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High Performance Reduction Lenses for Microelectronic Circuit Fabrication*

Abstract: Data are presented for three families of objective lenses useful in making high resolution plates and improving the process of photoresist exposure. These lenses have 7 to 10 elements each, spherical surfaces only, and were designed with the aid of computers. Many of the lenses have been fabricated and these have confirmed the soundness of the design methods, assessment criteria, and manufacturing techniques.

Introduction

With the advent of electronic circuit fabrication using photochemical methods, the need for high quality lenses has increased considerably. The requirements on optical techniques for microcircuitry manufacturing give a new dimension to lens design and lens manufacturing technology. The need for highest quality optics for microscopes and telescopes has been well recognized in the past. In the electronics industry, however, the same image quality must now be obtainable over an extended area and not just on, or in the immediate proximity of, the optical axis of the instrument. A new class of lenses has had to be designed with diffraction-limited performance over fields from 3 to 100 mm in diameter.

This paper presents data for a large family of lenses useful in most methods of photoreduction. Lenses suitable for exposure of high resolution silver emulsions and of photoresists are described, with particular attention given to lenses for projection printing. All the lenses described here have spherical surfaces only† and have been designed with the aid of IBM 7074 and 360/67 computers using automatic design and diffraction frequency response programs.[1] To obtain the theoretically predicted performance, extremely tight tolerances are kept in their manufacture.[2]

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† If aspheric surfaces of the proper type were to be employed and placed in the correct location, still larger field diameters would be achievable.

Design requirements

Since any particular microcircuit layout will consist of lines of various widths, the contrast ratio (modulation) at all desired frequencies of the lens used to produce it must be optimized. Such lenses are extremely well corrected at one reduction and have uniform resolution across the desired field.[3] The off-axis resolution in all meridians must be the same as the axial resolution and the use of such words as "average" off-axis resolution has no place in specifying lens quality. A lens having astigmatism or coma will yield a poor or unusable image near the edge of the field, thus lowering the percentage of available field area within which usuable circuit layouts can be printed. The elimination of field curvature is just as important since it improves the possible focal range. The modulation for any linewidth given below is constant across the entire stated field diameter and is calculated for the same focal setting with astigmatism and all orders of coma reduced well below the Rayleigh tolerance, even if all aberrations are combined.

The types of reduction lenses fall into three fairly distinct groups which overlap only slightly: those having extremely high resolution over a relatively small field, those having moderately high resolution over an optimally large field, and an intermediate group. For example, it may be desirable to produce circuit layouts having micrometer or submicrometer linewidths in a field of linear dimension less than 5 mm, 1 to 1.5 μm linewidths over a 3 to 10 mm field, and 1.5 to 5 μm or greater linewidths over a 10 to 110 mm or larger field. Various designs

Table 1 Specifications for some existing lens designs.

	Lens	Reduction factor	Image field diameter (mm)	Calculated linewidth at 50% contrast (μm)	Mean wavelength (Å)	Maximum distortion (%)
1	31 mm NA 0.35	30	3.0	1.2	5461	−0.4
2	31 mm NA 0.35	30	3.0	0.9	4047	−0.5
3*	44 mm NA 0.32	20	4.3	1.2	5461	−0.5
4	45 mm NA 0.32	20	4.3	1.0	4047	−0.4
5*	25 mm f/1.6	20	5.4	1.4	5461	+0.004
6	35 mm f/1.6	20	5.4	1.0	4047	−0.004
7*	25 mm f/2.6	20 10	7.0	2.1 2.2	5461	−0.004
8	27 mm f/2	20	7.0	1.4	4047	−0.007
9	27 mm f/2	10	7.2	1.3	4047	−0.004
10	35 mm f/1.8	20	7.2	1.4	4047	+0.003
11	55 mm f/2	10	14.0	2.5	5461	+0.006
12*	112 mm f/3	20 15	32.0	2.5 2.6	5461	−0.007 −0.04
13*	112 mm f/3	10	32.0	2.2	4047	−0.006
14	184 mm f/3	5	50.0	2.5	4047	+0.003
15	254 mm f/3	5	63.5	2.5	4047	−0.003
16	385 mm f/4	10	110.0	3.7	5461	−0.002

* These lenses have been constructed and their specifications validated in practice.

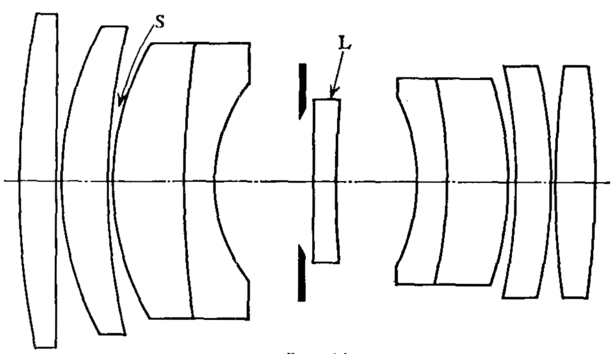
meeting these needs are described below; some of these have already been fabricated and tested. Others are presented to exemplify the state of the art.

Reduction lens data

Table 1 contains data for some of the reduction lenses designed for a variety of field sizes, reductions, and spectral regions. The pertinent lens specifications have been gleaned from a larger body of data and are presented in an orderly form for ready reference. Asterisks denote lenses that have been fabricated and have confirmed in practice all design criteria. The linewidths stated for each lens are constant across the field, the values having been calculated for monochromatic light. All lenses, however, have been corrected for both axial and lateral chromatic aberrations and may be used over an extended bandwidth centered on the mean wavelength.

Lens 14, shown in Fig. 1, covers the largest field with fine linewidths and is representative of the other lenses with regard to the state of optical correction. The lens is a modified Gauss lens of high index glass. Modulation transfer function curves calculated according to diffraction theory at one focal setting are shown in Fig. 2. The similarity of all curves in all orientations (tangential, sagittal, and 45° azimuths) across the field is readily apparent. The state of tangential correction ensures well-resolved lines in the orientation perpendicular to any wafer radius, the sagittal correction ensures the same for radial lines, and the 45° azimuthal correction ensures the quality of lines bisecting the tangential and sagittal directions. This uniform correction yields in turn uniform linewidths, a greatly desired feature in the microelectronic industry. The phase angles shown in Fig. 3 are very small at all frequencies, effecting steep edge gradients on

Figure 1 Structure and characteristics of Lens 14; this lens is typical of the class discussed in this paper.



Lens 14

Object-image distance	1255 mm
Working reduction	5.0×
Mask diameter	250.0 mm
Image field diameter	50.0 mm
Mean wavelength	4047 Å
Maximum distortion	0.003%
Line width @ 50% contrast	2.5 μm

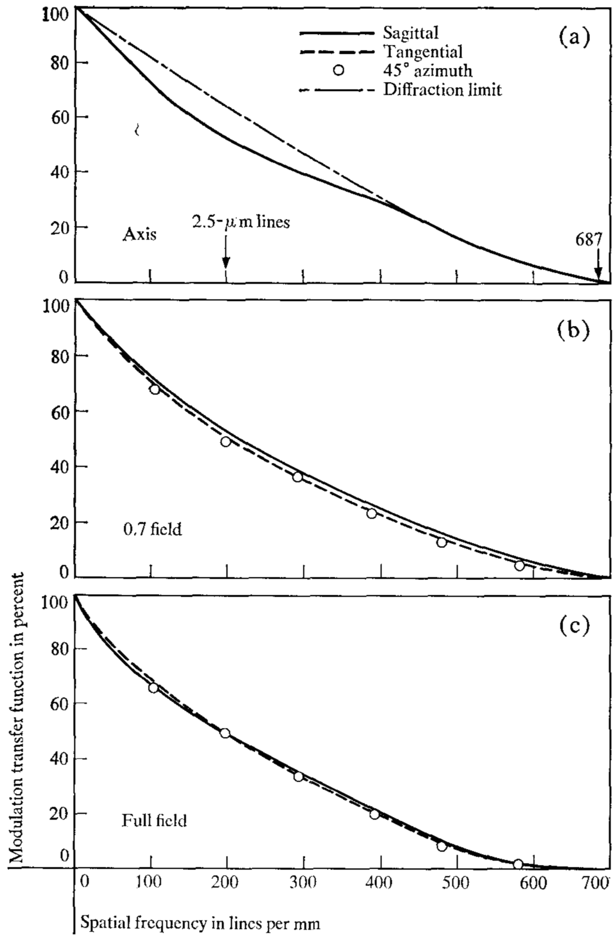


Figure 2 Modulation transfer functions for Lens 14 for (a) the optical axis, (b) 0.7 field, and (c) full field. The numerical aperture (NA) is 0.139, the shift from the paraxial focus ($\delta l'$) is 0.064 mm, and the wavelength is 4047Å.

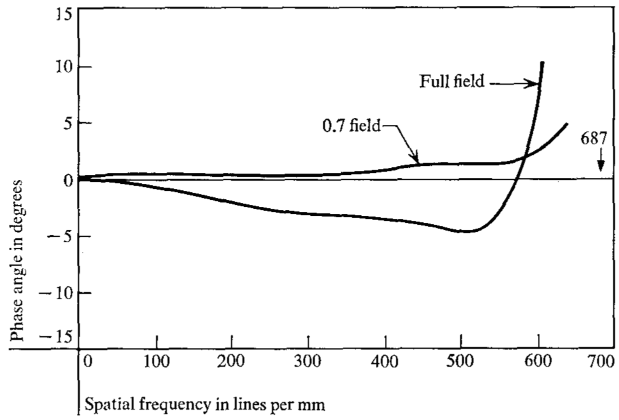


Figure 3 Phase angle vs. spatial frequency for Lens 14.

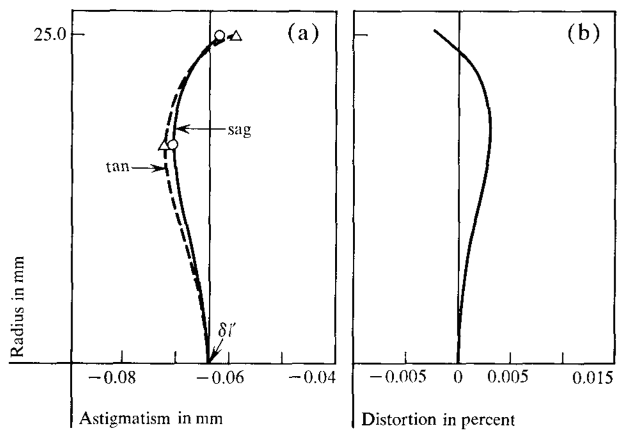


Figure 4 (a) Astigmatism and (b) distortion vs. radial distance from the optical axis for Lens 14.

different linewidths. For a 3-μm linewidth, the phase angle of the third harmonic is 7°, resulting in a phase shift of only 7/360 of the period of the third harmonic with respect to the fundamental frequency. For coarser linewidths the phase shift is even less, thus yielding sharp line edges in the tangential orientation and permitting square corners for larger geometries.

The residual astigmatism measured in the radial direction is shown in Fig. 4a. It is less than 3 μm, the maximum zonal field curvature being 13 μm, much less than the allowable focal range of 21 μm. It should be noted that the field curvature is calculated at full aperture for positions of the image plane yielding maximum contrast for a frequency equal to one-fourth of the cut-off frequency (for 3-μm linewidths).

The distortion is shown in Fig. 4b. The higher order distortion is properly balanced with the primary term to ensure the minimum spatial error at any point in the field, this error being 0.5 μm. The actual departure of a circuit element from a straight line would be substantially less.

Lens configurations and groups

If we consider field diameters ranging from 2 to 110 mm, certain lens constructions evolve. For micrometer and submicrometer linewidths over a rather small field (up to about a 5-mm diameter), a modified flat-field microscope objective has been found best, but it must be corrected for both axial and chromatic aberrations since it is to be used without a compensating eyepiece. Unfortunately, this micro-objective construction, designated Group 1, has a very short working distance and high distortion. To improve these two shortcomings without impairing the state of optical correction over the same field diameter,

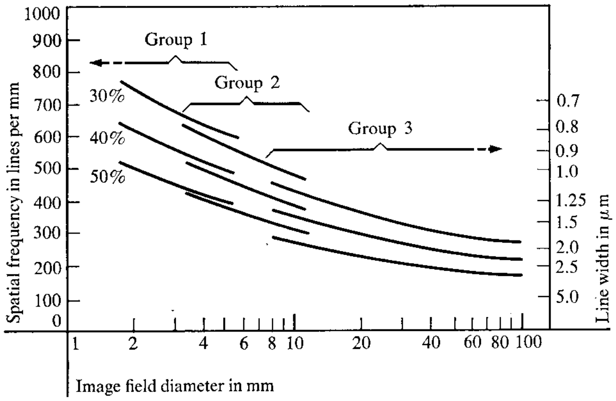


Figure 5 Achievable spatial frequency and linewidth potential vs. field diameter for the three characteristic groups of lenses at three contrast ratios. The reduction is 10× and the wavelength is 5461Å.

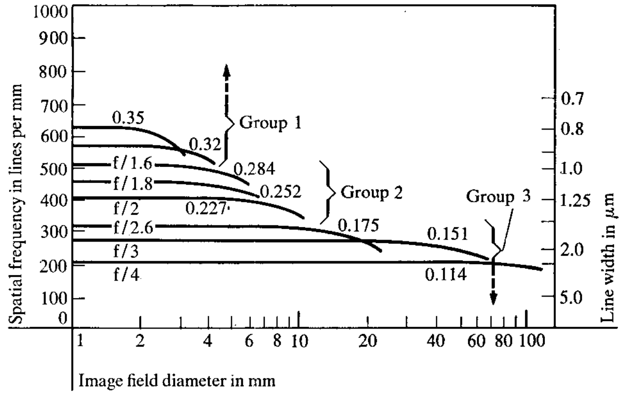


Figure 6 Lens performance at 40% contrast with no mechanical vignetting. The reduction is 10× and the wavelength is 5461Å.

a modified Gauss lens of very high index glass ($n_D = 1.8$) was developed (Group 2). This second group, although more complex to make and slightly more expensive than Group 1 lenses, has a much greater working distance and negligible distortion. Group 2 lenses cover field diameters from 4 to about 12 mm. For larger diameters, the reduction lenses required are physically larger and the cost of the very high index glass becomes prohibitive. Therefore Group 3 lenses are of the modified Gauss type, containing only the more easily workable lanthanum crown glass ($n_D = 1.7$), and have been designed so far to cover diameters up to 110 mm.

Lens selection curves

If in Table 1 there is no reduction lens meeting a particular application, one can scan the family of curves given in Fig. 5 that shows which lenses are within the realm of feasibility. In both Fig. 5 and Fig. 6 the bounds are shown for each group, with all lenses standarized at 10× reduction at 5461 Å wavelength.

In Fig. 5 the linewidths at three contrast ratios are given for a selection of reduction lenses covering a great variety of uses in the microelectronics industry. At a calculated value of 40% contrast, finished prototypes have shown a contrast reduction of no more than 5%. The three lens groups shown may overlap slightly, depending on performance requirements, near the transition regions. These curves are based on data from 35 different lens designs and are a true representation of our present experience. Given the desired linewidth over some field diameter, one can select a lens from Fig. 5 for a new photoreduction machine and be assured that such a lens can be produced. Figure 5 will suffice for contrast values from 30 to 50 %, with interpolation for intermediate values if desired.

Currently attempts are underway to increase the possible line density (spatial frequency), but the data as plotted are an indication of lens performance at this point in time. If a part of the spectrum other than the range from 4047 to 6561 Å is to be used, the linewidths should be scaled by the ratio of the wavelengths. For example, a lens capable of a 2-μm linewidth at 5461 Å should provide, at the same contrast, a linewidth of 2 μm × 4047/5461 (1.5 μm when redesigned for best correction) at 4047 Å, not a trivial proposition for the designer.

For a clearer knowledge of linewidths at 40% contrast and the relative aperture-field diameter relation, the lens performance has been plotted in Fig. 6 for each lens of a similar f-number (f/⊙) with no mechanical vignetting. The working numerical apertures (NA) at 10× reduction are also shown. [The working NA is $(2f/\odot)^{-1}$.] The field limitations as a function of f/⊙ are readily apparent. If, at this given f/⊙, one exceeds the field-size limit, the linewidth at 40% contrast quickly increases or, more precisely, the image rapidly deteriorates.

When some field diameter has been selected, a vertical line on Fig. 6 at that diameter immediately shows the possible linewidths at 40% contrast as functions of f/⊙. (The 40%-contrast value has been chosen as typical; if some other contrast is desired, a new family of curves can be drawn.) There is, of course, no lower limit on field diameter, since each curve shown begins at the diffraction-limited value of linewidth at a 1-mm diameter, with the possible exception of high numerical aperture micro-objectives, none of which are shown here. Again as in Fig. 5, the regions of feasibility based on our experience are apparent and a lens selection can be made easily. For a wavelength other than 5461 Å, scaling of the linewidths is necessary and a change in reduction is possible since lenses of various reductions were each standardized at 10× reduction for uniformity in preparing Figs. 5 and 6. The scaling for some new reduction factor R' at a given f/⊙ is

$$f/\odot' = (1 + 1/R')f/\odot .$$

Interpolation of the data in Fig. 6 will show potential lens performance.

Vari-reduction lenses

Since all the above lenses perform best at their designed reduction, a slight change in this reduction from, say, 10 to 9× will deteriorate the image to such an extent that no usable images can be produced over the entire field. Apparently a new lens should be designed for each different reduction. Since the inventory of reduction lenses then becomes excessive, however, a cheaper and simpler method of reduction change becomes necessary. Referring to Fig. 1, we note that merely replacing the lens element L by another of a different shape and adjusting the airspace S will allow an infinite number of reductions between approximately 6 and 40× without appreciable loss of image quality over the full field. The user of such a vari-reduction lens would need to buy only the basic lens plus as many inexpensive elements as the number of reductions he requires. The proper element could then be inserted, the airspace adjusted by means of a calibrated ring, and the lens would perform equally well at the chosen reduction. For a manufacturer of microelectronics employing various mask sizes, the economy of such a system is obvious. The scheme works only for lenses from Group 2 and 3, however; no similar artifice has yet evolved for Group 1 lenses.

The vari-reduction feature has been effected in Lenses 7 and 12, their reductions having been changed from 20 to 10× and from 20 to 15×, respectively, by the simple expedient outlined here. The distortion, however, is only partially correctable and drifts from 0.007 to 0.06% at the 15× reduction. Both lenses at each reduction have been producing exceptionally clean images for a period of two years.

Summary

Three families of reduction lenses, using spherical surfaces exclusively, have been described. Their manufacture requires the most careful workmanship achievable using current technology. Many of the designs have been fabricated, however, and these confirm the soundness of the design methods, assessment criteria, and manufacturing techniques.

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