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ELECTRON BEAM DEFLECTION WITHOUT OFF-AXIS ABERRATIONS

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Abstract

A novel focusing/deflection system for high accuracy, high throughput E-beam lithography, denoted as Variable Axis Immersion Lens (VAIL), has been successfully demonstrated. The main attributes of this system include: 1)Perpendicular landing at all points of a deflection field > (10 x 10 mm), 2)Elimination of transverse chromatic aberration, 3)High resolution (< 0.2μm edge slope) over the entire deflection field, 4)Elimination of eddy current effects in the target area, and 5)Total magnetic shielding of the target from external fields.

Key Words: Variable axis lens, Immersion lens, Transverse chromatic aberration, Telecentric lens, Parallel deflection, Predeflection, Eddy currents, Normal landing, Ferrite shielding, Dynamic focus

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Introduction

The Variable Axis Lens (VAL) was demonstrated [7,8] to have very desirable properties for sub-micron large field electron lithography systems. By electronically shifting the electron optical axis in synchronism with the deflected beam the resolution remains essentially constant over a 10 x 10mm^2 field since all deflection aberrations are eliminated. Practical implementation of the system for production machines, however, was hampered by eddy current generation in the target area by the dynamic field of the correction yoke, stray field effects from the X-Y table and general complexity and instability of required driving electronics. All these problems have been alleviated in the Variable Axis Immersion Lens (VAIL) configuration. This has been accomplished by replacing the lower pole piece of the projection lens with a solid ferrite disc. This configuration creates an asymmetrical lens with zero bore in the lower pole piece, with the target plane located slightly above the pole piece. This eliminates the need for the lower field correction yoke and two dynamic focus coils, hence there are no dynamic fields in the target area. In addition, the solid pole piece acts as a shield for any extraneous fields which might otherwise affect beam stability.

Description

The variable axis concept was first discussed by Ohiwa et al.[2] It was denoted as MOL (Moving Objective Lens) but was not reduced to practice due to unsatisfactory field matching[1] and prohibitive design constraints.[3] The VAL theory of operation and experimental results have been published by Pfeiffer et al.[7,8] It consists of a telecentric lens, double deflection yokes and a projection lens capable of moving its axis in synchronism with the deflected beam. See Fig. 1. The variable axis capability is established by the superposition of field correcting yokes (see Fig. 2) and the lens field, providing the condition:

$$B_x(Z)_{yoke} = 1/2 \frac{dB_{lens}(Z)}{dZ} X_o \qquad (1)$$

where X_o is the axis displacement and is directly proportional to the deflection yoke current. The double pre-deflection yokes are precisely balanced in sensitivity so as to provide a deflection which is always parallel to the geometrical axis of the beam. Since both yokes are outside the magnetic fields of adjacent lenses, they no longer have to be air core. This allows for yoke designs with improved sensitivity and speed. As was shown in Ref. 7, the field correcting yoke over-compensates the radial field component of the lens field resulting in the field configuration shown in Fig. 3. This condition is corrected by introducing dynamic focus coils which provide a field to counter this effect, such that:

$$B_{dyn}(Z) = -1/4 \, B_L''(X) \, X_o^2 \qquad (2)$$

In the VAL configuration two field correction yokes and four dynamic focus coils symmetrically positioned in the upper and lower pole pieces are required to obtain the aforementioned conditions. As can be seen from Fig. 1 the close proximity of the lower correction yoke and dynamic focus coils to the target impose difficult design and material restriction on the sample holder and X-Y table since any bulk conductive material will generate detrimental eddy currents and stray fields from any magnetic material will likewise adversely affect the beam.

The VAIL configuration eliminates the dynamic and stray field target problems and in addition simplifies mechanical alignment and driving electronics requirements. The concept can be easily deduced from Fig. 4. If the excitation of the VAL lens is increased until the focal plane coincides with the geometrical center of the lens, then theoretically a slab of infinitely high permeability material can be inserted in the center of the lens and the magnetic field configuration will remain unchanged. By introducing a zero bore lower pole piece and "immersing" the target inside the lens we have accomplished the following:

1. Eliminated one field correction yoke.
2. Eliminated two dynamic focus coils.
3. Eliminated dynamic fields from the target area.
4. Shielded the target from stray fields.

The implementation of such a lens requires that a means be provided for introducing and removing samples from the target area. The practical design, as shown in Fig. 5, provides a gap above the lower solid pole piece sufficiently far removed so that its fringing fields have no effect in the target area. We have found that for our lens geometries a 2.5 cm gap presents no adverse effects on the beam over a 10 x 10mm^2 field. The fact that there is no dynamic field influence on the target can be seen from Hall probe measurements (Fig. 6) of the dynamic correction yoke field which has essentially zero field strength in the 2.5 cm gap where the target and its holder are located. The same figure also illustrates field matching between the correction yoke and the transverse field of the lens. The extent to which the condition of Eq. (1) is satisfied can be seen in the same figure. The small difference between the yoke field and the transverse field of the lens is symmetrically distributed in both directions so that the integral over the difference is vanishingly small.

Figure 7 illustrates the entire VAIL configuration. It consists of two lenses which image the object plane into the target plane acting as a telecentric system. The upper lens is of the conventional type with finite bore pole pieces, while the lower, projection lens, has a zero bore lower pole piece and utilized as an immersion lens. Deflection is achieved by means of two composite predeflection yokes which shift the beam parallel to itself.
The variable axis projection lens contains only one field correction yoke and two dynamic correction coils. The predeflection and excitation of the field correction yoke takes place in synchronism so that the predeflected beam always enters the variable axis projection lens on its electron optically displaced axis. The focused spot is located a short distance above the lower pole piece, and the beam landing is always perpendicular to target plane.

Telecentricity of the beam entering the projection lens is required to assure that the object point will not move when electrons undergo energy changes, and provide complete elimination of transverse chromatic aberration.

A dynamic stigmator coil assembly, located in the collimating lens, permits the correction for axial astigmatism. It consists of two quadrupoles rotated by 45° to each other in the same plane.

Experimental Results

In order to demonstrate that VAIL eliminates transverse chromatic aberration, the following experiment was performed. The beam was first aligned on the geometrical axis of the lens and observed to have no positional shift due to changes in lens excitation or accelerating potential. The double predeflection yokes were then excited to deflect the beam to a corner of a 10 x 10mm^2 field (i.e., 7.07mm displacement). Here the beam profiles, in both X and Y were observed by the well known method of traversing wires in both directions, collecting the transmitted signal and looking at its derivative.[5,6] The accelerating potential was first changed by 100 volts and then 200 volts, each time the beam profile was stored and finally a composite picture photographed, see Fig. 8. Although the beam defocussing effect is very evident (as expected) the position of the beam did not change, proving the elimination of transverse chromatic aberration.

Since the VAL virtually eliminates the transverse chromatic aberration (which was the dominant aberration) and coma, the system parameters, particularly the beam semi-angel α, can now be chosen such that the spherical aberration ($\sim \alpha^3$), the axial chromatic aberration ($\sim \alpha$), and the interaction blur (α^{-1}),

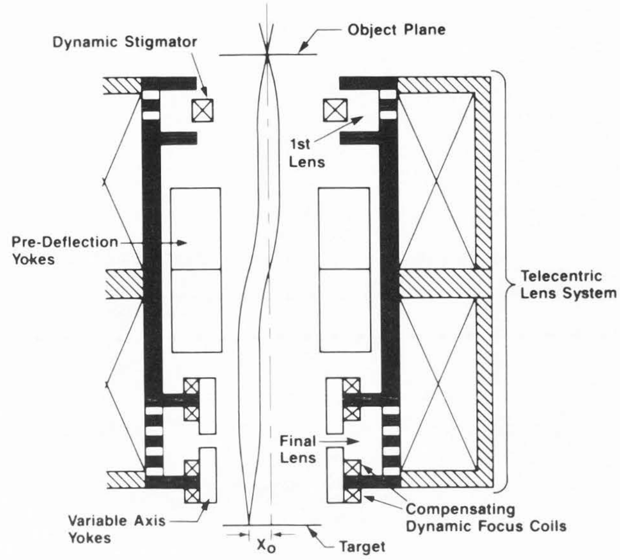

Fig. 1 Variable Axis Lens (VAL) diagram.

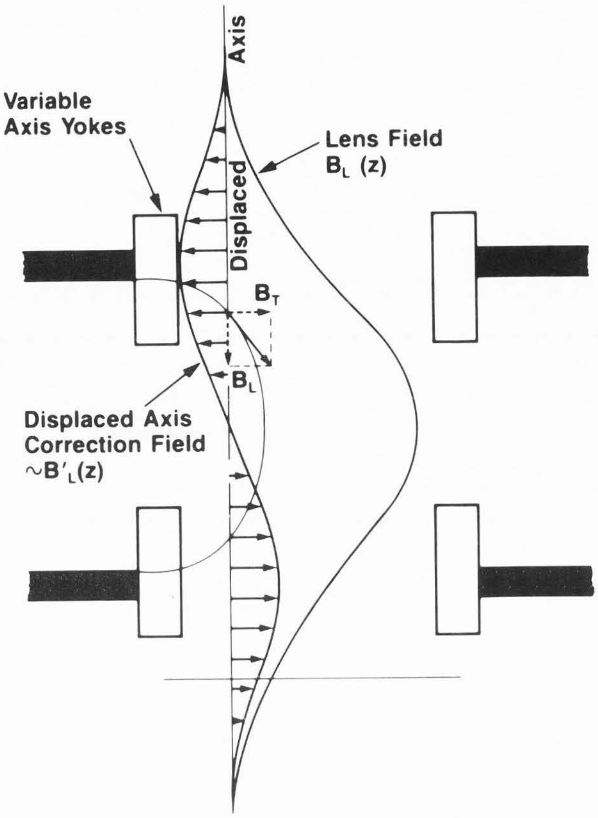

Fig. 2 Variable axis field correction concept.

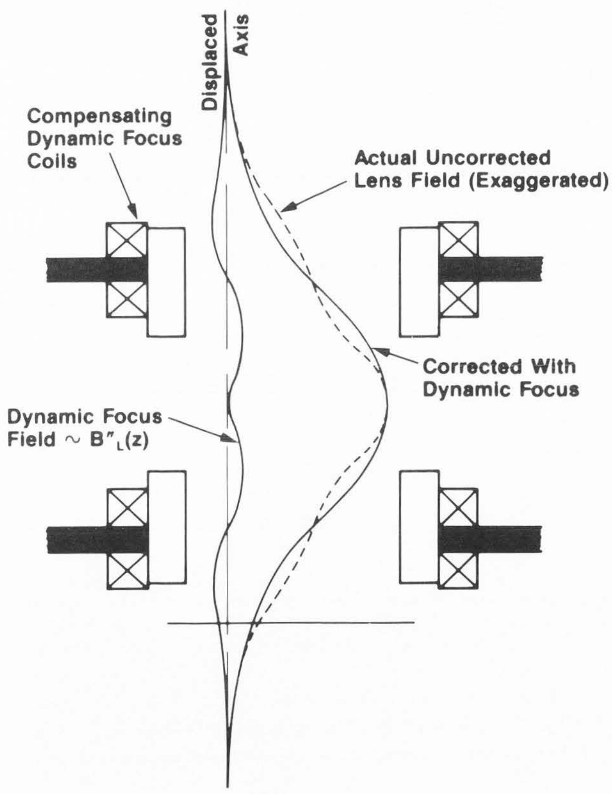

Fig. 3 Variable axis dynamic focus correction concept.

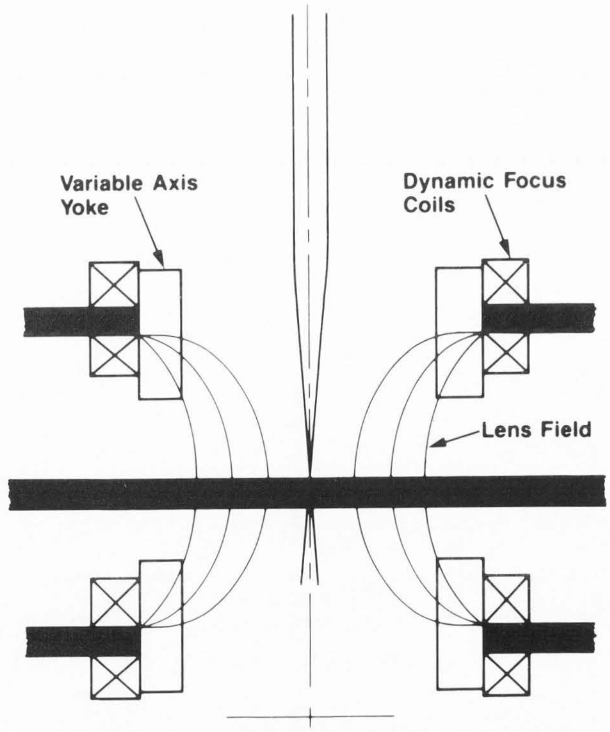

Fig. 4 Immersion lens concept.

are balanced and their geometrical sum is minimized. Experimental results in Fig. 9 indicate that the optimal α for our VAL geometry occurs at 7.2 mrad. It is also evident that the edge slope deteriorates with increased current density, as evidenced by the two sets of data, one for 50 amps/cm^2 and the other for 14 amps/cm^2. It can also be noted that the edge slope for the lower current density reaches a minimum at smaller α. Since the filament temperature is kept constant, the improvement in resolution for smaller beam current due to chromatic aberration is less significant than that due to electron interaction, hence the optimum has shifted to 6.5 mrad. For a more detailed explanation of this effect see Ref. 4.

Figure 10 illustrates edge slope of $<0.2\mu m$ with current density of 14 amps/cm^2. Similar photographs were taken at nine points of a 10 x 10mm^2 deflection field (see Fig. 11). From the composite photograph of all nine locations it can be seen that the edge slope remains essentially constant over the 10 x 10mm^2 field. Dynamic focus and stigmatism are of course compensated at each location. All are directly proportional to the square of the distance from the geometrical axis.

Summary

When looking at requirements placed on E-beam lithography systems for the future, submicron resolution over $\geq$ 10 x 10mm^2 fields, greater field stitching accuracy (vertical beam landing) and improved overlay capability (elimination of deflection aberrations) are commonly heard as key words. The variable axis lens in theory provides these necessary improvements and the VAIL construction allows for its practical implementation.

Elimination of transverse chromatic aberration has always been of prime concern in the development of IBM's high throughput E-beam lithography tools. A summary of these improvements, evidenced by manufacturing systems EL1 and EL3, are shown in Fig. 12. The EL1 system with a single yoke provided 0.5 µm resolution over 5 x 5mm^2 field. The EL3 with double deflection yokes extended the field coverage to 10 x 10mm^2 with the same 0.5 µm resolution. VAIL technology maintains 0.2 µm resolution over 10 x 10mm^2 field and allows for further expansion of the field size.

Acknowledgements

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References

(1) Ohiwa H. (1978) "Design of electron-beam scanning systems using the moving objective lens", J. Vac. Sci. Technol. 15, 849-852.

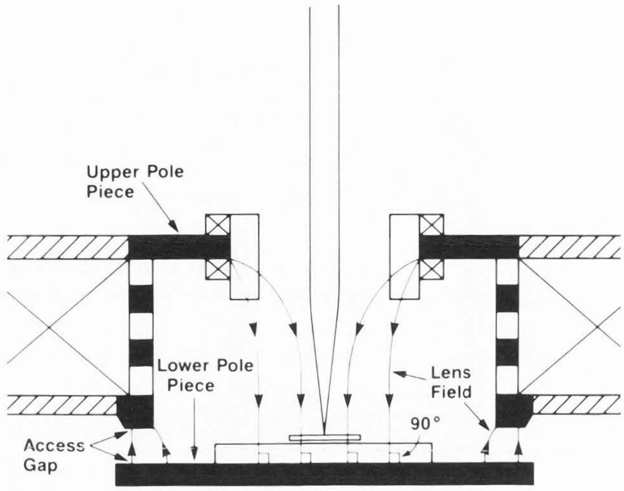

Fig. 5 Immersion lens practical design.

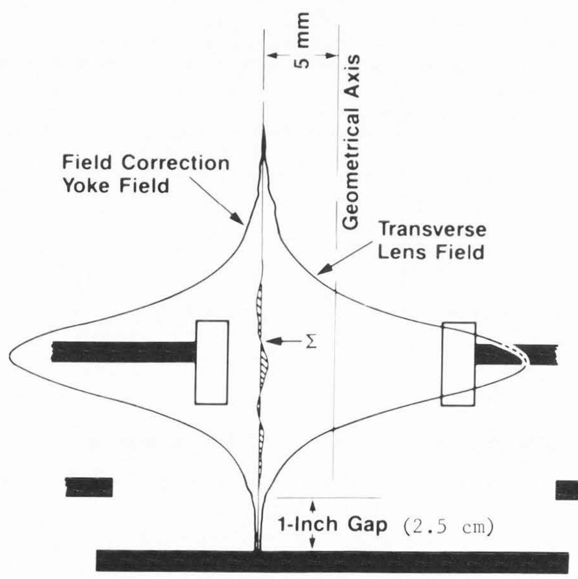

Fig. 6 Variable Axis Immersion Lens (VAIL) compensating field Hall probe measurements.

(2) Ohiwa H, Goto E, Ono A. (1971) "Elimination of third-order aberrations in electron-beam scanning systems", Electron. Commun. Japan Sect. Vol. 54-B, No. 12, 1971, 44-51.

(3) Pearce-Percy HT, Spicer DF. (1980) "Integration of trajectory equations for deflection and focusing systems avoiding paraxial type approximations", Microcircuit Engineering, edited by Ahmed, H., and Nixon, W. C., Cambridge University, London, p. 535-545.

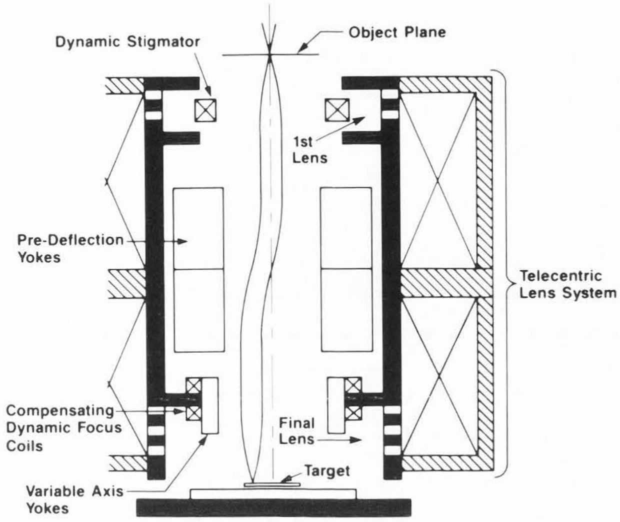

Fig. 7 Variable Axis Immersion Lens (VAIL) diagram.

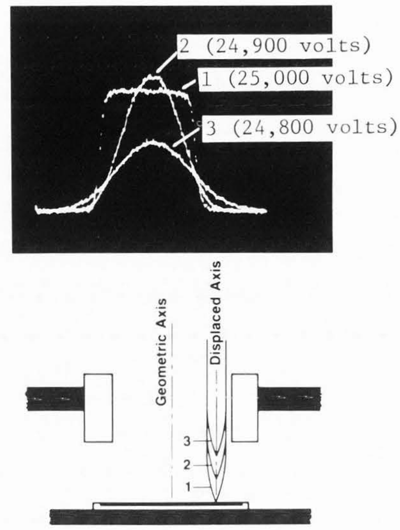

Fig. 8 Elimination of transverse chromatic aberration.

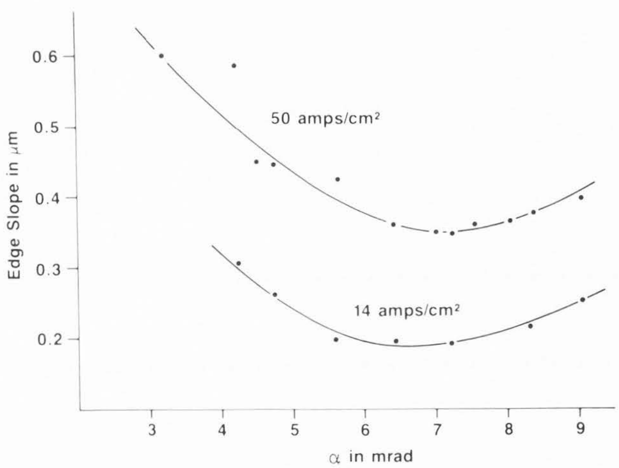

Fig. 9 Optimization of alpha.

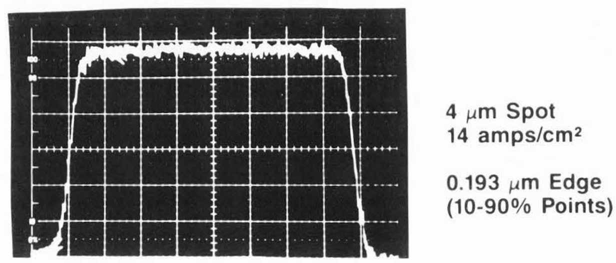

Fig. 10 Edge slope measurement.

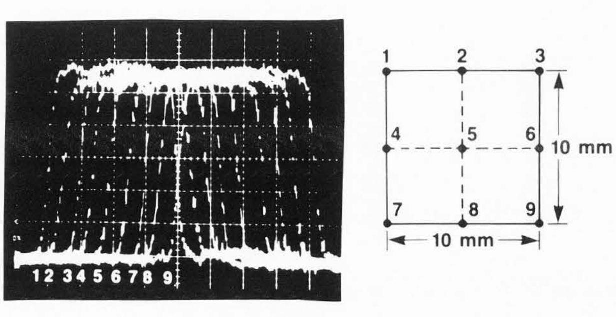

Fig. 11 Resolution over 10 x $10mm^2$ field.

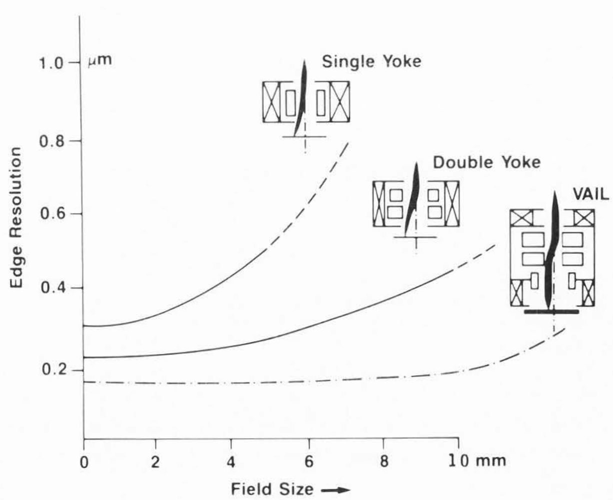

Fig. 12 Comparison of the edge resolution over the deflection field for three projection/deflection system concepts.

(4) Pfeiffer HC. (1972) "Basic limitations of probe forming systems due to electron-electron interaction", Scanning Electron Microsc. 1972:113-117.

(5) Pfeiffer HC. (1975) "New imaging and deflection concept for probeforming microfabrication systems", J. Vac. Sci. Technol. 12 (6), 1170-1173.

(6) Pfeiffer HC. (1979) "Recent advances in electron-beam lithography for the high-volume production of VLSI devices", IEEE Trans. Electr. Dev. ED-26 (4), 663-674.

(7) Pfeiffer HC, Langner GO. (1981) "Advanced deflection concept for large area, high resolution e-beam lithography", J. Vac. Sci. Technol. 19 (4), 1058-1063.

(8) Pfeiffer HC, Langner GO, Sturans MA. (1981) "Variable axis lens for electron beams", Appl. Phys. Lett. 39 (9), 775-776.