Reduction Cameras: Optical Design and Adjustment

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This paper describes the optical design of the photolithographic reduction cameras and discusses in detail several aspects of the illumination system including the light source spectrum, the method of attaining even illumination, and the use of a Fresnel condenser lens. The camera design provides for first-order correction of focus and magnification shifts due to changes in ambient temperature. To adjust the cameras for best focus and proper magnification, a new technique using a special test reticle and digital computers was developed. It automates much of the procedure and processes much more data than would otherwise be possible. The reticle allows simultaneous measurement of focus and magnification errors throughout the image field, and a time-shared computer calculates the required corrective shifts on the object- and image-spacer bars.

I. INTRODUCTION

This paper and the paper immediately following describe the two reduction cameras which have been developed to serve as part of the photolithographic mask-making facility described in this issue.

The primary pattern generator[1] generates artwork masks which are nominally 17.5 cm square. This size was determined by various optical and mechanical considerations. The two reduction cameras reproduce these masks at the two specific, reduced sizes required for use as masters for tantalum thin film circuits and interconnection substrates; the reduced masks from one of these cameras (the 3.5X camera, shown in Fig. 1) can also serve as the reticle in the step-and-repeat camera.[2] The two reduction ratios, together with the corresponding mask size and minimum linewidths, are summarized in Table I. In each size the minimum linewidth is 1/5000 of the width of the mask.

This reduction in mask size carried out by the reduction cameras must be accomplished without significant loss of resolution in the

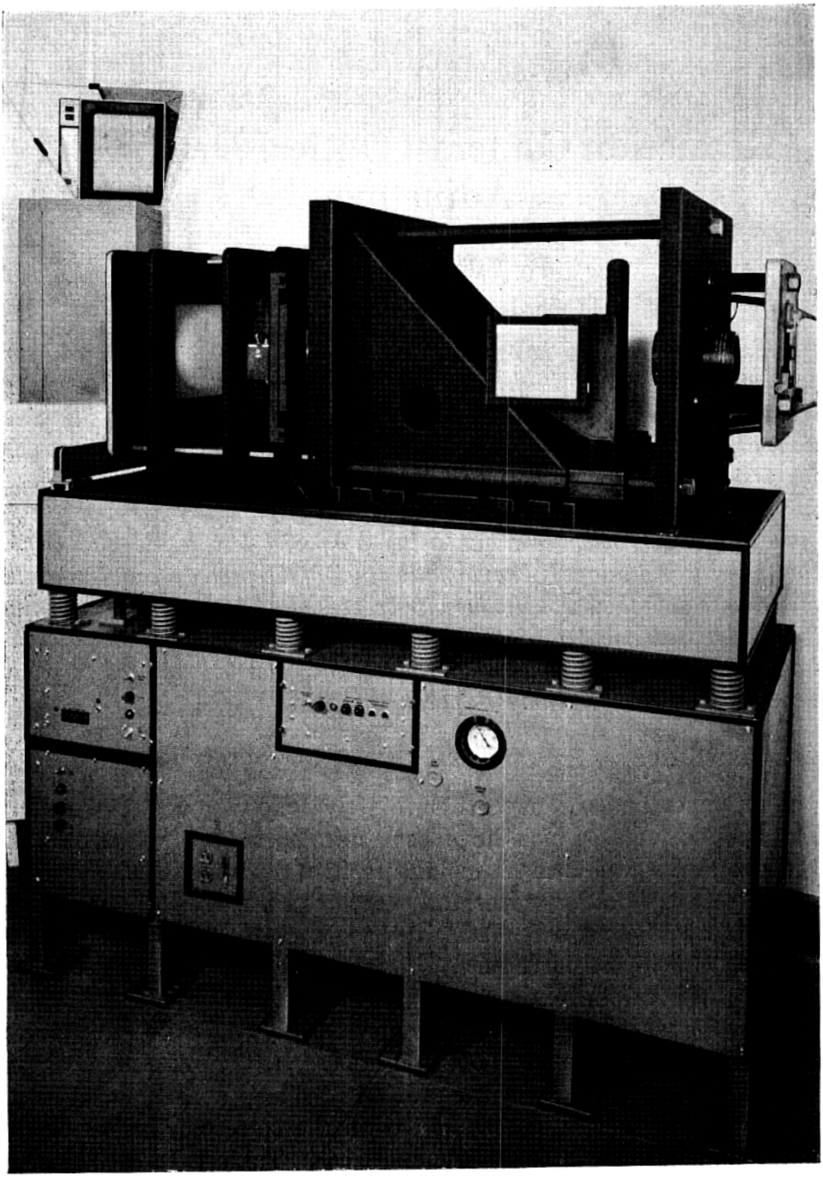

Fig. 1—The 3.5× reduction camera.

TABLE I—COMPARISON OF THE ARTWORK PLATE WITH THE OUTPUT PLATES OF THE 1.4X AND THE 3.5X CAMERAS

	Artwork	1.4X Reduction	3.5X Reduction
Size (max. nominal)	17.5 cm sq	12.5 cm sq	5 cm sq
Minimum Linewidth	35 μm	25 μm	10 μm
Use	Input to Reduction Cameras	Tantalum Thin Film Masks	Tantalum Thin Film Masks, Step-and-Repeat Reticle

minimum-width details and without introducing distortions greater than about half of the minimum linewidth. The degree to which these two requirements can be met is primarily determined by the resolution and distortion characteristics of the reduction lens; the design considerations of such lenses are a major topic in themselves, presented elsewhere in this issue.[3] Given a lens of suitable quality, however, the camera's performance is still critically dependent on three factors: (*i*) The mechanical design of the camera must be such as to maintain its performance in the presence of environmental perturbations such as vibration, changes in ambient temperature, and variations in the operators' handling techniques. (*ii*) Camera performance is dependent upon the proper design and adjustment of the illumination system. (*iii*) The performance of the camera can be no better than one's ability to adjust the completed camera for best focus and proper magnification over the whole image field, not a trivial task for cameras in this performance class. The mechanical design of the reduction cameras is discussed in the following paper. In this paper, we consider the problems of the optical design and the final adjustment.

II. OPTICAL DESIGN

Figure 2 shows the optical layout of the reduction cameras. The light source is a 100-watt mercury arc lamp operating at a pressure of about 10 atmospheres. This light source, suitably filtered, diffused, and modulated as described below, is imaged by a two-element Fresnel condenser lens onto the entrance pupil of the reduction lens. The convergent beam illuminates the artwork plate, which the reduction lens images onto the output image plate at the right. The image plate used is a Kodak Microflat High Resolution Plate with ground edges.

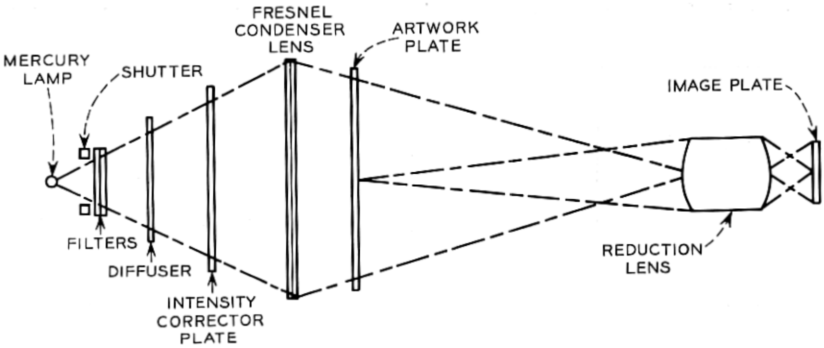

Fig. 2—Optical layout of the reduction cameras.

One of the design requirements for the two reduction lenses was that they have equal entrance pupil distances. This allowed us to use a single illumination system design for both the 1.4X and the 3.5X cameras. It was found that such a restriction could be imposed on the reduction lenses without significantly compromising their design performance.

A mercury arc light source was chosen for reliability and spectral narrowness. The 4358 Å blue line was selected rather than the 5461 Å green line because of the extra resolution afforded by the shorter wavelength, and because it left open the possibility of direct exposure onto photoresist surfaces which are sensitive to the blue but not to the green light. Although the scattering of light within the emulsion (which varies as the fourth power of the light frequency) is greater for the blue line, it is not a serious problem in this case, where the emulsion is 6 μm thick and the finest structure to be written on it is 10 μm wide.

The lamp chosen, a General Electric H100 A4/T, represents a compromise between brightness and spectral narrowness. High-pressure lamps, though brighter, exhibit sufficient pressure (Lorentz) broadening (see for example Ref. 4) of the 4358 Å line to complicate the color correction of the reduction lens, which would necessarily compromise its overall performance. The lamp brightness results in exposure times of 3–4 seconds for the 3.5X camera and 20–25 seconds for the 1.4X camera.

Two glass filters (Corning Filters No. 3389 and No. 5543) are used to isolate the Hg 4358 Å spectral line.

The image of the arc source projected onto the entrance pupil by the

Fresnel condenser, although magnified slightly by the Fresnel lens, is still too small to fill the entrance pupil. Therefore, a ground-glass diffusing screen is placed in front of the mercury lamp to increase the apparent size of the light source. The amount of this increase can be controlled by adjusting the axial position of the ground-glass diffuser. This position is adjusted until the diffused image of the source just overfills the entrance pupil.

The accumulation of reflection losses at air-glass interfaces throughout the camera results in considerable transmission loss. While this in itself is not serious, the difference in the losses experienced by paraxial rays and by rays near the edge of the field, which arises because of differences in the angles of incidence, results in an illumination intensity which falls off seriously with field angle. This intensity fall-off is compensated by the intensity corrector plate (see Fig. 2) which has a thin, vacuum-deposited absorbing layer of Inconel. The amount of deposited Inconel decreases radially from the plate center so as to compensate for the field-angle-dependent losses of the rest of the camera. Figure 3 shows

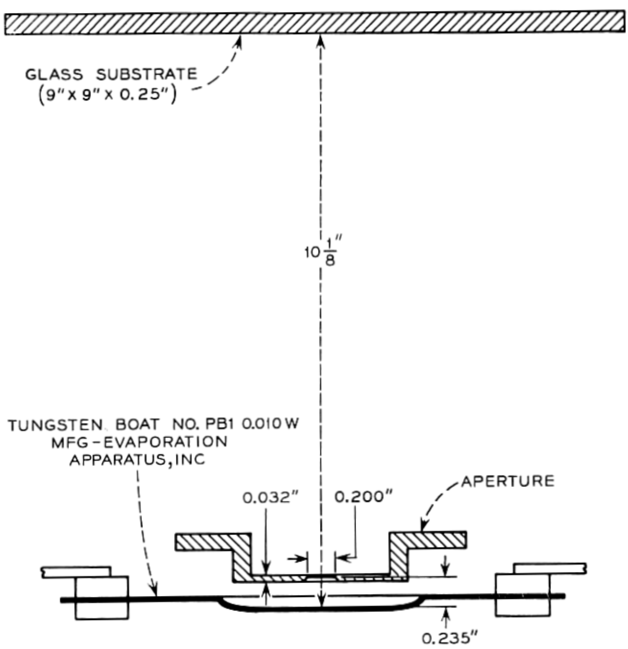

Fig. 3—Arrangement used in the vacuum evaporation of the Inconel coatings onto the intensity corrector plate.

the arrangement used in the vacuum evaporation process. The aperture defines a finite area source for the Inconel vapor. The aperture diameter and height, and the height of the glass substrate, were adjusted empirically to yield the flattest intensity distribution in the image plane. This was determined by scanning the image plane with a pinhole, integrating sphere and photomultiplier tube assembly. The result is shown in Fig. 4 which is a plot of the measured illumination intensity as a function of position within the image plane. Each horizontal scan extends beyond the active image area; the vertical tic marks on each scan delimit the actual image field. Figure 4 also shows the plane of constant intensity which best fits the measured data. It can be seen that the measured intensity distribution deviates from this plane of best fit everywhere by less than ± 7 percent.

The Fresnel condenser lens* was designed specifically for these cameras and provides for zero spherical aberration at the particular object and image distances of our illumination system. The material is Rohm and Haas VM plexiglass. The lens is made up of two elements, each approximately 0.060″ thick, cemented around the rim face-to-face, as illustrated in Fig. 5. Opposing facets on the two halves have dissimilar facet angles; these angles were chosen to equalize the optical power of opposing facets, thereby minimizing reflection losses. The ability to specify the angle of each facet is equivalent to allowing general aspheric surfaces on a conventional lens. The result is that axial spherical aberration can be eliminated completely from the lens design, minimizing the problem of illumination fall-off with field angle. In addition, the ability to specify the angle of the cutback facet assures that the scattering of light by this facet will be minimal. The Fresnel lens is laterally located in the camera with three corner pins riding in radially oriented slots, so as to allow free thermal expansion without buckling or decentering.

A Fresnel condenser was chosen rather than a conventional glass condenser largely because of the difficulty in obtaining large glass lenses sufficiently free of bubbles. Such bubbles, if larger than a millimeter or so, modulate the illumination light cone at sufficiently low spatial frequencies to seriously perturb the intensity distribution in the image plane. On the other hand, the ring pattern of the Fresnel lens facets is at a sufficiently high spatial frequency that its effect is not detectable in the image plane. The moiré effects and erratic illumina-

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* Designed and fabricated by the Alliance Tool and Die Co., Rochester, New York.

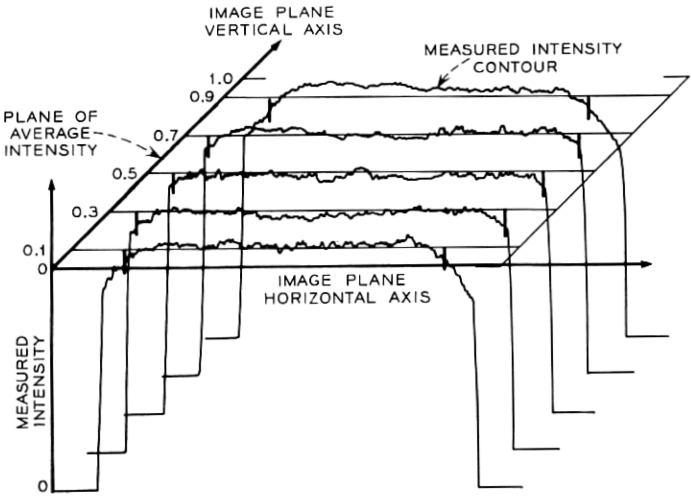

Fig. 4—Measured intensity distribution in the image plane. The maximum deviations of the measured intensity contours from the plane of average intensity are ± 7 percent.

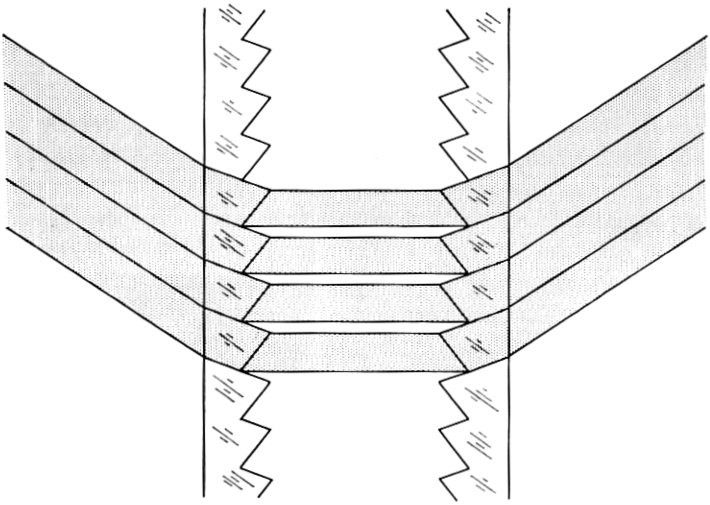

Fig. 5—Optical design of the special two-element Fresnel lens.

tion uniformity usually seen in Fresnel lens combinations are eliminated by maintaining a tight tolerance on the alignment of the two Fresnel elements during fabrication.

The design and performance of the 3.5X and the 1.4X reduction lenses are discussed in another paper in this issue.[3]

III. TEMPERATURE COMPENSATION

The reduction cameras are designed to operate in an environment in which the temperature is regulated to ±0.25°F. Nonetheless, as an additional precaution, it was decided to provide first-order compensation for changes in focus and magnification due to changes in ambient temperature. For this purpose a computer program was written* which determines the effects of temperature changes on the focus and magnification of a lens, taking into account the thermal coefficients of volume expansion, refractive index, and dispersion of each glass element, and calculating approximate changes in air gaps from the thermal expansion coefficient of the lens barrel material. It is then possible to calculate, using either the ACCOS† lens optimization program or an equivalent optimization program, how the object and image distances must change with temperature in order to maintain best focus and proper magnification. First-order temperature compensation is then attained by selecting the spacer materials to provide the appropriate thermal expansion coefficients.

IV. FOCUS AND MAGNIFICATION ADJUSTMENT

As the resolution and magnification accuracy demanded of photolithographic lenses increase, it has become apparent that traditional methods of focus and magnification adjustment are impractically slow. In order to adjust the reduction cameras properly it was necessary to develop an adjustment system which automates much of the procedure and processes much more data than would otherwise be possible. The system is broadly divisible into three parts: (*i*) a special test reticle which allows simultaneous measurement of focus and magnification errors at nine points distributed over the image plane; (*ii*) a computer-controlled, interferometric, coordinate measuring machine[5] to locate fiducial marks on the test image plates and punch their co-

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* The Fortran IV TEACOPS program (*T*emperature *E*ffects *A*nalysis of *C*omplex *O*ptical *S*ystems) is available on request from the author.

† ACCOS (*A*utomatic *C*orrection of *C*omplex *O*ptical *S*ystems) is copyrighted by Scientific Calculations, Inc., Rochester, N. Y.

ordinates on paper tape; and (*iii*) a set of computer programs to analyze the paper tapes, establish the current camera errors, and calculate the necessary corrective shifts on the spacer rods. The rod adjustment mechanism is based on the elastic compression of Belleville spring washers and is described in detail in the following paper.

The test reticle is shown in Fig. 6. An 8″ × 10″ photographic plate has a test pattern consisting of horizontal and vertical bar patterns of various spatial frequencies, arranged in continuous vertical stripes. Nine glass prisms are cemented to the face of the plate in a 3 × 3 array covering the desired object field. Nine identical prisms are cemented to the back of the plate to compensate for the refraction of the illumination beam. The effect of the first nine prisms is to tilt the apparent plane of the object test pattern seen in the prism. Nine flat spacer pads displace the test reticle to the rear when mounted in the camera, so that the tilted object test patterns straddle the true

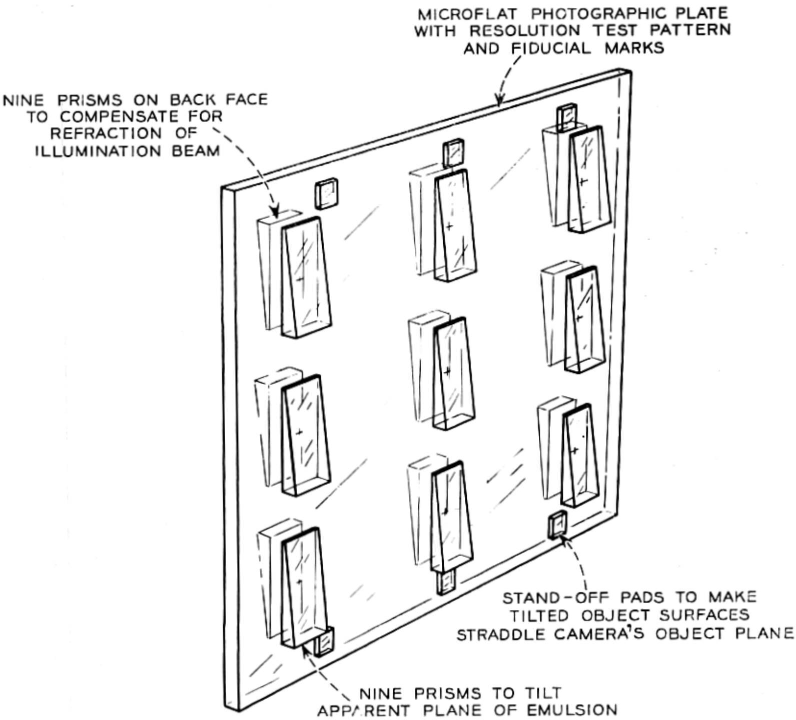

Fig 6—The special test reticle used for simultaneous adjustment of focus and magnification.

object plane. In addition, fiducial marks are placed in the center of each prism field, to be used to check magnification.

The test reticle is placed in the camera and a test image plate is exposed and developed. Measurements are made, in each of the nine prism areas on the image plate, of the vertical position where the pattern appears sharpest. Additionally, the coordinates of the nine fiducial marks are measured. This information, when compared with reference measurements made on the test reticle itself, yields the focus errors in each of the nine prism regions and twelve magnification errors, corresponding to twelve distances between the nine fiducial marks. Figure 7 shows focus and magnification error maps printed by our time-sharing computer program. The data shown is that for a well-adjusted 3.5X camera. Note that the magnification errors, Fig. 7(b), are at worst 0.37:10,000 and average 0.20:10,000. This is to be compared to the maximum allowable error of 1:10,000. Similarly, the focus errors, Fig. 7(a), are at worst 9.4 μm and average 4.1 μm. These numbers are comparable to the diffraction limited depth of focus.

Other parts of the time-shared computer program calculate (using paraxial optical equations) the object- and image-distance shifts necessary to bring each of the nine prism regions into best focus and magnification. These shifts are then fitted (using the method of least squares) onto tilted and axially displaced object and image planes. Finally, the program calculates the length changes required on each of the six spacer rods to bring the existing object and image planes into conjunction with the desired planes.

In general, approximately 6–8 iterations of this correction cycle are required to bring the camera into adjustment such as is shown in Fig. 7. During the last few iterations, a modified procedure is followed in which a test reticle without prisms is used in addition to the prism test reticle: the former provides the magnification error data, and the latter provides the focus error data, as before. This procedure eliminates the small magnification error introduced by the prisms. Such errors amount to about 1:10,000 and can be neglected during the first several iterations.

Figure 8 compares a resolution test pattern and the corresponding image taken with a well-adjusted 3.5X camera. The narrow lines in each of the five "L" patterns are (on the reduction camera plate) 4, 6, 8, 10, and 12 μm. (The finest detail required in normal operation is 10 μm.) It can be seen that the 4 μm detail is adequately resolved

FØCUS SHIFT IN MICRØNS. PØSITIVE MEANS IMAGE IN GLASS

UPPER, FAR CØRNER
ØF THE IMAGE WHEN
ØN THE CAMERA

-2.11	-2.42	-1.93
-4.96	2.74	-9.37
-0.77	-3.66	0.83

RMS FØCUS DEVN= 4.063, LARGEST FØCUS DEVN = 9.369

(a)

1/(-MAGN), AND ERRØR (PARTS PER 10,000)

LØWER, NEAR CØRNER
ØF THE IMAGE WHEN
ØN THE CAMERA

+	3.499956 -0.13	+	3.499968 -0.09	+
3.500113 0.32		3.500027 0.08		3.500044 0.13
+	3.500025 0.07	+	3.499875 -0.36	+
3.500130 0.37		3.499993 -0.02		3.499923 -0.20
+	3.499968 -0.09	+	3.500021 0.06	+

RMS MAGN DEVN = 0.199, LARGEST MAGN DEVN = 0.370

(b)

Fig. 7—Computer-generated maps of focus errors (a) and magnification errors (b) for a well-adjusted 3.5× reduction camera.

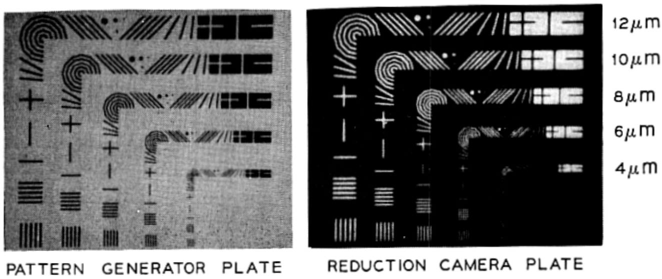

Fig. 8—Photomicrographs of an artwork resolution test pattern (left) and the corresponding image plate (right) taken with the 3.5× camera. The image-plane linewidths are indicated at the right. The finest image linewidth required in normal use is 10μ.

and that the 10 μm (fundamental) detail is well resolved with sharp edges.

V. ACKNOWLEDGMENTS

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