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Integrated Focal Plane Array Programs by DARPA

July 1980

D. Patz

R. McDaniel

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July 1980

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Deputy Director
Tactical Technology Office

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(U) The technology of four differing approaches to the development of integrated, staring focal plane arrays operating in the ~~IR~~ infrared regime for application on a small tactical missile are reviewed. Monolithic and hybrid architectures are included with both CCD and CID charge transfer processors. Arrays of both intrinsic and extrinsic detector materials are included. The relative merits of these design choices are presented. Each of four designs is shown to provide potentially satisfactory performance with the selection of a preferred design dependent on the outcome of field tests scheduled for late 1980.

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ATTACHMENTS

INTEGRATED FOCAL PLANE ARRAY PROGRAMS BY DARPA

Only a few years ago, staring focal plane arrays (FPAs) in the infrared were considered beyond the state of the art (p. 199, R.J. Keyes). However, because of the progress in focal plane technology and the promise of a mechanically simpler seeker, the Defense Advanced Research Projects Agency (DARPA) has recently undertaken a program, Tank Breaker, which utilizes staring FPAs.

This article describes the emerging technology of integrated staring FPAs under DARPA sponsorship. DARPA functions as an agency of the Secretary of Defense and his research staff reporting directly to the USDRE and has a broad mandate to pursue technology in all disciplines that could add to the effectiveness of our defense capability or insure against technological surprise by a potential enemy. It is located in Arlington, Virginia, a suburb of Washington, D.C. DARPA maintains no independent laboratories but, instead, relies on the technological expertise of industry, universities, and laboratories operated by the Army, Navy, and Air Force and other government agencies. It maintains a small technical staff of knowledgeable specialists, each preeminent in his field of expertise. Its annual research budget is about $500 million. DARPA operates with streamlined administrative procedures that permit rapid response to new technical opportunities.

Integrated staring FPA technology is an example of how DARPA can perceive a technical opportunity that requires basic research, initiate programs to develop the technology, and then demonstrate one or more applications for use by the military services. In this instance, the technology is aimed at new operational capabilities not available with current technology.

It has been well publicized that FPAs with processing on the focal plane are providing new capabilities in high altitude and space surveillance under the Teal Ruby and HI-CAMP programs. It is less well known that this technology will also offer a lower-cost, more effective alternative to tactical thermal imaging weapons sights than current systems using conventional common module technology.

Although staring FPAs are certain to see application on many strategic and tactical systems, the small size, light weight, and low cost potential of these arrays provides a particularly significant opportunity for manportable antitank guided missile systems. The need for a highly effective manportable guided missile to attack tanks and other battlefield targets has been recognized by DARPA, the Army, and the Marine Corps for a number of years. During the early 1970s, DARPA developed the technology of laser beam-rider guidance for lightweight missiles as part of a program designated ATAADS (Antitank Air Defense System). Feasibility of the concept was successfully demonstrated and the technology was transitioned to the U.S. Army Missile Command at Huntsville, Alabama for further development and application. The potential of FPAs to provide a fire-and-forget battlefield missile was perceived, and a program to demonstrate the technology of a missile seeker employing this potential was initiated with contracts to Hughes Aircraft Company and Rockwell International.

As this technology successfully progressed from milestone to milestone, an urgency for a more effective antitank missile system developed. These milestones included field demonstrations of high quality imagery involving tactical target scenes. New developments in armor technology available to the Soviets severely jeopardized the effectiveness of the available antitank systems. DARPA scientists quickly turned to the fire-and-forget seeker concepts under development for a solution to the advanced armor problem. The FPA seekers have a high frame rate (∿ 60 Hz) that can accommodate the scene change resulting from the missile's approach to the target at high velocity. This accommodation is essential to the tracking function. It was found that this high frame rate could also accommodate the target scene change when the target was maneuvering or turning during the missile's flight. This feature would permit a missile that was launched against a tank's frontal view to fly a lofted trajectory up and pitch down at the end so as to strike the tank on the top if an appropriate guidance and control concept could be devised. If implemented on a lightweight man-portable missile, it could kill even advanced tanks, since tanks are much more vulnerable to munitions striking them on top.

Finally, a guidance and control mechanization evolved that could be implemented with modest gimbal angles, and it would allow the missile to strike tanks on the top while flying a relatively shallow trajectory. Missile system designs quickly followed and are being pursued on contract to Hughes Aircraft Company, Rockwell International, Texas Instruments, Inc., and McDonnell Douglas Astronautics Company under a development program called Tank Breaker. Each of these four contractors is proceeding with unique design features for their missile, including the FPA-based seekers. Each is developing its own seeker except McDonnell Douglas. The FPA and associated seeker (except for the target tracker) for the McDonnell Douglas Tank Breaker missile is being developed by RCA. One or two of these contractors will be selected early next year for demonstration of a full missile system concept by guided firings. The design selection criteria for the guided missile demonstration phase will emphasize design refinement and technology demonstration efforts, including captive flight tests of missile seekers incorporating FPAs. Since this program addresses a serious operational deficiency and could lead to very large production runs, the four participants in this initial phase are proceeding in a highly competitive environment.

STARING ARRAYS

The possibility of using two-dimensional FPAs in a non-scanned i.e., staring mode is very attractive from the standpoint of system simplicity and size. A staring focal plane would eliminate many of the disadvantages associated with scanned systems. Some of the advantages of staring systems are: (1) mechanical scanners are not needed; (2) sensitivity is increased due to the ability to select long integration times and to the absence of scan inefficiency; and (3) integration times are easily varied. A photograph of a 32 x 32 element hybrid staring FPA mounted on a cold finger is shown in Figure 1. (Individual elements are invisible to the eye when viewed from this side of the array).

There are, however, stressing requirements associated with staring arrays such as: (1) better detector response uniformity or compensation for array nonuniformities, (2) a relatively large number of detectors (required for full resolution in both dimensions), and (3) accommodation of the very large background signal levels that arise with long integration times. To a large extent, staring arrays will require the replacement of mechanical/optical complexity with additional electronic processing complexity. If processing techniques can be developed that are both effective and economical, staring operation will be highly desirable for many applications.

Spatial response uniformity requirements are more stressing for a staring, as compared to a scanning, seeker with time delay and integration (TDI) processing because, in the latter system, the response of the detectors within a row are averaged. Hence, the response variation from row to row is reduced by the square root of the number of detectors in a row, if the response variations are random over the FPA.

ARRAY RESPONSE UNIFORMITY

The requirement for array response uniformity when viewing an object in a 300°K background scene is stringent; less than 0.5 percent rms response variation to achieve a noise equivalent ΔT of 0.10°K, a nominal contrast requirement. This uniformity not only establishes requirements for the material uniformity but also for the dimensional tolerances of the pixels. An array of 50 μm x 50 μm elements with a spatially uniform response would require an rms dimensional tolerance of 0.25 μm. With recent advances, devices have been able to achieve this response uniformity directly or indirectly through the use of electronic processing to compensate for detector response nonuniformities. Even at this level of uniformity, the quality of the image is limited by the fixed-pattern noise due to the small variations in responsivity. Thus, further improvements in response uniformities would produce realizable gains.

Uniform Detectors

The Schottky barrier, depicted in Figure 2, consists of a silicon substrate and a platinum-silicide surface layer in which photo-excitation occurs. Photo-excited carriers that have energy greater than the metal-semiconductor potential difference (ϕ_{ms}) are emitted from the metal into the semiconductor where they become majority carriers. Since the emission process is virtually independent of the semiconductor doping and minority carrier lifetime, much better response uniformity can be attained than with other detector types. Schottky devices with a rms response variation of less than 0.5 percent have been demonstrated.

Electronic Compensation

Another approach to achieve the required response uniformity is through the use of electronic compensation. Figure 3 depicts the uncompensated output from each of the 1024 detector elements of a Hughes Santa Barbara Research Center/Carlsbad Research Center 32 x 32 FPA when viewing a 25°C uniform scene. The need for response compensation can be easily seen in this figure.

Figure 4 demonstrates the effectiveness of dc offset compensation while still viewing a 25°C uniform scene. FPA dc offset nonuniformities were reduced by factors of up to 13; however, compensating for dc offsets at a single temperature is not sufficient as can be seen in Figure 5. This figure shows the array output with 25°C dc offset compensation when viewing a 45°C uniform scene. When gain (responsivity) compensation is also included, the array output is as shown in Figure 6. The gain compensation factors were calculated from the measurements made when the seeker successively viewed the two different uniform scene temperatures (25°C and 45°C).

The reduction in nonuniformities between Figures 5 and 6, although not as dramatically apparent as with dc compensation because of the relatively uniform gain of the array, is required for best quality imagery and tracker performance. Most of the elements have responsivity variations within ± 2%, necessitating nonuniformity reduction factors of up to 6. Remaining uncompensated elements shown in Figure 6 are below the compensation threshhold and will be corrected using defective cell logic.

CHARGE TRANSFER DEVICES

The large number of detector elements of a staring FPA necessitates some form of signal processing to reduce the number of signal lines to a manageable level. Reducing the number of leads also reduces the thermal load on these cooled devices. Both charge coupled devices (CCDs) and charge injection devices (CIDs) can accomplish this goal.

Charge capacity was a limitation of earlier charge transfer devices. Photons from surrounding objects in the FPA's field of view would cause the device to quickly saturate. Since both the background and the target are at nearly the same temperature, the infrared detectors that are sensitive to the target are also sensitive to the background. This is analogous to trying to discern with the naked eye regions of the sun which vary by a degree or so.

One technique for suppressing the background is that proposed by Rockwell for the Tank Breaker program. Rockwell's CCD utilizes two forms of background suppression: background skimming and charge partitioning. The operational sequence of this unit cell is depicted in Figure 7. The integrated charge is stored under gate S. This gate is divided into two areas by a second partition gate (P). P is on during charge integration, but is turned off to subdivide the charge into two packets, depending on the storage areas on each side of gate, at the end of an integration time. The transfer gate is then turned on to a level to provide background skimming, i.e., pass a small fraction of the partitioned charge to the CCD multiplexer. The unit cell is on 68 μm centers with a 4.5:1 gain reduction from partitioning. With background skimming, this will provide a total background reduction of about 15-20, sufficient to achieve an integration time of 8 ms with a 4.0 μm cutoff and F/2 optics. This assumes that the CCD well is capable of holding about 5 x 10^6 charges. A 64 x 64 multiplexer has been fabricated and is yielding working arrays with charge transfer efficiencies as high as 0.9995. Functioning of the input cell is currently under test.

Whereas the CCDs must transfer charge sequentially, the CID has the capability of random access. Since each row and column can be individually controlled, the integration time and duty cycle can be adjusted so that the generated charge does not exceed the storage capability. This row/column addressing results in highly-flexible control but would result in a large number of leads from the dewar/cryostat to the tracker unless the lead requirement is reduced by some technique such as multiplexing.

Texas Instruments' CID configuration is shown in Figure 8. The read cell is completely surrounded by a storage cell. The device cross-section and operation are also depicted in Figure 9.

During the integration period, the photon generated charge is collected in the potential well established by the read column. At the end of the desired integration period, the address row is turned off, which causes the charge to be collected in the read column potential well. The voltage of the read column is stored on an external clamp-sample-and-hold circuit; an injection pulse is capacitively applied to the read column, which collapses the read well; and the charge in the addressed elements is injected into the substrate. In the unaddressed rows, the row potential is set to maintain a potential well beneath those electrodes and the collected charge simply transfers laterally beneath the row, then transfers back to the read column when the inject pulse is applied. Subsequently, the voltage of the read columns is again sensed for comparison with the stored clamp voltage. The difference in voltages is proportional to the injected charge.

FPA INTERCONNECTIONS

Charge transfer devices (CTDs) and detector arrays can be fabricated either on a common substrate (monolithic) or separately and then connected (hybrid). The hybrid technique allows the detection and processing chips to be independently optimized whereas the monolithic approach has the advantage of not having to solve the mechanical/electrical interconnect problem.

Hybrid fabrication is a two step process. Typically, indium columns are first electroplated on both the multiplexer and detector array. Then the two die are aligned, face to face, with the aid of an IR microscope viewing through the silicon multiplexer. The die are then electrically and physically mated to form a hybrid using a pressure/heat cycle. (See Figures 10 and 11.)

Interconnect yield for 32 x 32 hybrids on 100 μm centers is normally over 99 percent, and thus not a significant yield loss factor. Mechanical and thermal testing of hybrids show that they withstand repeated thermal cycling, as well as shock and vibration levels expected for field use.

Four FPA Approaches

The baseline approaches on the Tank Breaker program utilize one of four different detector materials, either monolithic or hybrid structures, either CCD or CID processing, and either the 3-5 μm or 8-10 μm infrared atmospheric transmission windows. Table 1 lists the approaches that are being pursued.

Table 1. BASELINE FOCAL PLANE APPROACHES ON THE DARPA/MICOM TANK BREAKER PROGRAM

Company	Wave Band	Detector Material	Processing	Structure	Array	Detector Spacing
Hughes	3-5μm	InSb	CCD	Hybrid	62x58	76x76 μm
McDonnell Douglas (RCA)	3-5μm	Pt:Si	CCD	Monolithic	64x128	60x120 μm
Rockwell	3-5μm	InAsSb/GaSb	CCD	Hybrid	64x64	68x68 μm
Texas Instruments	8-10μm	(Hg,Cd)Te	CID	Monolithic	64x64	50x50 μm

HUGHES FPA

The FPA is a 62 x 58 element backside-illuminated indium antimonide (InSb) mosaic detector array hybridized with a CCD-readout signal processor chip using indium bump "flip chip" assembly as shown in Figure 11. This FPA is an evolution of the advanced fire-and-forget 32 x 32 FPA. The CCD is a direct injection signal processor chip with a 3 x 3 mil unit cell size.

In the basic approach of backside illuminated InSb, diode detectors are interconnected to the silicon CCD by means of plated indium pads or bumps. The incoming radiation strikes the backside of the InSb surface, with the InSb thinned such that the back surface is within a diffusion length of the diode depletion layer. Since the detector interconnect does not obscure the active detector area, very high filling factors are possible. The detector element size is 3 x 3 mils. Hybridization techniques and CCD fabrication technology are directly applicable to hybrid HgCdTe FPAs currently under development at Hughes.

Nonuniformity Compensator. A nonuniformity compensator is used to minimize the effects of FPA fixed-pattern noise and compensates for defective elements or cells. The compensator provides real time dc offset compensation and gain compensation for each cell.

McDONNELL DOUGLAS/RCA FPA

McDonnell Douglas has selected a monolithic silicon Schottky barrier (Si-SB) FPA that has been under development at RCA Laboratories since 1972 for their proposed seeker concept. This development was initially sponsored by the Air Force Rome Air Development Center with continuing support provided by DARPA. Significant technical progress in array and camera performance was achieved during 1979, and highly successful demonstrations and performance tests have been made at RCA and the government laboratories since August of 1979.

The basic construction of the Schottky barrier IR CCD FPA is shown in Figures 12 and 13. IR radiation is passed through the silicon substrates and received by the Schottky diodes (white squares of Figure 12). Interline column CCD registers are used to receive charge from the diodes and to shift information one-line-at-a-time into a horizontal shift register for serial readout. This parallel-to-serial on-chip multiplexing provides a high photon collection efficiency, no mechanical scanning, and a minimum number of off-chip electrical connections.

Monolithic silicon construction employs well-understood precesses for both Schottky diode and CCD fabrication. Furthermore, due to the excellent array uniformity inherent to Schottky barrier detectors, spatial uniformity data processing is not needed. The photoemissive photodetection process ensures high speed, high MTF (modulation transfer function), and very low hot-spot bloom. The 25 x 50 Schottky barrier array shown in Figure 12 has been used for development and demonstration of the technology. Improved versions currently under development at RCA will be available for the Tank Breaker seeker development, i.e., a 32 x 64 array and a 64 x 128 array in late 1980. A summary of these three arrays is given in Table 2.

Table 2. SILICON SCHOTTKY BARRIER FPAs

Array	Pixel center-to-center spacing (µm)	Schottky cell size (µm)	Total array size (mm)
25 x 25	82 x 163	47 x 47	4.1 x 4.1
32 x 64	82 x 163	55 x 59	5.2 x 5.2
64 x 128	60 x 120	40 x 50	7.7 x 7.7

ROCKWELL INTERNATIONAL FPA

Rockwell proposes a 64 x 64 element backside-illuminated epitaxial InAsSb/GaSb hybrid FPA as the baseline structure for the advanced FPA. A schematic of this hybrid FPA is shown in Figure 10. The hybrid FPA consists of three components: a 64 x 64 InAsSb/GaSb photovoltaic detector array, a corresponding CCD area multiplexer, and electro-plated indium columns which electronically and mechanically connect the detector array to the Si CCD multiplexer. In operation, the infrared scene radiation is incident on the GaSb substrate, which is transparent to photons with wavelengths longer than 1.6 µm. Infrared photons will be absorbed in the InAsSb epitaxial layer which has a cut-off wavelength of 3.95 µm at 77°K. The electrons generated by the absorbed photons will be collected by the planar p-n junction arrays formed in the InAsSb epitaxial layer by Be ion implantation. The resulting photocurrent from each detector element is injected into the Si CCD via the individual indium interconnects. The CCD input cell for each detector performs a background suppression function to reduce background flux and to enhance CCD dynamic range (described earlier).

InAsSb Detector Technology

InAsSb/GaSb detector arrays are fabricated in a fully planar process on an epitaxial layer of InAsSb about 7 μm thick, which is grown on a transparent GaSb substrate by liquid phase epitaxy. Diodes are then fabricated by selective implantation of Be followed by an anneal to activate the Be. The process is completed by chemical vapor deposition of SiO_2:N, a metal field plate (guard ring) over the p-n junction, and metallization of the contact areas. The electro-optical characteristics of these diodes are summarized in Table 3.

Table 3. InAsSb DETECTOR SUMMARY (77°K)

Feature	Performance
Detector Impedance (R_oA)	$>10^5$ Ω-cm² for >90% $>10^7$ Ωcm² for select detectors
1/f noise knee	<2 Hz
Quantum efficiency (η)	≳80%, 1 σ = 3%
Cutoff wavelength (λ_c)	3.95μ; 1 σ < 0.02 μm

During the last two years, emphasis has been placed on establishing a well-defined repeatable processing sequence for InAsSb that will yield detectors that are fully passivated and have high yield. Detectors have been routinely baked at 105°C, stored in vacuum for long periods of time, and repeatedly thermal cycled with no evidence of degradation. Growth and processing yield has been greatly improved; the highest yielding InAsSb wafer was processed this fall. Nineteen of the 25 die on this wafer were functional, and typically 95 percent or more of the 100 elements that were probed had RA products greater than 5×10^8 Ω-cm².

TEXAS INSTRUMENTS FPA

Texas Instruments' focal plane is a 64 x 64 monolithic HgCdTe array sensitive to 8- to 10-μm radiation utilizing a CID. Figure 14 shows the design of a 32 x 32 CID presently produced by Texas Instruments. This design is similar to that planned for the Tank Breaker focal plane. (Initially, a 32 x 32 FPA will be utilized.)

The CID shown in Figure 14 is a two-dimensional matrix of cells with 32-column sense lines. Separate preamplifiers sense the 32 elements in each column by measuring changes in potential caused by the signal charge on the column electrode. The 32-row address lines are pulsed to select which of the elements within the column are to be sensed during any particular read cycle. Cell centers are 50 μm in both directions. One-half the column output connections are at the top of the array, the other half at the bottom. Likewise, one-half the row address electrodes are on either side to facilitate bonding to the auxiliary processors.

Figure 8 is a schematic of the cell design. The central read column surrounded by the semitransparent electrode offers several advantages: (1) aliasing is decreased because of the larger sampling window; (2) edge field effects are decreased because of a total voltage drop that occurs across two regions; (3) high transfer efficiency is attained because of radial transfer; (4) crosstalk between elements is reduced because injection occurs at the cell center; and (5) high focal-plane coverage is achieved. Present designs provide a 1.6 mil^2 semitransparent area and 0.93 mil^2 column (read) well out of the 4.0 mil^2 total area. Insulator thicknesses are adjusted to achieve equal storage capacity under both regions. This device design has proved extremely successful in 3- to 5-μm 32 x 32 HgCdTe CIDs.

Uncorrected response was uniform within 10 percent over the array area and background-limited detectivities have been shown to be feasible. These devices have been integrated with two silicon 16-channel integrated circuits onto a focal plane for evaluation in a staring IR imaging seeker, and initial rooftop testing has provided excellent imagery. This technology is being extended to 10-μm focal planes and will result in 32 x 32, 8- to 10-μm arrays. This is a particularly challenging undertaking; however, progress has been excellent. Storage times already demonstrated in 10-μm material are adequate to provide seeker sensitivity within a factor of 2 of baseline requirements. The challenge occurs because of the narrow bandgap ($E_g = 0.12$ eV) necessary for detection of this radiation. The onset of band-to-band tunnelling (when the bands overlap as the surface potential is increased) limits the storage capacity of these devices. The high flux levels and required storage times, on the other hand, require a large storage capacity ($N \approx 10^{-7}$ C/cm^2). The 32 x 32 array with this cell design is expected to be used in Phase I of the Tank Breaker program with extension of 64 x 64 elements in Phase II.

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Dr. James A. Tegnelia is currently Deputy Director, Tactical Technology Office within the Defense Advanced Research Projects Agency (DARPA), and is responsible for a wide range of developments related to tactical warfare. He has a special interest in advanced seekers and sensors operating in the millimeter wave and IR spectrums. Prior to his assignment to DARPA, Dr. Tegnelia served at the Army's Night Vision and Electro-optics Laboratory where he played a key part in advancing thermal night vision systems into operational status. As Captain in Vietnam, he earned the Bronze Star Medal while gaining firsthand field experience on the employment of night vision systems. Dr. Tegnelia received his Ph.D in physics from Catholic University.

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LIST OF FIGURES

(PHOTO PROVIDED)

Figure 1. 32 x 32 element backside-illuminated epitaxial InAsSb/GaSb hybrid FPA mounted on a dewar cold finger. (Courtesy of Rockwell International.)

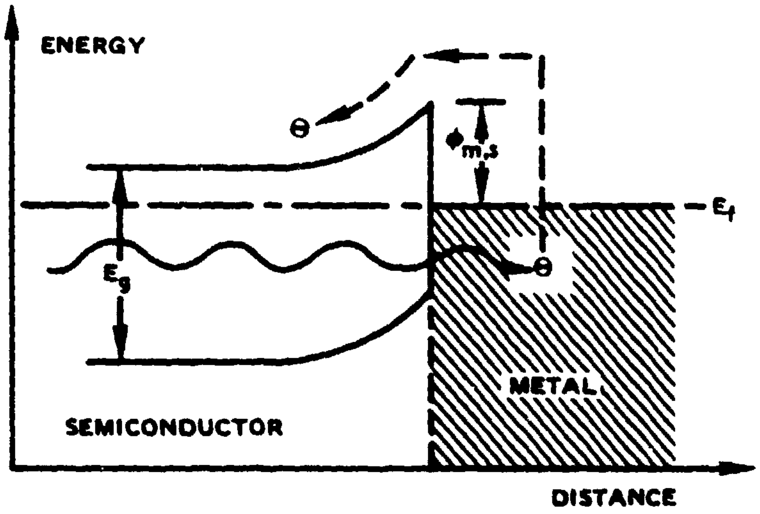


FIGURE 2. UNCLASSIFIED
BAND DIAGRAM OF SCHOTTKY-
BARRIER DETECTOR

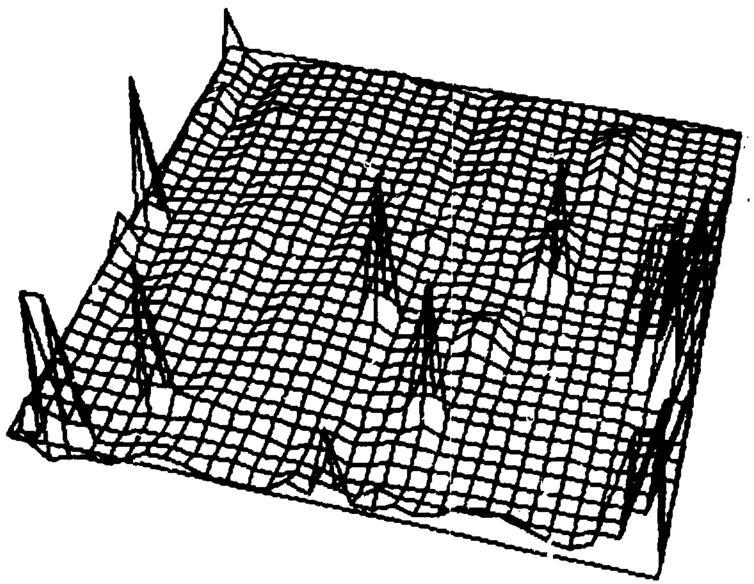


Figure 3. Uncompensated Output When Viewing a 25^0C Uniform Scene. (Courtesy of Hughes Aircraft Company)

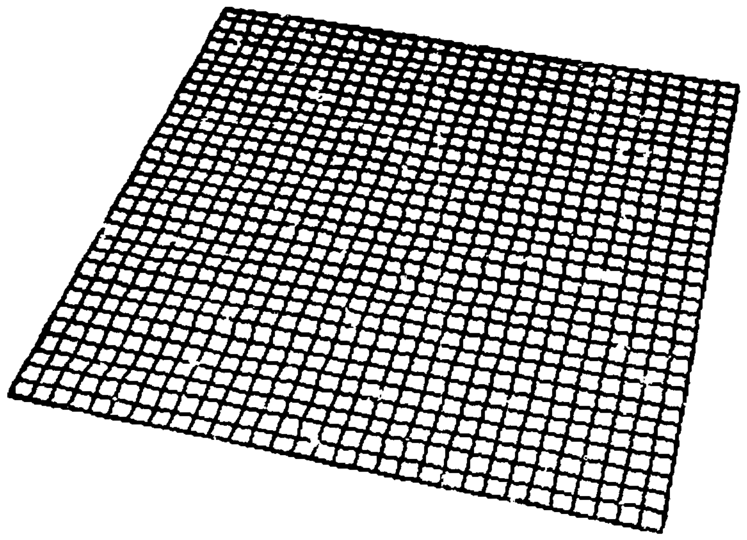


Figure 4. DC Compensated Output When Viewing a 25°C Uniform Scene. (DC compensation dramatically improved the uniformity at the compensated temperature.) (Courtesy of Hughes Aircraft Company)

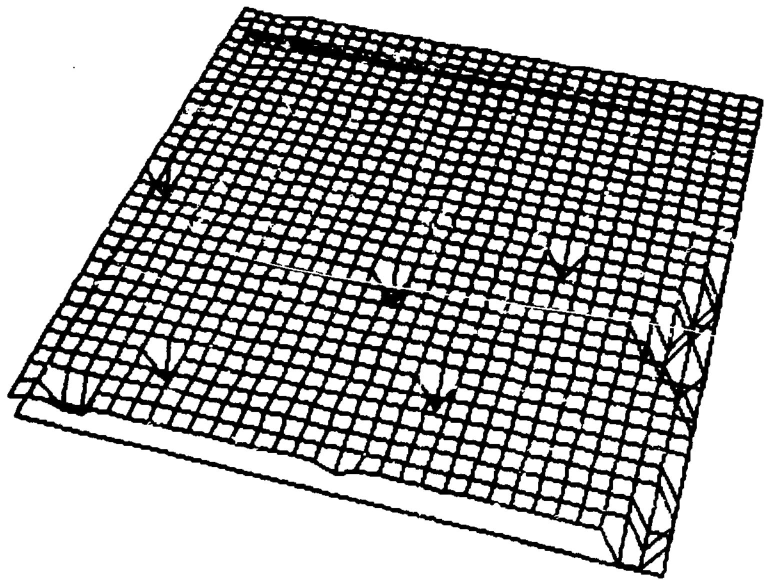


Figure 5. DC Compensated Output When Viewing a 45°C Uniform Scene. (The nonuniform gain results in decreased uniformity.) (Courtesy of Hughes Aircraft Company)

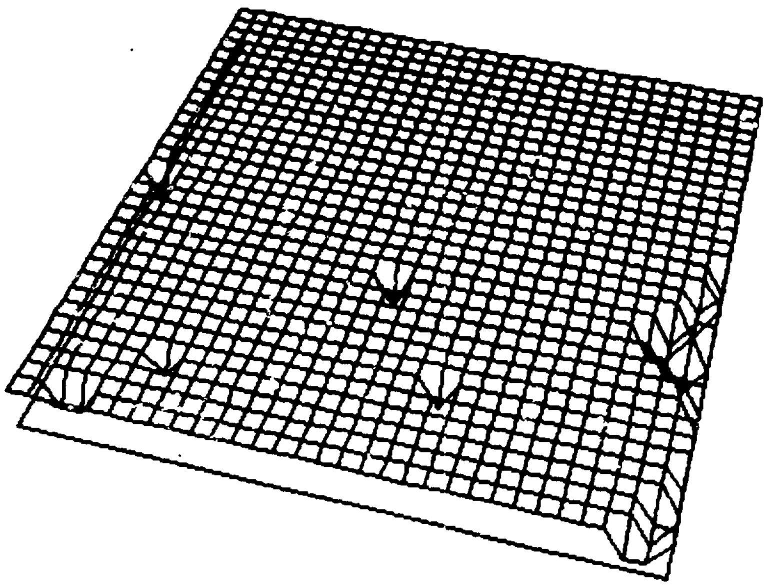


Figure 6. DC and Gain (Responsivity) Compensated Output When Viewing a 45°C Uniform Scene. (Gain compensation is necessary for best quality imagery and tracker performance. Defective cell logic will compensate cells below compensation thresholds((not shown)). (Courtesy of Hughes Aircraft Company)

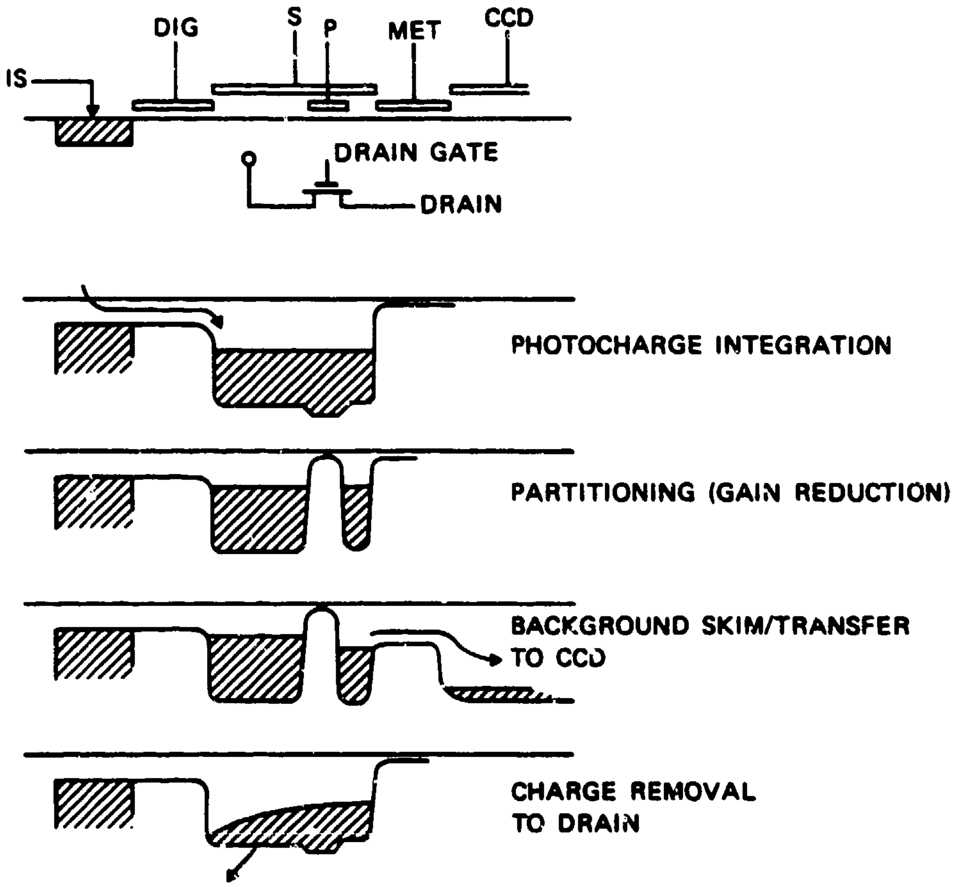


FIGURE 7. UNCLASSIFIED
CHARGE PARTITIONER GAIN REDUCER SCHEMATIC AND OPERATIONAL SEQUENCE

(Courtesy of Rockwell International Corp.)

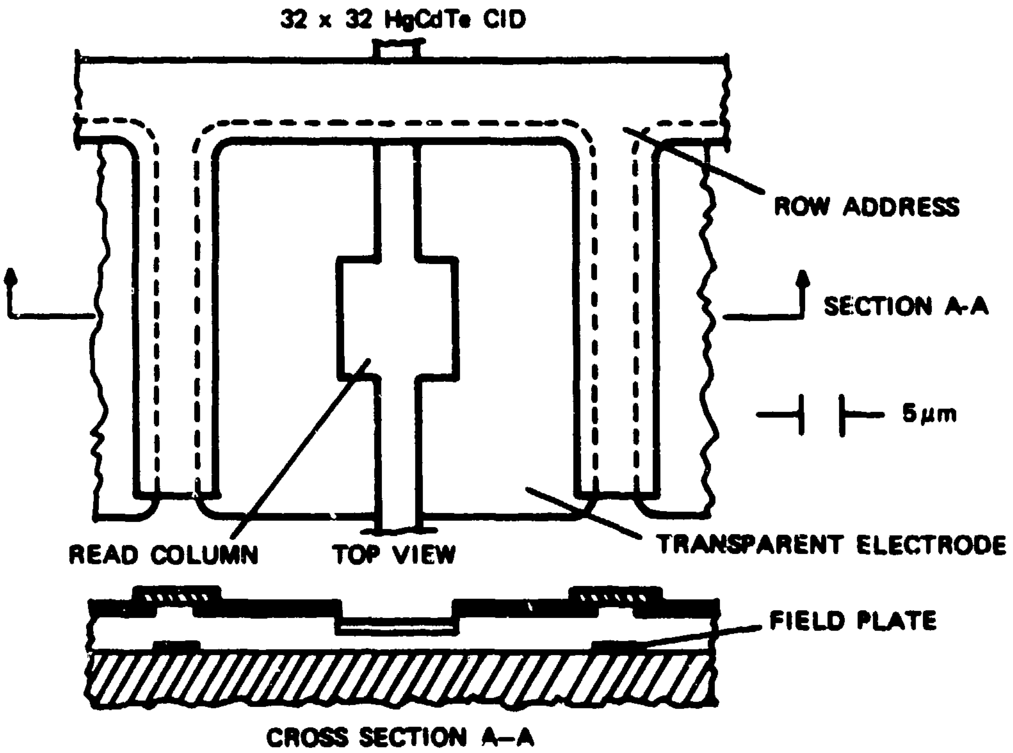


FIGURE 8. UNCLASSIFIED
(U) MONOLITHIC HgCdTe CELL DETAIL

(Courtesy of Texas Instruments, Inc.)

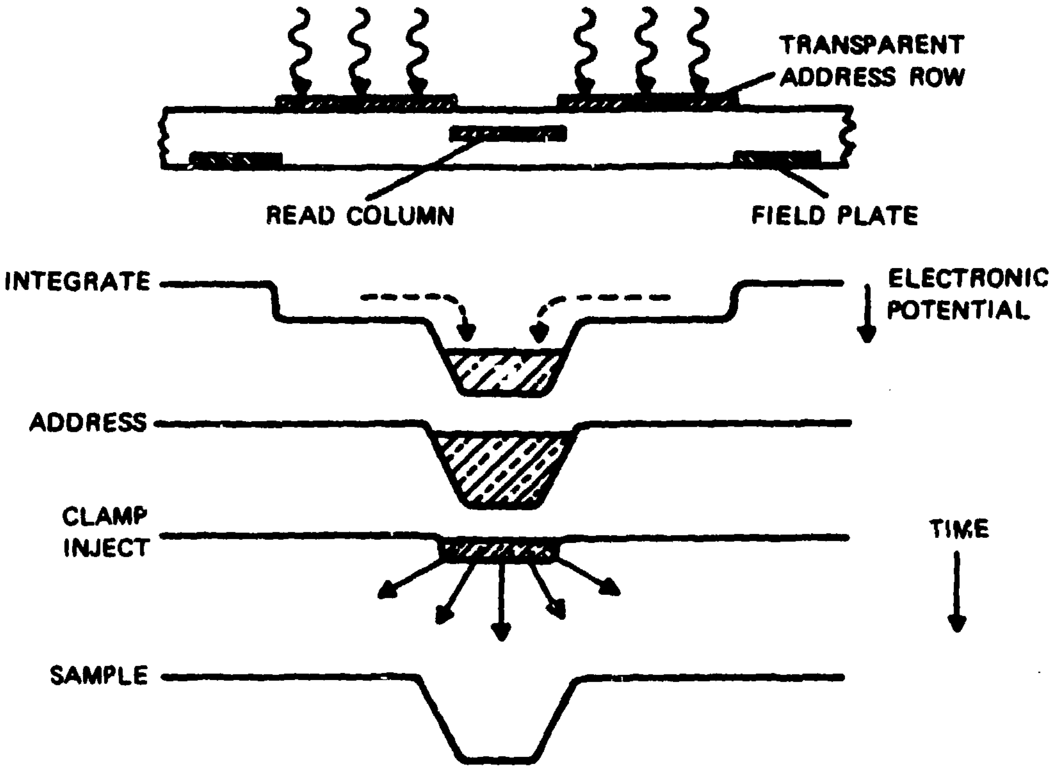
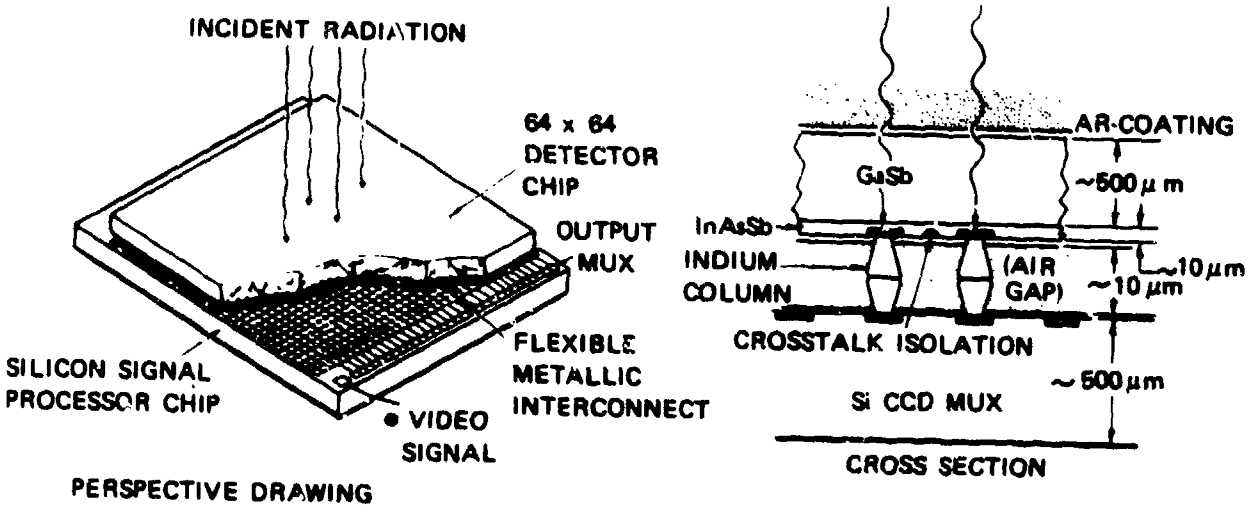


FIGURE 9 UNCLASSIFIED
(U) HgCdTe CID CLOCK SEQUENCE



PERSPECTIVE DRAWING

CROSS SECTION

FIGURE 10 UNCLASSIFIED
(U) A BACKSIDE-ILLUMINATED EPITAXIAL InAsSb/GaSb HYBRID FOCAL PLANE ARRAY (ROCKWELL INTERNATIONAL CORP.)

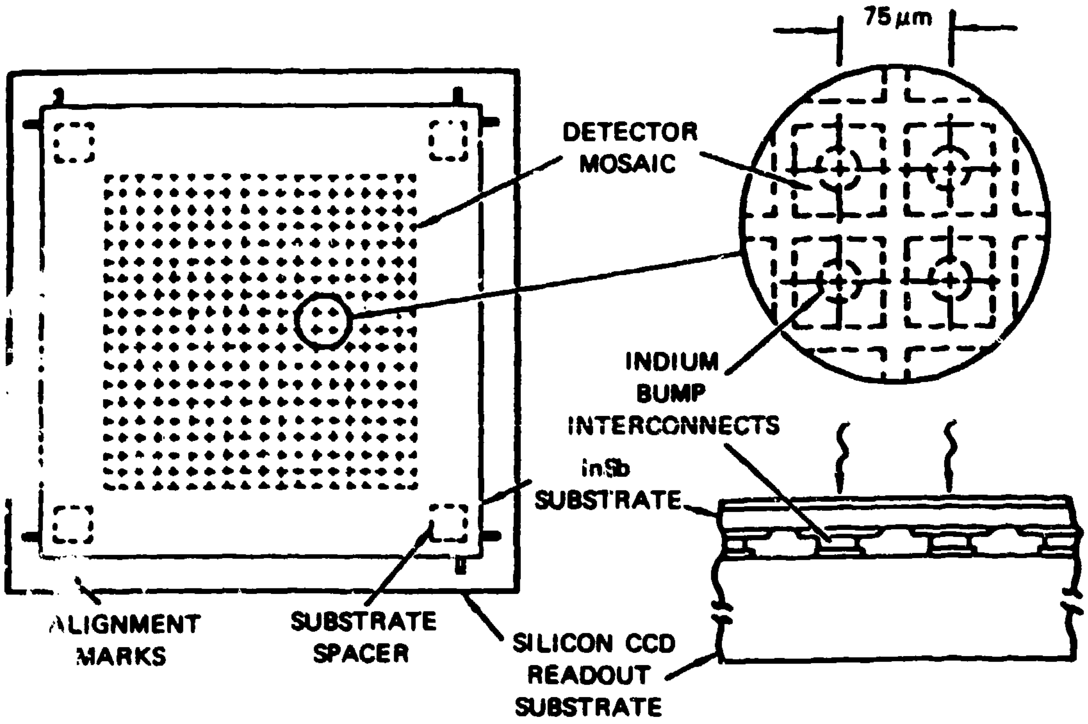


FIGURE 11 UNCLASSIFIED
(U) BACKSIDE-ILLUMINATED InSb FOCAL PLANE ARRAY

(PHOTO PROVIDED)

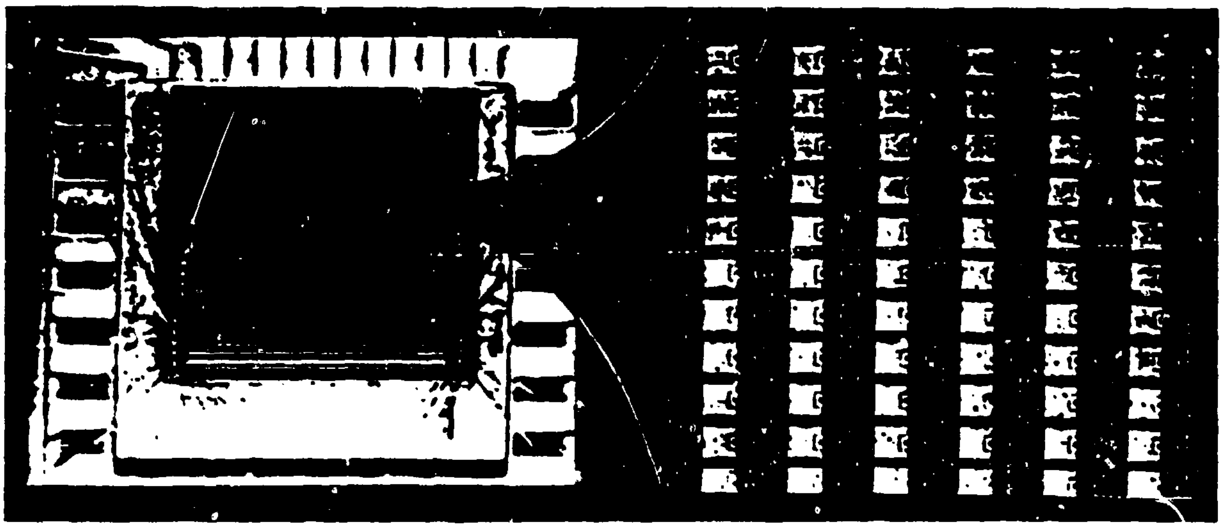


Figure 12. 25 x 50 Schottky Barrier Array. (Courtesy of RCA)

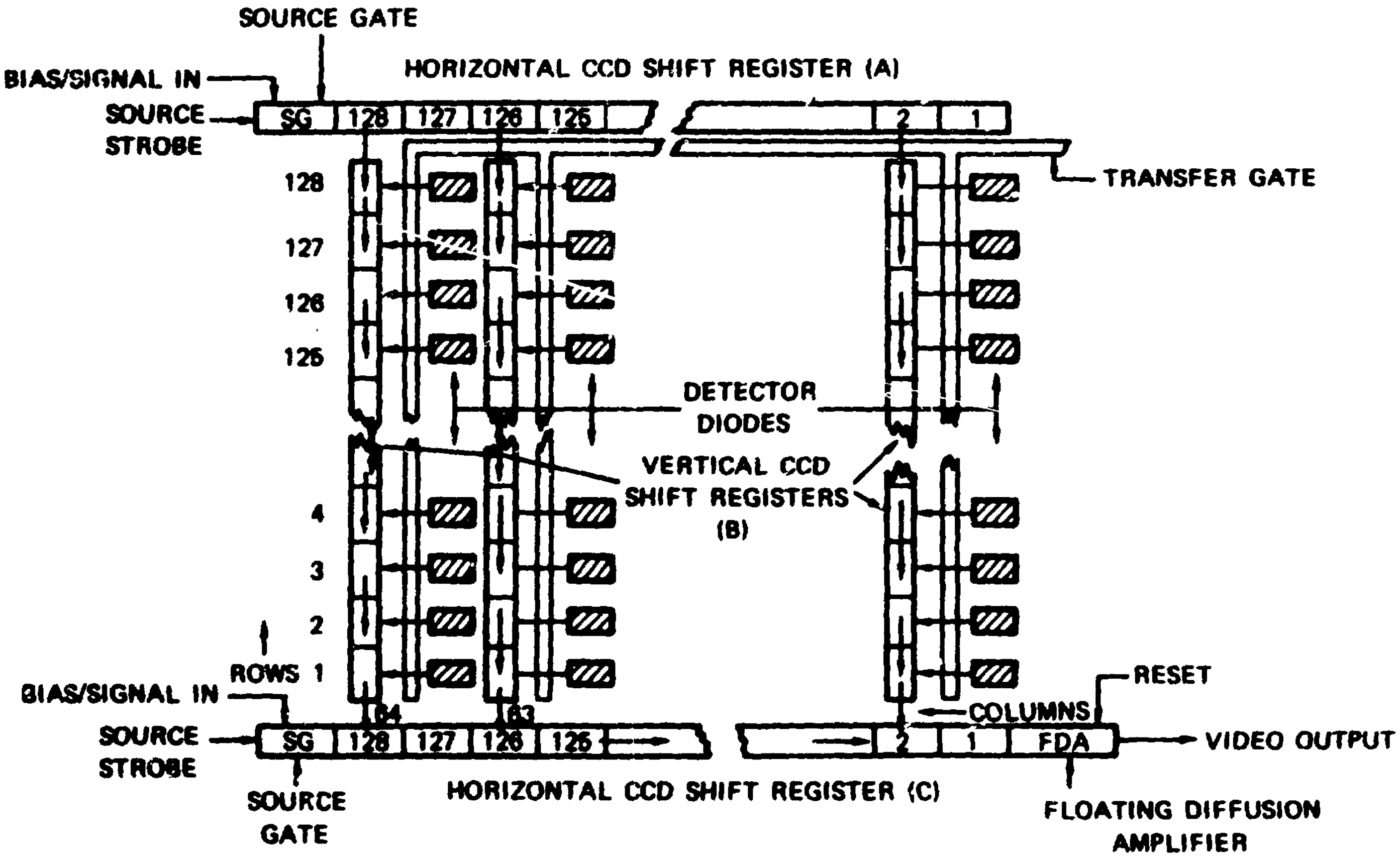


FIGURE 13 UNCLASSIFIED
(U) SILICON-SCHOTTKY BARRIER CCD ARRAY

(COLOR PHOTO PROVIDED)

Figure 14. Photomicrograph of Monolithic HgCdTe 32 x 32 Element CID. (Courtesy of Texas Instruments, Inc.)