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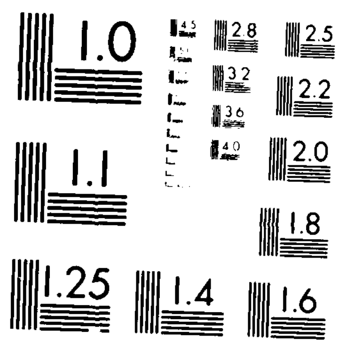

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Optical Technique for Increasing Fill Factor of Mosaic Arrays

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A novel optical technique for improving the performance of focal plane staring arrays by increasing the fill factor ratio is described. The specific mosaics considered are 64 × 32 and 128 × 64 arrays of infrared detectors with infrared charge coupled devices (IRCCD) made from monolithic silicon. The video enhancement is accomplished by means of a refracting silicon faceplate that redirects focused image irradiance from nonsensitive CCD areas to the infrared detector elements. Operational theory and design

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parameters for this unique faceplate construction are detailed. With the optimum faceplate configuration installed at the IRCCD front surface, a sensitivity increase of at least 150% is predicted from the analysis presented here.

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FIGURES

I. INTRODUCTION

Focal plane staring arrays consisting of Schottky barrier infrared detectors and infrared charge coupled devices (IRCCD) are currently under development for use in several remote sensing applications. These IRCCD arrays use monolithic silicon construction for sensing image irradiance in the optical field-of-view. The radiant intensity at each Schottky platinum-silicide (Pt-Si) detector is converted to an electronic charge that is integrated and read out by the charge coupled device (CCD) in the adjacent row. Although this type of image sensor has high response uniformity, large dynamic range, and excellent survivability characteristics, the elemental quantum efficiency and sensing area density are lower than is realizable from other staring mosaics. This report describes a novel optical technique that significantly improves the responsivity of Schottky IRCCD arrays by increasing the sensitive-area fill factor.

II. THEORY OF OPERATION

Improved array performance is attained through installation of an optical refracting faceplate at the IRCCD front surface. This faceplate must redirect the focused image irradiance that would normally fall on nonsensitive CCD areas adjacent to the Schottky detector elements. To accomplish this selective bending of optical rays, the primary faceplate design considerations are the front-surface geometry of the faceplate and the refractive index of the material. Specifically, it was determined that the faceplate should be made of a material with a high refractive index, such as silicon or germanium, with a one-dimensional scalloped front-surface pattern extending over each row of detectors. The physical dimensions of current IRCCD chips were used to perform the calculations detailed in the following section to determine realizable faceplate dimensions for collecting optimum irradiance at the Schottky detectors.

III. FACEPLATE DESIGN

The following faceplate design is operational with the 64 × 32 IRCCD mosaics (2048 detectors). This 64 × 32 array is 0.64 cm square, with each detector measuring 59 × 55 μm. The 101-μm gap between each 64-element row is occupied by the associated CCDs. Figure 1 shows these dimensions for the 2048-element configuration.

The special silicon faceplate installed on the Schottky IRCCD chip should have a scalloped front surface to optimize irradiance collection, and an optically flat back surface to maximize transmission efficiency. This analysis uses F1.2 optics to focus imagery onto the IRCCD chip. For such a fast optical system, the angular cone of image irradiance extends over a ± 22.6-deg range. On the basis of this angular range and IRCCD element dimensions, the required front-surface arc radius and retinae thickness (faceplate plus IRCCD thickness) for maximum optical collection can be calculated from the following equations:

$$d(A)_{max} = w/2 \sqrt{n_2^2(4F^2 + 1) - 1} \tag{1}$$

$$X_B = \left[d(B)_{max} - \frac{(w + s)(1 - \cos\theta_a)}{2 \sin\theta_a} \right] \tan \left\{ \sin^{-1} \left[\frac{\sin(\theta_F - \theta_a)}{n_2} \right] + \theta_a \right\} - s/2 \tag{2}$$

$$X_C = \left[d(C)_{max} - \frac{(w + s)(1 - \cos\theta_a)}{2 \sin\theta_a} \right] \tan \left\{ \sin^{-1} \left[\frac{\sin(\theta_F - \theta_a)}{n_2} \right] - \theta_a \right\} - s/2 \tag{3}$$

The derivation of these faceplate parameter equations is contained in the Appendix of Reference 3.

The optical paths for extreme rays directed through the collecting faceplate and IRCCD front surface to each Schottky Pt-Si junction are shown in Figure 2. Since these extreme rays can be redirected to fall on an active detector area, all rays at lesser angles also reach the sensing elements.

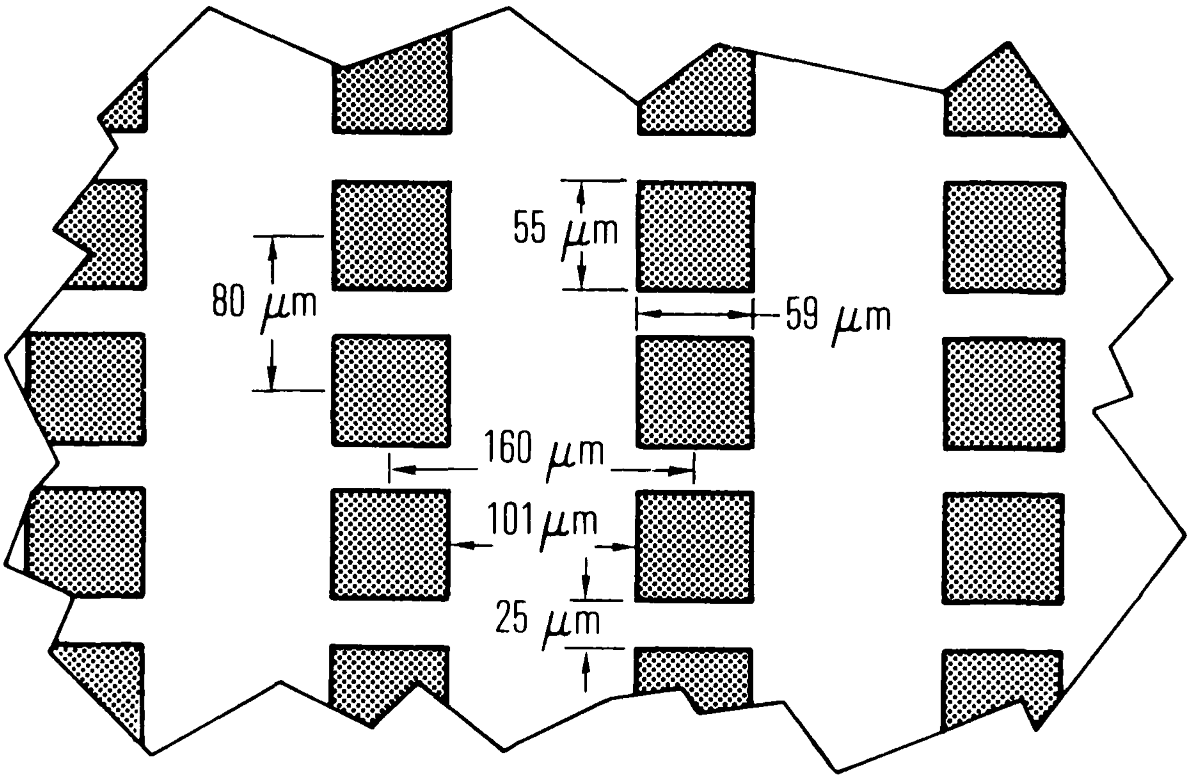

Figure 1. Elemental dimensions for 64 × 32 Schottky IRCCD mosaic

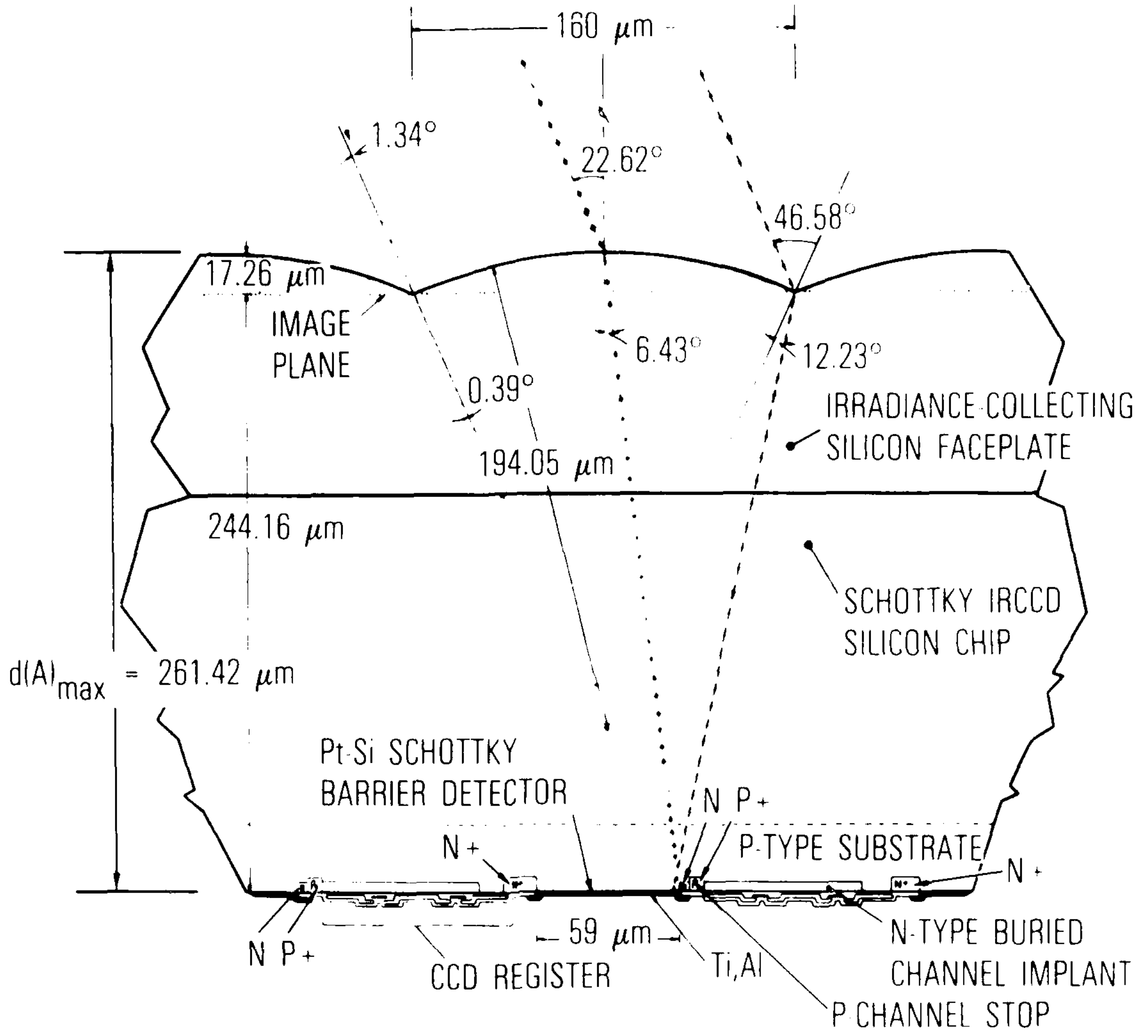

Figure 2. Optical ray tracing diagram for collecting faceplate and 64 × 32 IRCCD mosaic. The extreme rays shown are for an F1.2 system and are symmetric about the center line.

By graphic method or analytical calculations, the faceplate arc radii and retinae thickness for optimum irradiance collection are found to be 194.05 and 261.42 μm, respectively. These calculations were verified by John W. Ellinwood (Reference 2) using Fresnel diffraction analysis.

Each arc radius can be defined in terms of the front-surface angular arc (θ_a) subtended by the 160-μm chord over each sensing element of the 64 × 32 array.

In Figure 3 the optimum value and allowable tolerance for θ_a is graphically found to be 24.35 ± 0.47 deg as determined by the intersection of the plotted extreme ray distances from the detector edge (X_B and X_C). This figure also describes the variation in X_B and X_C as a function of faceplate θ_a. These results were also verified with a computerized ray tracing program. Figure 4 is an illustration of the special faceplate design as installed on a typical 64 × 32 Schottky IRCCD array.

The second collecting faceplate design is operational with the 128 × 64 array (0.64 cm square), with each detector measuring 50 × 40 μm. The 70-μm gaps between the 128-element rows are occupied by the associated CCDs. These dimensions are diagrammed in Figure 5 for the 8192-element configuration. Using graphic and analytical methods described above, the faceplate arc radii and retinae thickness for optimum irradiance collection are found to be 164.3 and 221.54 μm, respectively. The optimum arc radius, defined in terms of the θ_a, is graphically found in Figure 6 to be 21.43 ± 0.37 deg, as determined by coincidence of the X_B and X_C curves. This figure also describes the variation in X_B and X_C as a function of faceplate θ_a.

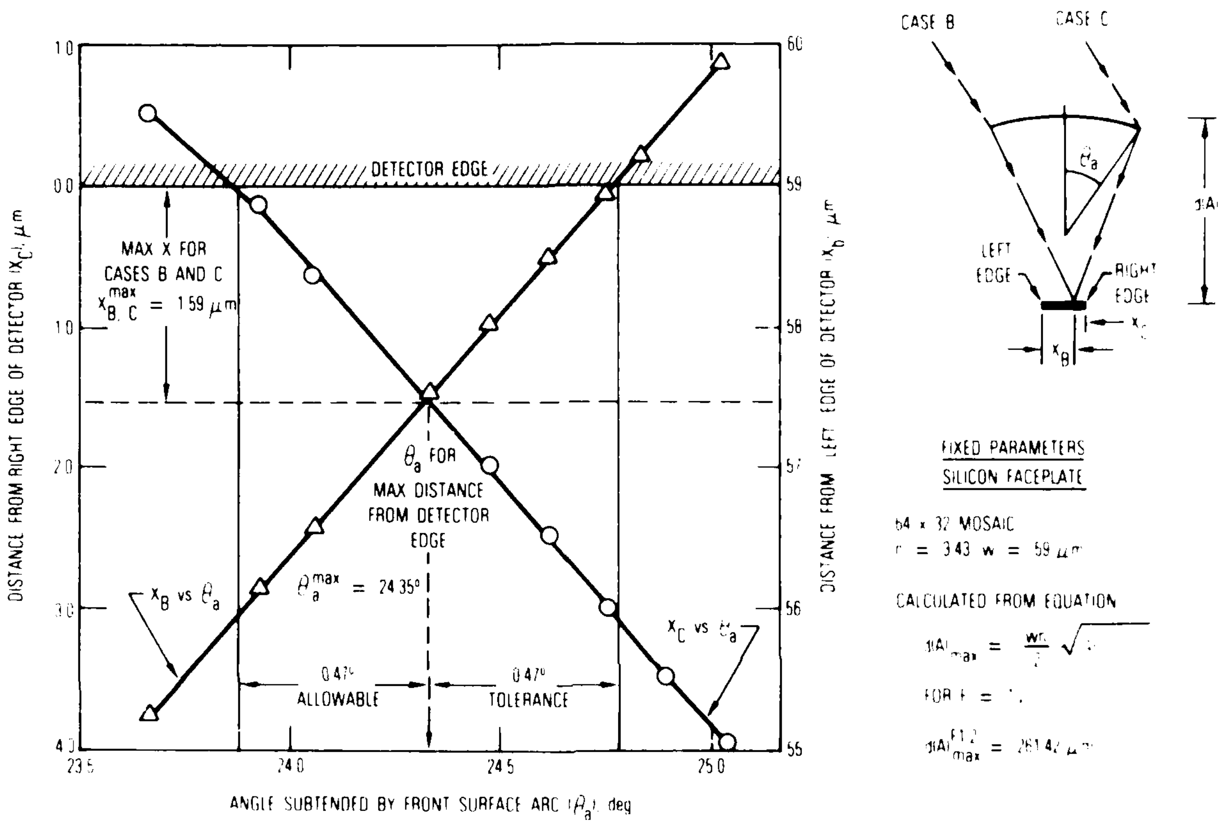

Figure 3. Focused irradiance distance from detector edge (X_B, X_C) vs. faceplate front surface arc (θ_a) for 64 × 32 Schottky mosaic

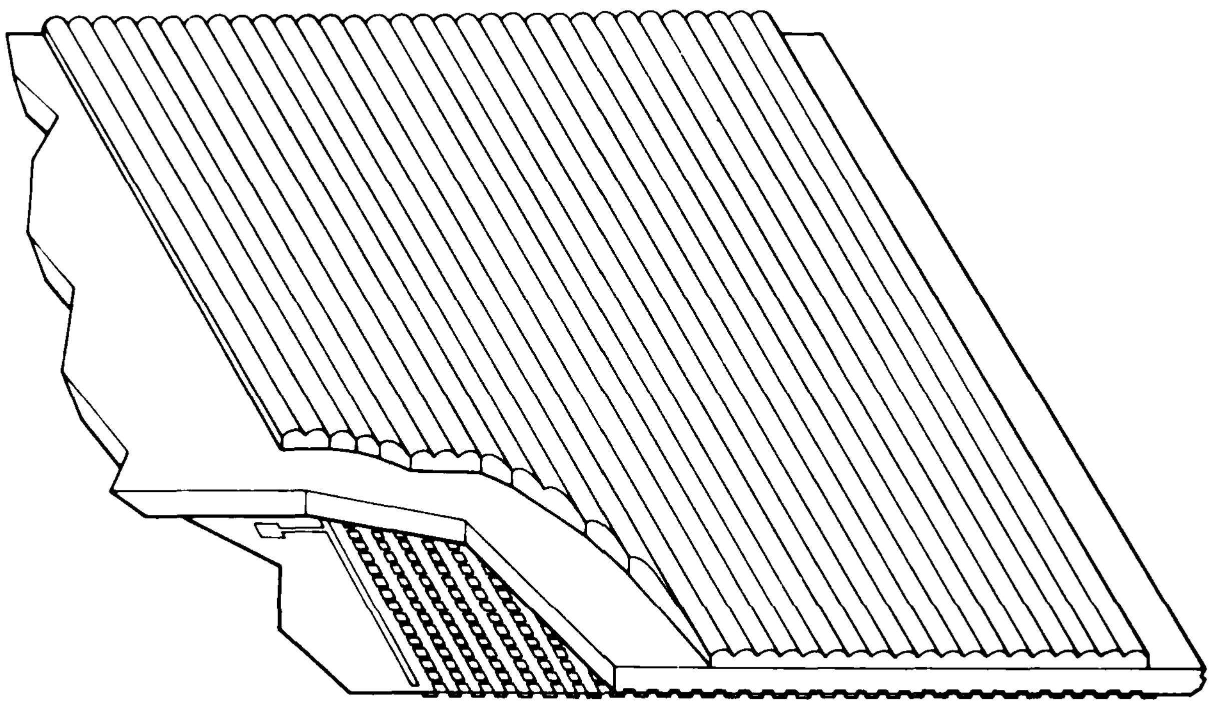

Figure 4. Schottky IRCCD mosaic with faceplate

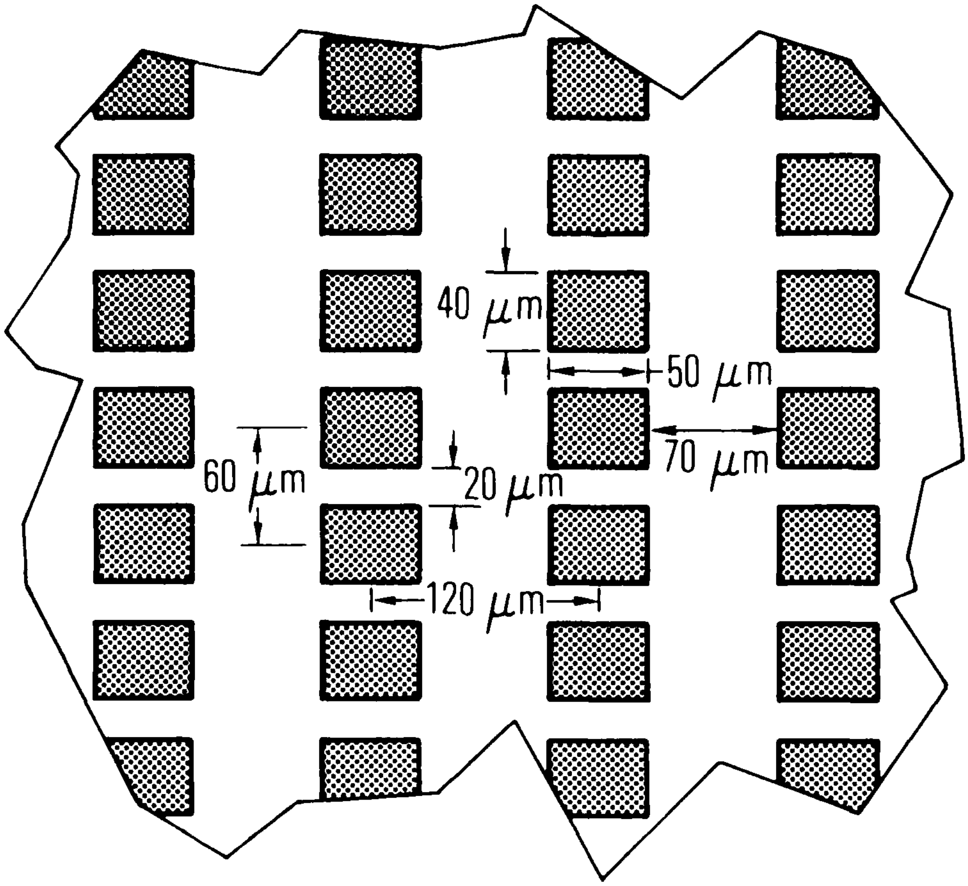

Figure 5. 64 × 128 detector array

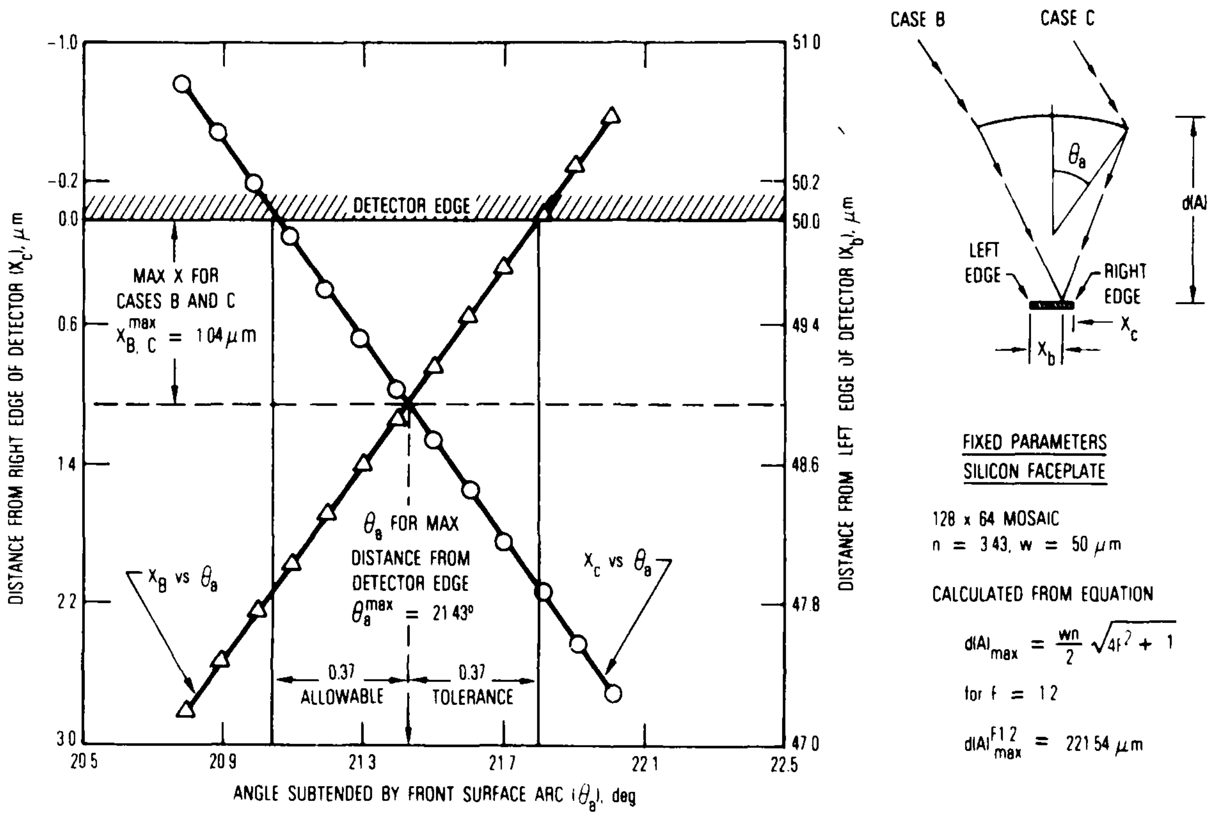

Figure 6. Focused irradiance distance from detector edge (X_B, X_C) vs. faceplate front surface arc (θ_a) for 128 × 64 Schottky mosaic

IV. FACEPLATE CONSTRUCTION

The silicon faceplate geometry can be fabricated with current state-of-the-art technology. One technique for fabricating the front-surface arcs would use precision diamond machining processes. However, construction difficulties could occur if the required faceplate thickness is below 70 μm. With slower optics the required faceplate thickness can be increased proportionally, as shown in Figure 7. It is also probable that faceplate thickness can be increased by reducing IRCCD chip thickness. If a sophisticated indexing technique could be devised, it may be possible to fabricate the curved surface geometry directly onto the IRCCD front surface.

To optimize performance of this composite focal plane retina, both faceplate surfaces and the front IRCCD chip surface should be antireflection coated for the spectral region of interest. In this manner signal irradiance losses between the outside silicon faceplate surface and the Schottky infrared detectors can be reduced by 50%. A germanium faceplate with similar geometry could be used to provide the optical collection, since this material has a refractive index of 4.0. Because of this higher index value, germanium produces greater optical path bending than silicon for the same faceplate thickness. Two disadvantages of such an approach are that (1) germanium faceplates at the required thicknesses are not easily fabricated because the material is very brittle, and (2) aligning the faceplate with the IRCCD chip is more complex because of differing thermal coefficients over the ambient-to-77 K temperature range.

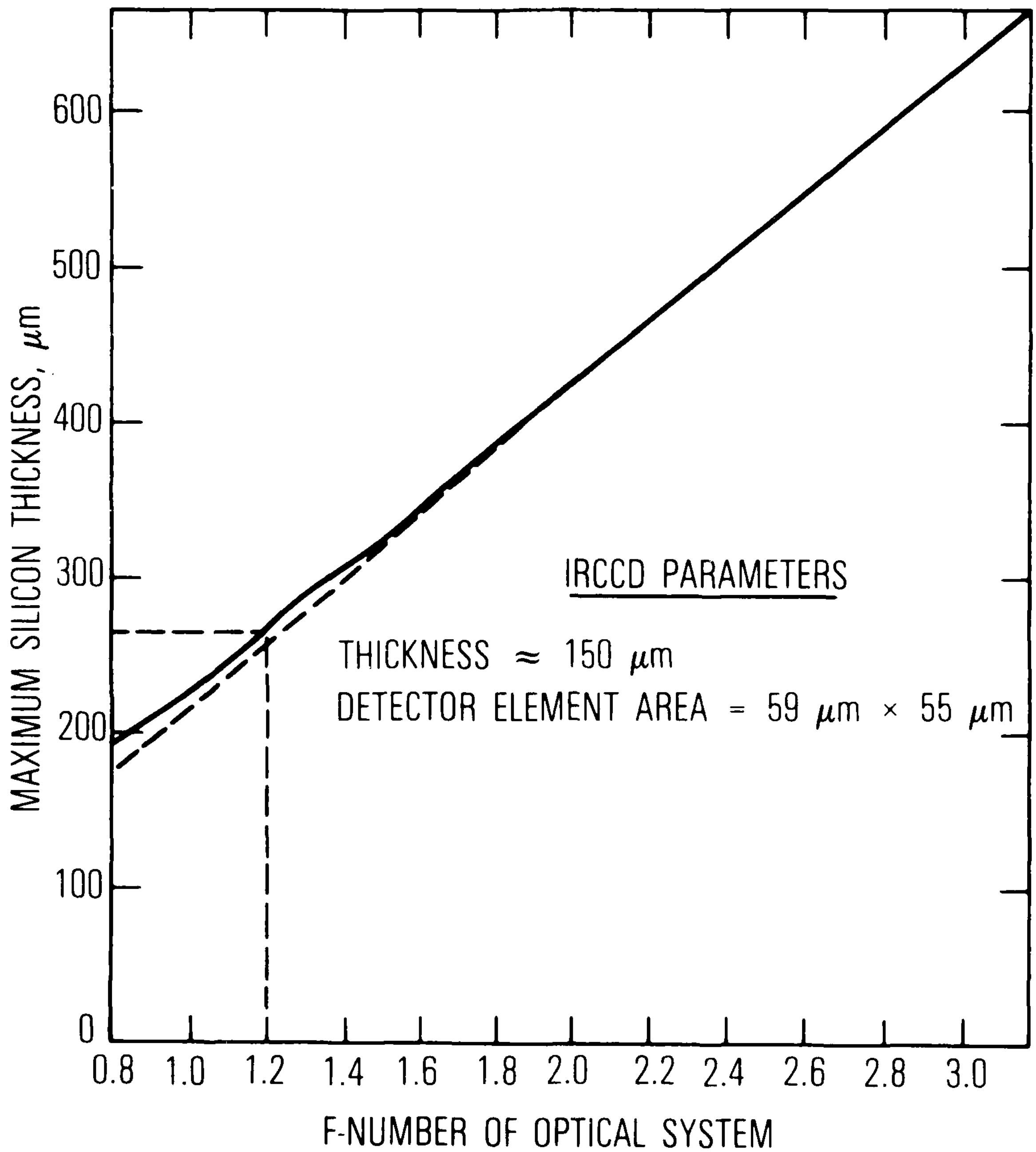

Figure 7. F number of optical system vs. maximum allowable silicon retina thickness

V. CONCLUSIONS

In summary, this novel optical technique can increase the sensitivity of current Pt-Si Schottky barrier mosaics by at least a factor of 1-1/2. The special silicon faceplate can be fabricated by means of state-of-the-art optical replication techniques. Since the mosaic and faceplate are both made of silicon, they remain aligned and perform as a single unit when cycled between ambient temperature and the 77-K operating temperature. The faceplate can also enhance performance of focal plane arrays in the specific design areas enumerated below:

1. By optically channeling signal irradiance from nonsensitive areas on the image plane, detector size, number, and density can be set up for optimum performance, with sensitive surface percentage becoming a less critical factor.

2. This silicon faceplate is designed to accommodate an F1.2 optical system, but equivalent percentage increases in sensitivity can also be achieved with slower (large F-numbers) optics without requiring any modification.

3. The improvement in sensitivity does not adversely affect the spectral response or dynamic range of detectors.

4. Detection probabilities for subaperture target images on the focal plane are significantly increased, because dead-zone areas between the horizontal sensing elements are eliminated by the collecting faceplate. Only the much smaller nonsensitive areas between adjacent vertical detectors remain unchanged.

5. With the increased fill factor, dead-zone area becomes a less significant design parameter in the construction restraint on focal plane electronics. By easing design criteria in this manner, more reliable and effective fabrication techniques can be adopted to improve IRCCD performance.

Although this novel technique has been specifically tailored for current Pt-Si Schottky barrier mosaics, it is applicable to other focal plane arrays. This approach would be especially beneficial to arrays where the sensitive area of the element area constitutes less than 50 percent of the image plane.

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3. E. F. Cross, et al., "Technique for Increasing Fill Factor of Mosaic Arrays," Proc. SPIE, Vol. 366.

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