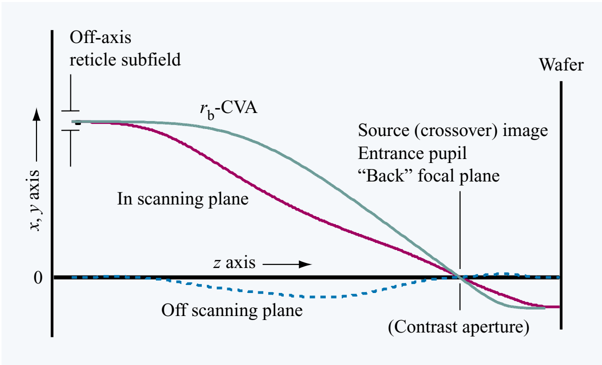

Figure 21

CVAL of imaging section of alpha system.

The high-voltage electron gun power supply provides a 100-kV potential with a load of several milliamperes. The voltage must be stable to better than 10 ppm over expected load, input line voltage, and temperature ranges. This is needed because at the maximum deflection of the beam of 2.5 mm at the wafer, a change in the voltage of that magnitude would shift the beam by 12.5 nm in the worst case, which is unacceptable. Specifications that are somewhat less stringent but still very tight apply to the filament and bombardment voltage supplies, which must regulate the electron gun emission current to better than 0.5%. A current and therefore dose fluctuation of that magnitude could cause significant CD variation in the resist.

Precision dc current source amplifiers have been designed to control the electromagnetic lenses within the column. Again, stringent stability specifications apply, and to meet them the critical circuit elements must be very accurately temperature-controlled. In addition, the use of very low-noise amplifiers and design techniques is essential.

Static beam alignment in the column with respect to lenses and apertures is controlled by x–y pairs of magnetic deflectors or *alignment coils* through precision coil drivers. The position of the electron beam with respect to apertures as well as the actual beam current is automatically maintained by "servos" [28], which periodically check the beam current impinging on the apertures and update the coil currents and gun emission parameters to compensate for drifts due, for example, to source aging, temperature-induced mechanical changes, or charge accumulation on surfaces due to electrically insulating contamination. This well-established technique significantly reduces the need to periodically dismantle and clean the column.

Precision high-speed, high-current amplifiers have been designed to drive the magnetic deflector coils in the column generating the CVAs. The challenge here is that these drivers, besides being very stable and accurate, must switch currents in an inductive load at high speed in order to meet the tool throughput requirements. This means that very careful attention must be taken to balance noise, power, and bandwidth. As for the lens supplies, tight temperature control is required for the drivers to prevent gain drifts. This reduces the need for frequent calibration checks, which would adversely affect throughput. All drivers receive a common deflection input signal generated by very high-precision digital-to-analog converters (DACs) in the beam positioning and timing (BPAT) unit, while their individual outputs are adjusted as required for the CVA.

In addition to the precision deflection signal from the DACs, information from the reticle and wafer stage laser metrology systems on instantaneous velocity, acceleration, and actual vs. nominal position is received on a periodic basis by the "beam feedback" system. The data is used to create a beam deflection correction signal that is added to the main deflection signal to accurately track the continuously moving stages with minimal time delay. At the stage speeds required for the tool to achieve acceptable throughput, nanosecond delays would translate almost directly into nanometer beam position errors. Thus, the accuracy requirements of the mechanical stages are reduced, an important advantage, as the feedback acts as a high-speed "fine stage" adjustment.

The dynamic correction elements in the column (focus coils and magnetic multipoles) are driven with precision current drivers, which receive digital data from the BPAT for every subfield in the deflection pattern in the time during which the beam advances from one subfield to the next.

Beam blanking control is provided by the BPAT via high-bandwidth voltage amplifiers and the blanking deflector. The amplifiers have the capability to automatically "rotate" the beam position around the blanking aperture surface to more evenly distribute the heat load, thus minimizing the thermally induced mechanical distortions of the aperture.

Low-noise signal amplifiers are used to measure the beam current absorbed by the various apertures and Faraday cups to facilitate alignment; they are also used to measure the portion of the beam current backscattered from targets with suitably structured topology to facilitate deflection and image correction calibration as well as position registration, e.g., relative to alignment marks on the wafer. Calibration and registration scans are performed by a dedicated deflector which functions at a higher speed than the main field deflectors. For measurements of high resolution at low beam currents or illumination uniformity, transmission detectors are used that contain scintillators to convert the electron beam into light detected by a photomultiplier tube (PMT), thus

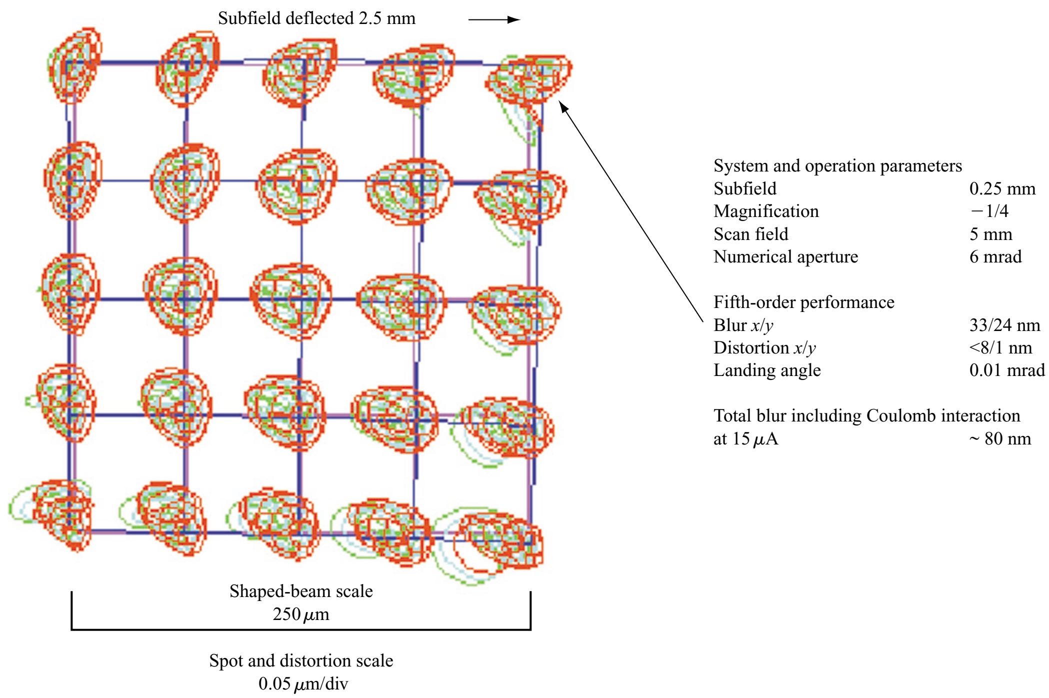

Figure 22

Performance of imaging section of alpha system, showing performance in terms of aberration figures and distortion at maximum deflection.

providing a high signal-to-noise ratio. Signals from these amplifiers and detectors are digitized with analog-to-digital converters (ADCs) to provide data through the digital feedback unit to the software for diagnostics and calibrations. Also, many of the analog drivers contain circuits to allow remote monitoring of many of their critical voltages and currents to aid in diagnostics and monitoring of the tool operation.

Digital electronics

Besides its main task of providing static and dynamic control inputs for the analog electronics through the aforementioned BPAT, the digital electronics performs several additional tasks: digitizing and processing of signals received from current detectors during calibration and real-time (alignment) registration operations, (mathematically) processing and analyzing of this data, and providing communication between the user and the system as well as between the units themselves. The former task is executed in the digital feedback unit, the latter in unit processors under the control of the electron optics system processor (EOSP).

The entire digital control in the EOS and its target interfaces is implemented in field-programmable gate arrays (FPGAs), allowing for a greatly reduced part number count and high flexibility in design changes.

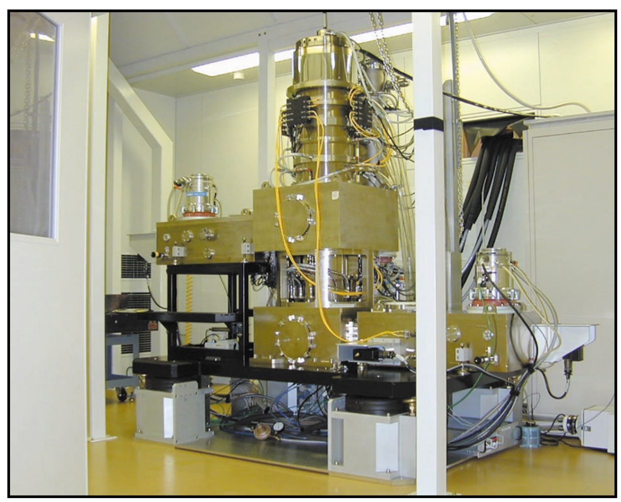

Figure 23

Test stand with alpha column, as installed at a Japanese factory of alliance partner Nikon.

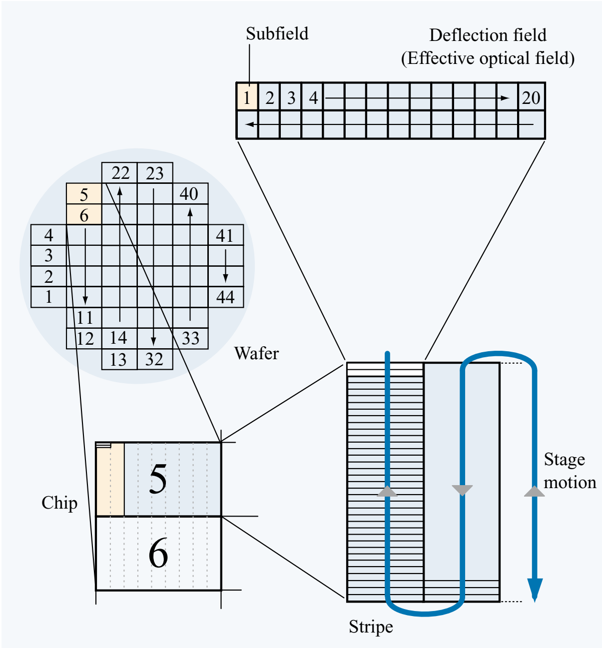

Figure 24

Wafer-writing scheme in alpha system, illustrating beam and stage motions and subfield stitching.

Using data defined by deflection and event lists, as described, the BPAT is responsible for providing the beam blanking, beam positions, and beam corrections for the electron beam. The BPAT is also responsible for system synchronization and timing with nanosecond accuracy, based on a master clock, between it and other critical units, such as the stage control unit. To ensure the required accuracy, design considerations such as ECL logic, controlled PC lengths, cable lengths, and resistances were observed. For each subfield the BPAT also processes *real-time* correction data from height and yaw measurements provided by the stage control unit during the time the beam dwells on a subfield. The number and period of these measurements are dependent on the subfield dwell time and the maximum time the stage can maintain its required accuracy. Focus, magnification, and rotation-correction values are calculated on the basis of the measurement values provided and predetermined correction coefficients in the deflection list.

Utilizing synchronization signals from the BPAT and a special deflection pattern, the digital feedback unit controls the high-speed scans for calibration and registration. Feedback data from the scan is provided through the ADCs from the beam-detection amplifiers as a result of a BPAT request and is stored by the digital feedback unit as "raw" or averaged for further analysis.

Control software

The EOS contains software for control, setup, and operation. The software is divided into two packages: real-time application control and the graphical user operator interface (GUI). Each of these packages runs on an individual processor, which permits the choice of different operating systems to optimize each task. The application control is based on the UNIX** OS, the GUI on Windows NT**. The subsystems communicate via a shared memory space using interrupt-synchronized "primitive" commands. The communication architecture has been designed to be independent of the operating system.

Upon power-up, the hardware requires configuration of the FPGAs and communication interfaces, and initialization, i.e., resetting the starting values in the logic driving. There are functions that allow sweeping of any of the beam deflectors with synchronized data collected from a selected source. Other functions allow monitoring of selected hardware test points throughout the EO subsystem. Special software facilitates the CVAL adjustments. Event list data is processed in real time, as is necessary for wafer writing. Analysis software is provided to examine beam feedback data collected during execution of the event list.

Multiple screens are provided to allow the user to individually set up all static and dynamic driver currents of lenses, alignments, and CVAL deflectors. Display screens allow the data collected during deflector scans to be shown as a line or color SEM-type image. With this feature, the effects of adjustments can be observed in real time. A key feature called "recipe processing," a text-based, interpreted file, provides the user with the ability to execute a series of high-level commands in sequence, to in effect "program" a series of specific column operations. Also, controls and displays have been provided to select, display, and monitor system test points.

Concluding remarks

The Electron Beam Technology Group at the IBM Semiconductor Research and Development Center in Hopewell Junction, New York, has been exploring the use of the PREVAIL approach for next-generation electron-beam lithography for almost a decade—the second half of which has been in alliance with the leading optical stepper manufacturer, the Nikon Corporation of Tokyo, Japan. The approach chosen was to first develop and construct a laboratory-scale system containing high-resolution large-area-reduction projection optics with beam-scanning capability and a high-emittance electron source. Upon successful completion of this first phase, a second phase was undertaken, jointly with Nikon, to develop and construct a PREVAIL-based alpha system, to be used to obtain production-level information for advancing toward a manufacturing system. Current plans call for a third phase involving the development of a "beta" system, adequate for consecutive nodes below 100 nm.

Acknowledgments

Members of the Nikon Corporation, Japan, and Nikon Research Corporation of America (NRCA), California, made significant contributions to the PREVAIL project. The authors would like to thank the management teams of Nikon, Japan, and NRCA, under the leadership of T. Yamaguchi and G. Varnell, for their advice and project support, and T. Okino, S. Kojima, S. Suzuki, K. Nakano, K. Hada, M. Sogard, and D. Stumbo for their theoretical contributions. Furthermore, and in particular, Nikon deserves a great deal of credit for providing the PREVAIL team with the extremely complex Column Thermal Control System (CTCS), without which the EOS of the alpha system could not have been operated.

The authors would also like to acknowledge the contributions made by W. Moreau and colleagues in the IBM Semiconductor Research and Development Center in Hopewell Junction, New York, for developing and providing advanced resist material, and J. Greschner and his team for manufacturing test reticles. Also, much appreciation is owed to members of the Mask Center of Competence at the IBM facility in Burlington, Vermont, who generated the test patterns on reticle blanks.

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