Infrared Technology XI

PROCEEDINGS

Irving J. Spiro, Richard A. Mollicone
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Irving J. Spiro, Richard A. Mollicone
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Volume 572

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Session 1—Infrared Imaging
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Session 2—Space Applications
Robert Perry, U.S. Air Force Space Technology Center

Session 3—Detectors and Sensors
H. Nakamura, The Aerospace Corporation

Session 4—Scientific Applications
Richard A. Mollicone, Analytic Decisions Inc.

INTRODUCTION

Four sessions comprised the eleventh annual conference on Infrared Technology. Sessions were held at the Town and Country Conference Center in San Diego, California on August 20 and 21, 1985.

Session 1. INFRARED IMAGING

Chairman: Irving J. Spiro, The Aerospace Corporation

D. E. Burgess, P. A. Manning, and R. Walton of Royal Signals and Radar Establishment open the session with a paper on the theoretical and experimental performance of a pyroelectric array imager. Their instrument was mounted on an aircraft and a two-dimensional scan was performed using a side-to-side scan of the instrument in one direction with the aircraft motion providing the other dimension. A 2×20 element pyroelectric array required no cooling, is available at low cost, and although of low sensitivity, good TV reception was displayed at resolutions down to 1/2 meter.

G. D. Wiemokly and others from the Aerospace Corporation describe the performance of a 32×63 Pt Si CCD array. Half of the face plate is covered by a series of lenticulated lenses that direct the energy away from a CCD well and onto a detector area. Recordings of different signal conditions showed that the irradiance received from detectors covered by the lenticulated portion was about 2.6 times that of the unlenticulated area. The predicted difference was 2.7 times.

A method for real time enhancement of obscured optical images is described by G. W. Seeley of the Optical Sciences Center of the University of Arizona and Eric Craine, Energy/Environmental Research Group, Inc. Various individuals were asked to examine a scene in a CRT or a video display. A number of false positives were reported. By superimposing the images from both displays the number of false positives dropped from greater than 8% to less than 2%.

P. N. J. Dennis, Royal Signals and Radar Establishment and R. J. Dann of Marconi Command and Control Systems Ltd. discuss arrays for the British FLIR common module. The present module uses a scanner with the usual dynamic disturbances and uncertanties in pointing. This paper presents results when the scanner is replaced, to good advantage, with a starer.

Problems in meeting a set of very rigid specifications in the design of a meteorological satellite are discussed in the next two papers by George Keene and Richard Kent from Eastman Kodak. The satellite, in the GOES series, had requirements for five year life, 24 hour operation and passive cooling to 105K.

Session 2. SPACE APPLICATIONS

Chairman: Lt. Col. Robert Perry, U.S. Air Force Space Technology Center

Cooling of IR detectors in geostationary orbit is discussed by Keith Harvey of Eastman Kodak. System parameters included five year orbital lifetime and a 20 mW heat load from the detectors. Major challenges for the passive radiator are temperature sensitivity, contamination and moisture trap design. Conclusions showed that the radiator concept is acceptable although the design is sensitive to backside heat leaks.

In a paper on radiometric instrument calibration, C. L. Wyatt of Utah State University describes the methodology for achieving linearity over a wide dynamic range despite nonlinear inputs. Some systems provided five orders of magnitude response with good linearity. Questions from the audience about the use of neutral density filters, wire grids and an integrating sphere were covered most adequately.

J.R. Schott of Rochester Institute of Technology presents a radiance model that permits the simple computation of radiance reaching a sensor as a function of view angle. Synthetic target/background images were used to evaluate the model. The method allows for the simulation of thermal images of a target model under a wide variety of physical conditions.

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With advances in IR measurement devices for production testing and maintenance applications and the requirement for more complex measurements, a need for an automated approach is indicated. R. A. Buchwald of C.I. Ltd., Israel describes a computerized systems approach to IR spectroradiometry.

Results of an experiment using a high performance image tranducer for advanced IR image projection is described by S. T. Wu of Hughes Research Labs. An IR liquid crystal light valve (LCLV) was used for target simulations under a variety of conditions showing high spatial and thermal resolution over a wide dynamic range. A CRT was used as the input source and a blackbody as the projection beam.

Session 3. DETECTORS AND SENSORS

Chairman: H. Nakamura, The Aerospace Corporation

N. S. Kopeika of Ben Gurion University of Negev, Beer-Shiva Israel presents the results of gamma irradiation on photodiodes. The gamma irradiation produced changes in surface and bulk properties of UDT-05D photodiodes that resulted in improved quantum efficiency at visible wavelength, decreased dark current at very low reverse bias, decreased infrared response and decreased minority carrier lifetime. A model based on x-ray photo disposition or surface impurities was developed and found to be consistent with the measurements.

An investigation of 1/f noise characteristics of mercury cadmium telluride, platinum silicide, and indium antimonide is described by A. L. Vinson of the University of Arizona. The 1/f noise based only on tunneling and surface features was observed in all the samples tested. The magnitude of the noise per unit bandwidth was greatest for the Hg Cd Te and smallest for the Pt Si.

Y. Miyamoto of Fujitsu Laboratories Ltd. in Japan, discusses the breakdown in a narrow bandgap Hg Cd Te metal insulated semiconductor. The data show a peak in the measured surface potential vs gate-voltage characteristics which is considerably less than surface potential predicted by the tunneling theory. A model based on the assumption that shallow traps condense around a dislocation was developed and fitted to the data using the trap density as a variable. The model appears to explain the unexpected breakdown characteristics and predicts that dislocation density and carrier concentration should be lowered to realize improved detector performance.

A non-equilibrium mode of operation for semiconductor infrared photodetectors that will enable their cooling requirements to be substantially reduced is presented by T. Ashley of the Royal Signals and Radar Establishment in England. The phenomena of minority carrier exclusion and extraction are utilized in order to maintain the densities of both carrier types below the near intrinsic, equilibrium values associated with these elevated temperatures, with consequent improvements in responsivity. Large increases in responsivities were observed, but only marginal improvement in D* due to high levels of flicker noise. Work is continuing to reduce the flicker noise.

Chen Lixin of Shandong University in China discusses the optical and electrical properties of three kinds of indium oxide doped films deposited on quartz glass substrates. Both experimental and theoretical results are discussed.

Session 4. SCIENTIFIC APPLICATIONS

Chairman: Richard A. Mollicone, Analytic Decisions Inc.

John Jarem discusses two transmittance models for atmospheric N_2O. The work, done at the University of Texas El Paso, shows that the Double Exponential model produces good results, particularly in middle bands, both at high and low resolution. Its generalization, the Equivalent Absorption Coefficient model, produces good results at low resolution. The question not yet answered is whether the generalization will work for higher resolution applications.

A sun sensor (gas correlation radiometer) being developed by NASA Langley is described by L. E. Mauldin III. The array, a self-scanned, monolithic Si CCD, tracks both solar edges to ± 1/2 arc minutes during the occultation event. The device and technique employed are an improvement in the state of the art.

Timo Hyvarinen, from the Technical Research Center of Finland, presents a methodology for determining free water content and grain size of snow. Reflectance measurements are made using three optimal wavelengths. Accuracies of ± 1.5 volume % and ± 0.2 mm in size can be achieved without the use of physical samples.

Optical performance of the Space Infrared Telescope Facility (SIRTF) secondary mirror is discussed by Daniel Vukobratovich of the Optical Sciences Center, University of Arizona. There is no apparent deformation problem imparted by the chopping motion of this fused silica mirror if its thickness and support-point locations are chosen properly.

Paul Klocek of Texas Instruments, Inc. describes the fabrication of IR optical fibers for use in the 2 to 14 micron region. The chalcogenide glasses are the only family of materials that exhibit all the necessary material properties. Applications of tapered fiber bundles for thermal imaging or sensing systems are discussed, as are some of the numerous single fiber applications such as remotely located detectors, temperature sensors and low-loss communications.

The requirement for covering an entire optical aperture with large revolving filters can be eliminated by use of a spectrally selective shutter between the optics and focal plane. Edward Cross of The Aerospace Corporation discusses design and performance characteristics where fast repetitive shuttering is required. The shutter is independent of aperture size and creates no loss of image quality while greatly improving spectral performance.

Chen Lixin from Shandong University, China, authored two papers for this session. A discussion of sensibility equations for an infrared system when the target and surrounding bodies have almost the same temperature is published here. Dr. Yang, of SBRC, read a summary of Dr. Chen's second paper about an instrument design for simultaneous measurement of emissivity and real temperature, as opposed to radiation temperature which is usually measured.

Irving J. Spiro
The Aerospace Corporation
Richard A. Mollicone
Analytic Decisions, Inc.

INFRARED TECHNOLOGY XI

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Contents

INFRARED TECHNOLOGY XI

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Session 1

Infrared Imaging

Chairman
Irving J. Spiro
The Aerospace Corporation

The theoretical and experimental performance of a pyroelectric array imager

D E Burgess, P A Manning, R Watton

Royal Signals and Radar Establishment, St Andrews Road,
Malvern, Worcs., U.K.

Abstract

Pyroelectric detector arrays have the potential to satisfy a number of infrared sensing and imaging applications because of their attractive features of room temperature operation and low cost. They are most suited to operation at moderate frequencies, in the 10 to 100 Hz region, where they can have an NETD of less than 0.2°C, limited by internal detector noise sources.

An experimental imager built to evaluate linear pyroelectric arrays is described, and its performance compared with theoretical predictions.

Introduction

During recent years, two requirements for future IR systems have led to the growth of interest in uncooled thermal infrared detectors. These requirements are firstly the freedom from cryogenic cooling, important if the sensor is to be used for extended periods, and secondly the need for inexpensive technologies for very large numbers of expendable sensors. Pyroelectrics, the most widely used of the thermal detectors, have the first of these attributes, room temperature operation. linear pyroelectric arrays in particular have the other, low cost, since simple wire bonding techniques can be used to couple signals from the detectors into adjacent silicon readout circuitry.

Linear detector arrays are particularly suited to those applications where there is relative motion between the sensor head containing the detector array and the object to be imaged. Examples are intruder alarms, where movement in the scene must be sensed, and push broom line scan, where an aircraft platform pans the sensor head in a continuous motion over the scene.

Pyroelectric linear arrays of up to 64 elements are now available, and when mounted with good thermal isolation from their package they have a D^* of up to 10^8 cm $Hz^{1/2}W^{-1}$ in the 8 to 14 micron waveband at a few 10's of Hz readout rate[1]. Translated into temperature sensitivity, this corresponds to a small fraction of a degree NETD with f/1 optics. Performance above about 100 Hz falls with increasing sampling frequency, but the high sensitivity decade from 10 to 100 Hz is just that range required for the intruder alarm and line scan applications mentioned above.

An imager has been built at RSRE to evaluate the performance of pyroelectric linear detector arrays. The detectors have been coupled only to minimal readout electronics in order to maintain their low cost attribute, and to facilitate future integration in miniature sensor heads. The imager is shown schematically in figure 1. On the object side of the detector is an infrared lens and a focal plane chopper, synchronised to the detector readout. Since pyroelectric detectors respond only to changes in radiation, this chopper is required to enable stationary scenes to be observed. The detector is followed by low noise buffers and a multiplexer, an image difference processor to subtract the shuttered reference signal from the scene signal, and a scan converter which outputs a TV signal to a display. The whole is mounted on a pan and tilt head to produce two dimensional imagery of laboratory scenes.

Theoretical imager performance

The performance of an imager using a pyroelectric detector is determined firstly by the pyroelectric detector material and its thermal structure, secondly by the noise properties of the detector and the readout electronics.

Linear pyroelectric detector arrays are made by bonding a wafer of pyroelectric ceramic, typically 30 microns thick, to a substrate. In order to minimise thermal radiation spreading between adjacent elements, the pyroelectric material is reticulated to produce thermally isolated islands separated by grooves, as shown in figure 2. In order to minimise the thermal loading of the detector by the substrate, the detector to substrate thermal conductance, g, is kept to a minimum.

Because of the sandwich structure shown, the thermal analysis and hence the responsivity calculations are complicated. For radiation modulated at a few hundred hertz and above the thermal energy does not penetrate beyond the pyroelectric layer, leading to a high frequency response which falls with frequency. Figure 3 shows a typical responsivity plot for a lead zirconate ceramic array with 200 micron square elements, 30 microns thick. At low frequencies the responsivity flattens to approach a constant level determined by the total thermal resistance of the sandwich structure.

The pyroelectric detector elements are wire bonded to the readout electronics by way of tracks on the base substrate. The first stage transistors are chosen for their low noise properties across the frequency band of interest. The present small arrays use discrete JFETS; for longer arrays an IC is being designed. There are several noise sources, shown in figure 4, which dominate in different frequency bands. Below about 10 Hz electronic noise in the form of shot noise on the JFET leakage current is the major contributor. Electronic noise again dominates at high frequencies, above 1 kHz, in the form of JFET voltage noise. At intermediate frequencies the dielectric loss noise of the pyroelectric will compete and may become the dominant term.

For any particular chopper rate, filtering bandwidth and multiplexing scheme, each noise source has to be integrated over the effective sampling bandwidth to determine its effect. The noise equivalent temperature difference (NETD) can then be calculated by dividing the summed integrated noise terms by the signal generated at the same point in the circuit for a 1°C modulation in the scene temperature.

Imager electronics design

The electronics have been designed to ease future integration into miniature sensor heads. In particular it was not thought appropriate to provide each detector with a noise-limiting filter, consequently the multiplexing process results in the aliasing of high frequency noise into the baseband.

A schematic of the electronics is shown in figure 5. An alternating voltage is produced by each detector element proportional to the difference in temperature between the scene and the rotating chopper. Due to the small amplitude of these signals (typically 1 μV/°C in the scene) aqnd the large offsets (typically 2 volts) caused by the leakage currents of the JFETs generating voltages across the high resistance detectors, even 12 bit analogue to digital conversion prior to digital image processing is inadequate to give detector noise limited performance. Accordingly, the signals are AC coupled after the JFETs to remove DC offsets. The multiplexed signal is then amplified, band limited and digitised to 12 bits accuracy.

The digital signals with the chopper closed are subtracted from those with the chopper open. The result is normalised to 8 bits, removing any DC signals caused by a chopper to scene temperature difference then written to a digital scan converter which outputs a TV signal to a display.

Results

Table 1 presents results of signal response, measured NETD and predicted NETD based on the known detector and silicon parameters for three values of chopper frequency. The agreement between theory and experiment is seen to be excellent, confirming the validity of the theoretical analysis.

Table 1. Theoretical and Experimental Results

Chopper frequency, Hz	20	30	50
Response, volts	0.16	0.10	0.07
Measured NETD, °C	0.07	0.12	0.16
Theoretical NETD, °C	0.067	0.11	0.16

sample of imagery produced by the prototype sensor fitted with a 64 element pyroelectric array is shown in figure 6. This image was taken with a 50mm f/1 lens and a chopper frequency of 50 Hz.

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Conclusion

Linear pyroelectric infrared detector arrays have the desirable attributes of room temperature operation and low cost which are required for future IR systems. A 64 element array has been demonstrated in a prototype sensor head which maintains the low cost ideal by minimising the electronics component count. A theoretical analysis of the signal from the detector and the detector and electronics noise has led to predictions of NETD which have been confirmed by measurements. The way is now clear for the successful introduction of these systems into more general use.

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Reference

1. Watton, Ainger, Porter, Pedder, Gooding. Technologies and performance for linear and two dimensional pyroelectric arrays. 28th SPIE Conf. Optics & Electro-Optics, 1984.

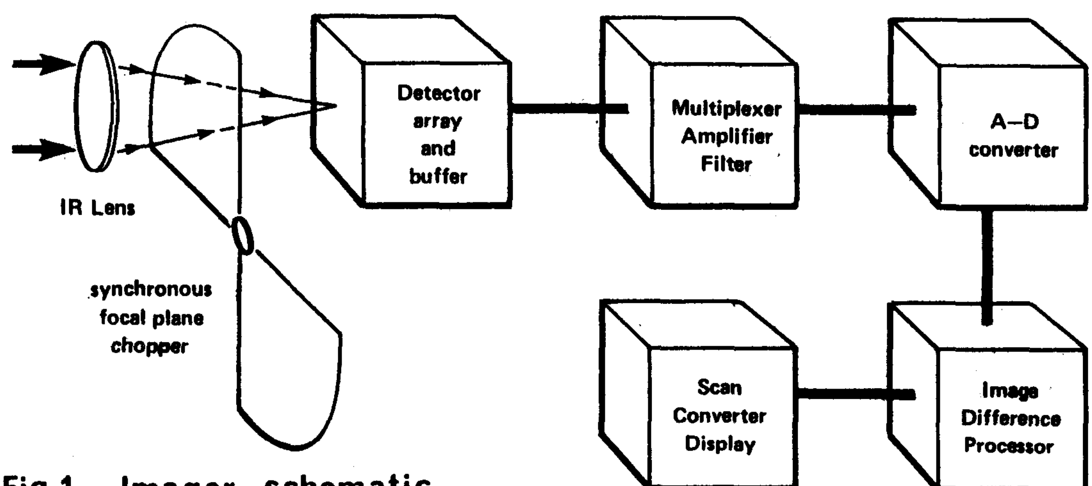

Fig.1 Imager schematic

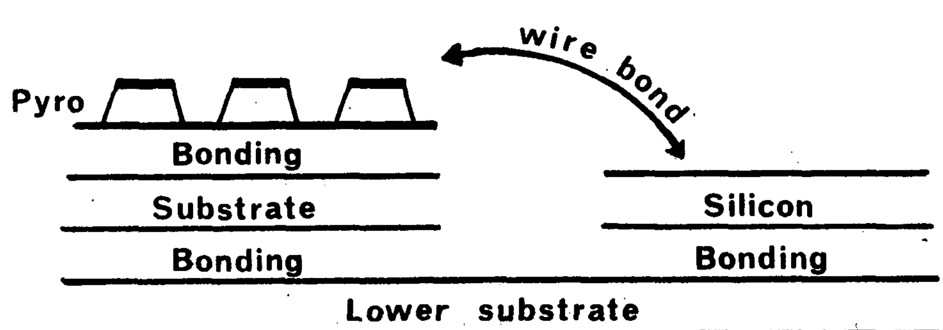

Fig. 2 Detector, substrate and silicon

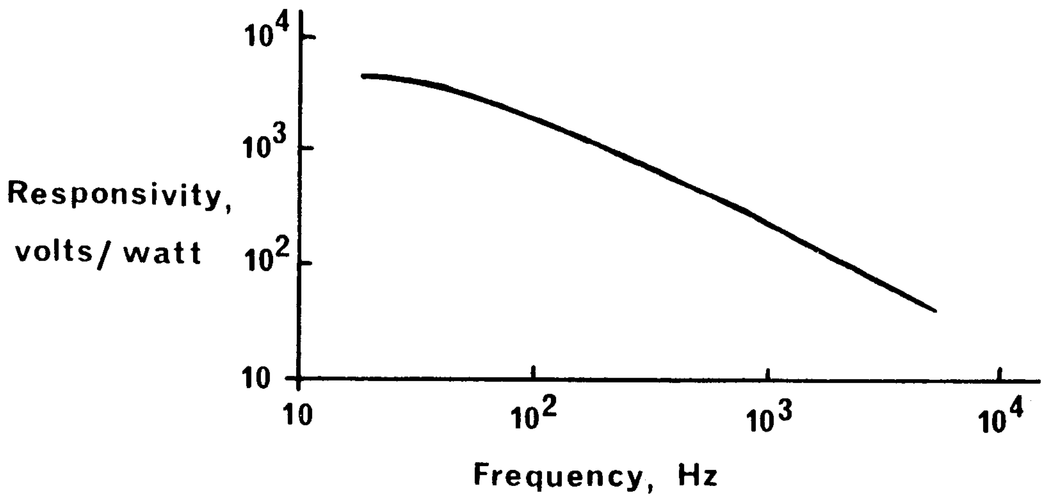

Fig. 3 Responsivity plot

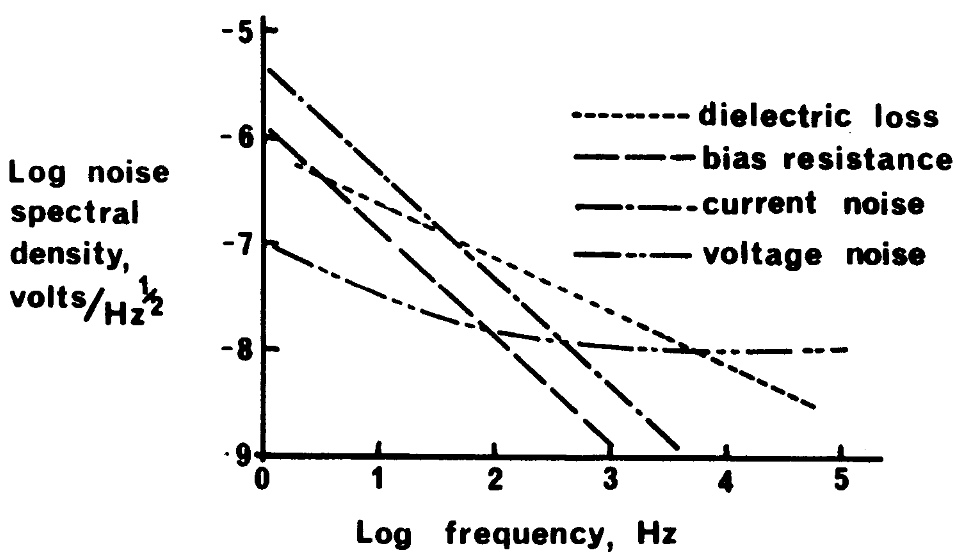

Fig. 4 Noise sources

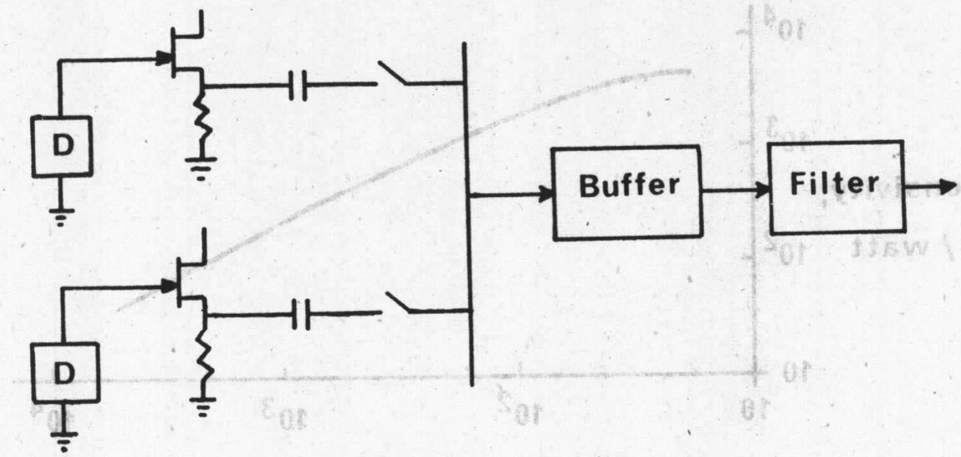

Fig. 5 Front end electronics

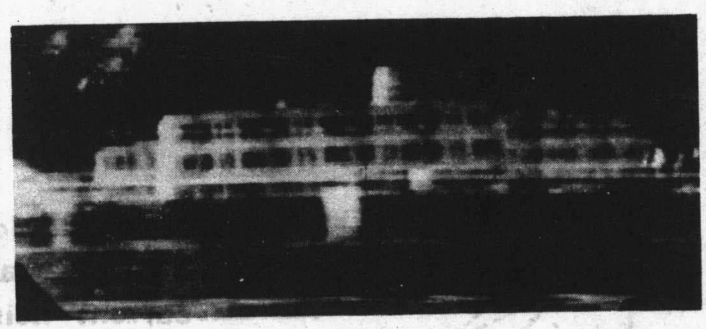

Fig. 6 Sample imagery

Improved Schottky array performance with lenticulated faceplate

Gary D. Wiemokly, Edward F. Cross, and Irving J. Spiro

Aerophysics Laboratory, The Aerospace Corporation
P.O. Box 92957, Los Angeles, California 90009

Abstract

Laboratory evaluation is provided of the improved focal plane array performance realized with a novel optical technique that increases the fill factor of Schottky IRCCD mosaics. Specifically, a lenticulated silicon faceplate is installed on the IRCCD chip to redirect focused image irradiance away from nonsensitive areas in the focal plane and to the infrared-sensitive elements. A technique has been developed for successfully fabricating these optical faceplates with the necessary geometrical requirements.

The performance data contained herein were obtained with an RCA-supplied 32 × 63 Schottky IRCCD mosaic having a lenticulated faceplate installed on a portion of the array surface. The adjacent dual construction allowed sensitivity and resolution differences to be easily evaluated under identical operating conditions. The enhanced performance was determined experimentally and then compared to predicted fill-factor improvement.

Introduction

Focal plane staring arrays consisting of Schottky barrier infrared detectors and 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 column (or directly connected to the detector using "bump-bond" technology).[1] Although this type of image sensor has high response uniformity, large dynamic range, and excellent survivability characteristics, the quantum efficency and density of sensing elements are lower than realizable from other staring mosaics.

In late 1982, E.F. Cross et al.[2] of The Aerospace Corporation described an optical technique to improve focal plane staring array performance by increasing the mosaic fill-factor ratio. Typical state-of-the-art fill factors, not considering recent developments in bump-bond technology, have ranged from 17% to 39%, depending on the area required for the CCD register readout.[3,4] As seen in Figure 1, a large percentage of array "real estate" is occupied by the CCDs placed in vertical columns beside the sensitive detector areas. All the necessary design criteria for an optical lens array fitted on top of the detector mosaic were described in the aforementioned S.P.I.E. paper. The columns of

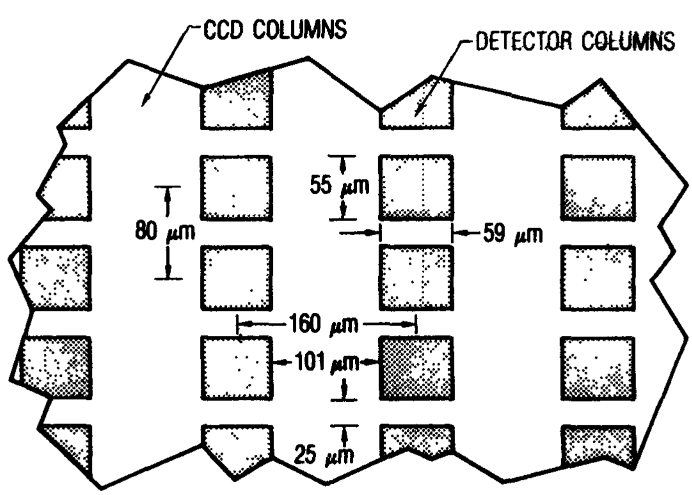

Figure 1. Elemental dimensions for 32 × 63 Schottky IRCCD mosaic.

cylindrical lenticulation focus light rays away from CCD areas and onto detector surfaces, as seen in the ray traces of Figure 2. A complete array and faceplate configuration is diagrammed in Figure 3.

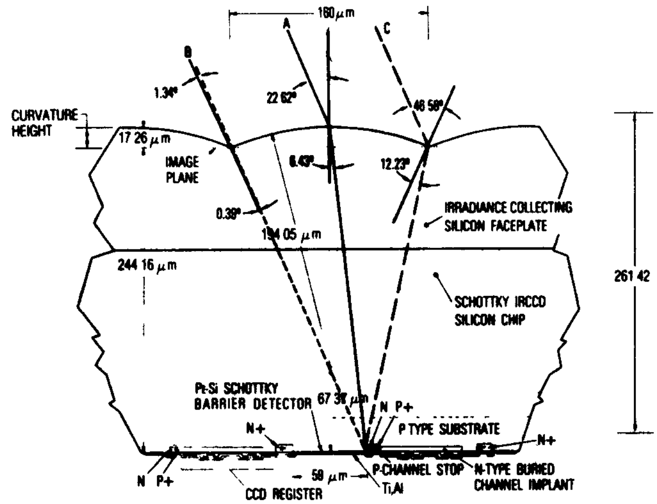

Figure 2. Ray trace diagram for IRCCD mosaic with lenticulated faceplate.

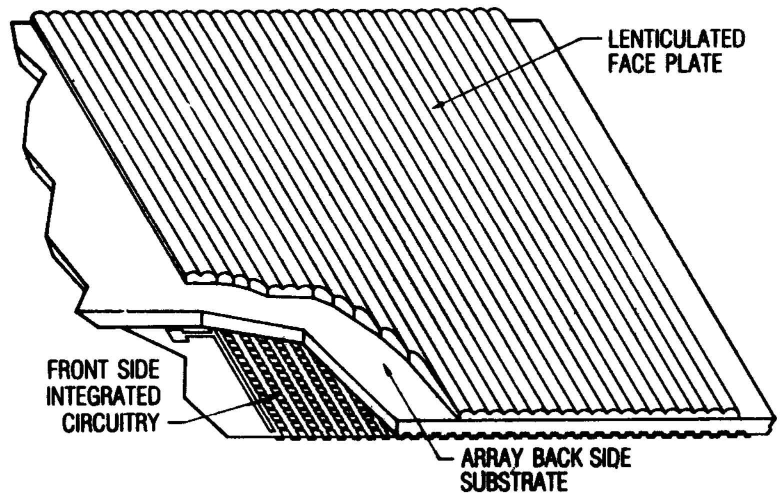

Figure 3. Schottky IRCCD mosaic with lenticulated faceplate.

At the 1984 San Diego S.P.I.E symposium, RCA Princeton Laboratories presented a paper that showed an initial glimpse of the performance improvement created by an IRCCD array with a lenticulated faceplate.[5] In 1983, RCA used a company-proprietary etching process to fabricate the lenticulated geometry onto the silicon faceplate. Although an elaborate evaluation was not conducted at that time, typical sensitivity improvements reported were greater than two.

In the latter part of 1984, The Aerospace Corporation obtained from RCA a 32 × 63 IRCCD Schottky barrier mosaic array with partial lenticulation (see Figure 4), along with the electrical IRCCD camera hardware from RADC, to evaluate this new retina assembly. This array (TC-1247) has 55 × 59-μm detectors with approximately 25.4% area efficiency (fill factor). The geometry has a theoretical maximum fill factor, with lenticulation, of 68.8% (a sensitivity improvement of 2.7 times). The RADC camera electronics included camera head readouts as well as an image post-processing system that used pixel-by-pixel background-averaged image subtraction to remove detector nonuniformities.[6] Although this

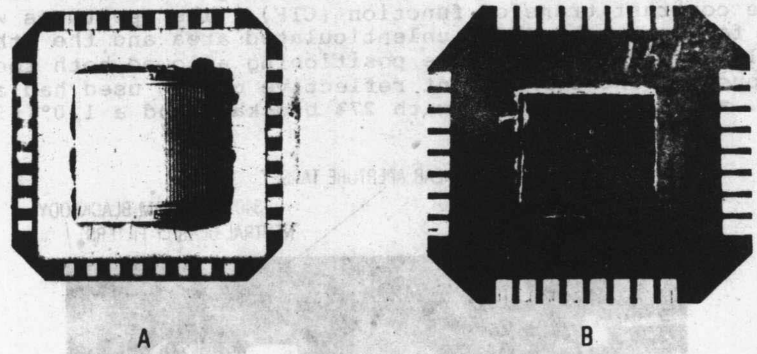

Figure 4. Photograph of 32 × 63 Schottky barrier IRCCD array with partial lenticulation. (a) Front (electronic circuit) side. (b) Back (illumination) side.

equipment represents an early experimental design, it proved very useful in evaluating camera sensitivity and resolution changes caused by the additional lenticulated faceplate.

Faceplate design and fabrication

Briefly, the special faceplate has a one-dimensional, scalloped lens array etched into silicon. Two primary parameters of faceplate design are faceplate thickness and arc radius. The initial theoretical design calculations given in the past article[2] were carried out for an f/1.2 optical system having a cone of image irradiance extending over ±22.6°; the optical rays that would otherwise fall on the CCD area are refracted by the faceplate onto the detector surfaces, as seen in Figure 2. Paths of the extreme rays shown here are used as criteria for optimizing dimensions of radius and thickness. On this basis, the faceplate plus array thickness and the radius of the lenticulated surfaces measure 261.4 and 194.1 μm for f/1.2 optics, respectively; theoretical curvature height is 17.26 μm. This f/1.2 lenticulation design will provide the same improved responsivity for slower optics but with less-restrictive tolerances. To effect the anticipated increase in threshold sensitivity, all surfaces should be antireflection coated. The optimum design configuration would be achieved by etching the lenticulated geometry directly onto the IRCCD back-substrate surface.

The lens faceplate is fabricated on a 3-in. silicon wafer by means of a single photography step and an RCA-proprietary three-step etching process.[7] A portion of the wafer is then cut to size and used for the faceplate. During this process the lenticulated profile is monitored so that it replicates theoretical characteristics to within 0.5 μm; an iterative profiling system of processing and measurement is continued until the exact profile is achieved. In actuality, the typical lens surface resembles an ellipse having a curvature height between 9.5 and 11.75 μm and a lens radius of approximately 380 μm. Faceplate thickness is typically 100 μm, which gives an overall faceplate plus device thickness of 480 μm. This overall dimension limits best performance to f/2.7.

The faceplate is attached to the back-side of the IRCCD substrate with an epoxy/particle mixture. Epoxy bonding does not transmit well in the infrared and can be severely stressed from thermal cycling. To attach the faceplate, RCA applied an epoxy mixed with particles of submicron size to maintain a uniform air gap and to eliminate material stress. Optimally, a monolithic fabrication process to increase optical performance is preferred over this hybrid technique.

The faceplate is aligned with the IRCCD array by viewing the silhouette of the front-side metal detector reflectors and the CCD metal bus lines under illumination from an infrared source. These silhouettes are then imaged through the substrate and onto the lenticular surface. Horizontal alignment is established when the shadow of the detector's reflective metal surface falls in the center of the lens arc. Vertical detector orientation is obtained by viewing bus line shadows.

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