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Abstract

An overview of integrated infrared (IR) array technology is presented. Although the array pixel formats are smaller, and the readout noise of IR arrays is larger, than the corresponding values achieved with optical charge-coupled-device silicon technology, substantial progress is being made in IR technology. Both existing IR arrays and those being developed are described. Examples of astronomical images are given which illustrate the potential of integrated IR arrays for scientific investigations.

Introduction

Recent advances in microelectronics technology have made possible the development of multiple-element arrays of infrared (IR) detectors. Although these arrays are much smaller than the optical arrays which preceeded them (and which are the primary focus of this workshop), IR arrays have reached a significant level of sophistication, and have already produced some substantial scientific results.

A brief outline of the terminology and technology of IR arrays will be given in this paper. It is assumed that the reader is familiar with optical charge-coupled-device (CCD) array concepts and technology, so emphasis will be placed on the unique aspects of IR-arrays. The material presented here is drawn primarily from the work of companies and investigators in the United States, although there are now important IR array evaluation and utilization projects under way in Europe and elsewhere in the world.

Infrared Array Concepts and Terminology

Infrared-detector arrays have evolved through a synthesis of discrete IR-detector technology and the CCD multiplexer schemes developed for optical

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arrays. Termed integrated arrays (since the detection and readout/multiplexing functions are performed in a integral package), these devices can in principle use a wide variety of intrinsic and extrinsic IR-sensitive detector materials (Fig. 1). The intrinsic materials such as InSb and HgCdTe are generally used in photovoltaic detectors; the extrinisic materials such as Si:Ga and Si:As are used in the form of photoconductors or photocapacitors. The crystal growth, material purity, and contacting techniques of discrete IR detectors have become quite advanced, and it is common for both discrete IR detectors and the detector elements of integrated arrays to perform in nearly ideal fashions.[1] The limitations to sensitivity are commonly imposed by the readout, which in the IR has been accomplished with a number of approaches, including CCD, charge-injection device (CID), and switched field-effect-transistor (FET-) multiplexers.

The early IR CCD arrays were produced in monolithic designs, with the detection and readout performed in a common (usually silicon) substrate. This
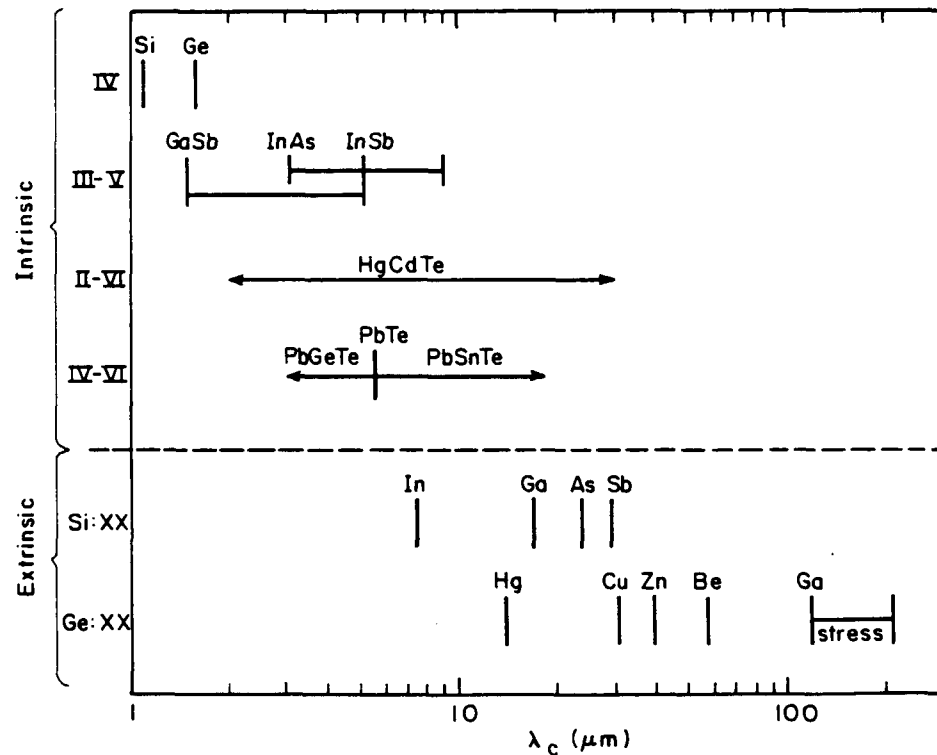

Fig. 1   Long-wavelength cutoff of various intrinsic and extrinsic IR detector materials.

monolithic approach proved to be only partially successful, since the processing steps required by the multiplexer circuit produced low responsivity in the adjacent detector region of the substrate. Monolithic IR array technology has been superseded by hybrid techniques, wherein two separate substrates are used (Fig. 2). By designing and processing the detector and multiplexer substrates separately and "bump-bonding" them together, optimum performance can be obtained from each. The indium bump technology is now well established, and interconnect yields of 100% for 32-x-32-element hybrid arrays are not uncommon.

The size of integrated IR arrays is determined by the maximum wafer dimension of uniformly doped, perfectly crystalline semiconductor material, and the design rules (i.e., minimum trace dimensions) for the transistors on the companion multiplexer chip. The latter constraint generally limits array pixel sizes to ≥ 50 μm. Infrared arrays with 64-x-64-element format are now common,[2,3] and 128-x-128-element devices are in the active laboratory-development stage.

As just mentioned, the first multiplexed readouts for IR arrays were CCDs. Since many IR detectors must be cooled to low (<20 K) temperatures, the surface-channel CCD structure must be used to avoid carrier freeze-out effects in silicon. Although CCD arrays offer large well capacities and good frequency response, they suffer from relatively high read-noise levels (~1000 e⁻).
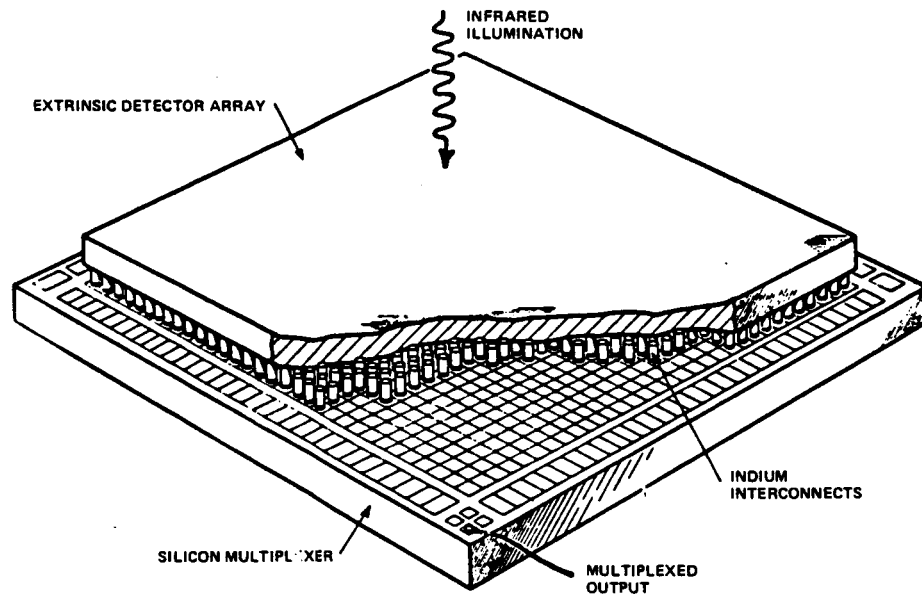

Fig. 2 Hybrid IR detector array.

Accumulation-mode CID readouts were developed around a simpler (detector-substrate/oxide-layer/metal-gate) structure, and read noises in the 100-200 e⁻ range have been achieved. They suffer from higher capacitance, since all elements in a row are connected in parallel, and charge-trapping in CIDs has been found to limit their sensitivity under low-flux conditions.[4]

At present, switched-FET multiplexers are used for best sensitivity. In this device, each unit cell of the array includes an individual charge-integration and reset circuit, which typically involves 3-5 metal-oxide semiconductor field effect transistors (MOSFETs) behind each detector element. Figure 3 illustrates a common switched-FET [or direct-readout (DRO)] circuit. As with the other two types of multiplexers, a correlated-double-sampling technique is used to read out the array. Photocurrent and leakage accumulate on the gate of the sense MOSFET, and the correlated-double-sampled signal is proportional to the difference of the voltage samples taken just before and just after the reset pulse.[5] The DRO arrays have achieved readout noises in the ~100-e⁻ range, and provide the ability to randomly access and nondestructively read the elements in the array. This technology is now the baseline for the
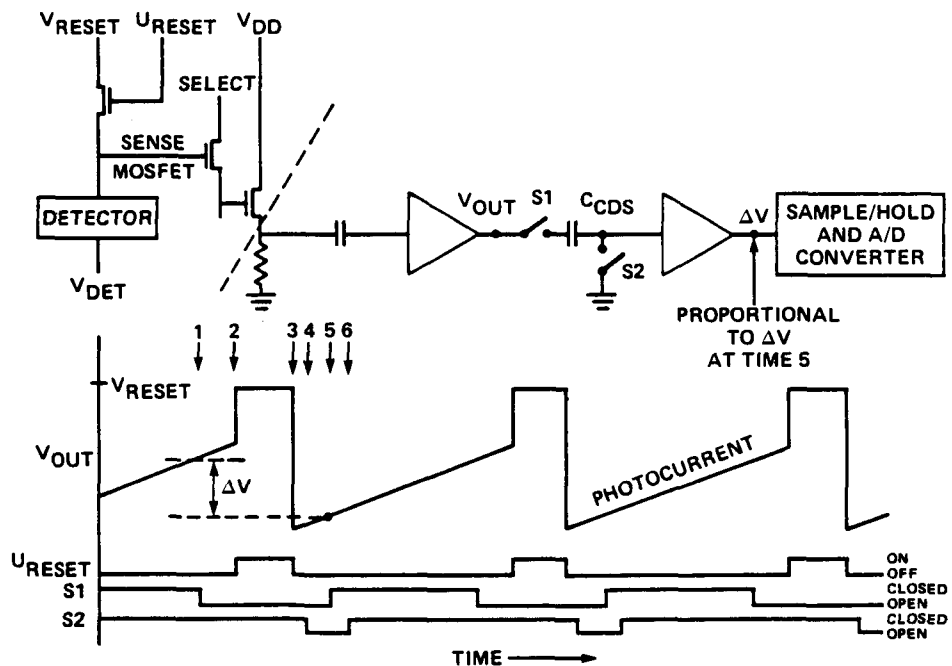

Fig. 3 Switched-FET multiplexer and correlated-double-sampling electronics. The "delta-reset" sampling scheme is shown, with the signal proportional to the difference between voltage samples 1 and 5.

integrated-array focal planes in the Space Infrared Telescope Facility (SIRTF).[6]

Integrated IR arrays typically have properties which make them useful astronomically. The uniformity of responsivity is commonly 2-5%, and crosstalk is generally <5%. The linearity of IR arrays has been found to be very good; for example, departures of less than 1% from linear have been reported for a HgCdTe array.[7]

The use of integrated IR arrays in ground-based observing, particularly near 10 μm, requires highly sophisticated, computer-based data-acquisition and control systems. The large IR photon arrival rates require that the arrays be read out at many hundreds of frames per second, which places challenging requirements on the drive-and-read electronics. Also, one must develop efficient means to correct (e.g., flat-field), organize, and archive data from a large number of frames, and to produce "quick-look" images or spectra to guide the course of the observation.[8]

Examples of IR Arrays

1. 32-×-32 InSb CCD

W. Forrest and J. Pipher (University of Rochester) have used a 32-×-32-element IR array from Santa Barbara Research Center (SBRC) for laboratory and observational testing. The device, with 90-μm pixels and a four-phase CCD multiplexer, has a quantum efficiency of 60-65%, a well capacity of 10^7 e^-, and a read noise of ~1400 e^-. Its surface-channel CCD is operable down to ~45 K, at which point the dark current is about 0.1 fA (1000 e^-/s).[9] This device has been used in a camera instrument at a variety of telescopes with great success.[10,11] An example of the imagery obtained is illustrated in Figs. 4 and 5. This array has been proven to have a lower noise equivalent power (NEP) than the best discrete-detector InSb instrument presently in use. A limiting sensitivity of +20.9 magnitude/pixel (1σ) has been achieved in a 1-hr integration at 2.2 μm, with a bandpass of 0.23 μm.[9] A 58-×-62-element DRO InSb array is currently under development at SBRC for the next phase of this project.

2. 16-×-16 Si:Bi CID

We have found the Si:Bi accumulation-mode CID array technology from Aerojet ElectroSystems Company to have a quantum efficiency of ~20% and read noise in the 100-300-e^- range.[4] Charge-trapping limits the applicability of these devices under low-background conditions, but a 16-×-16-element CID array (150-μm
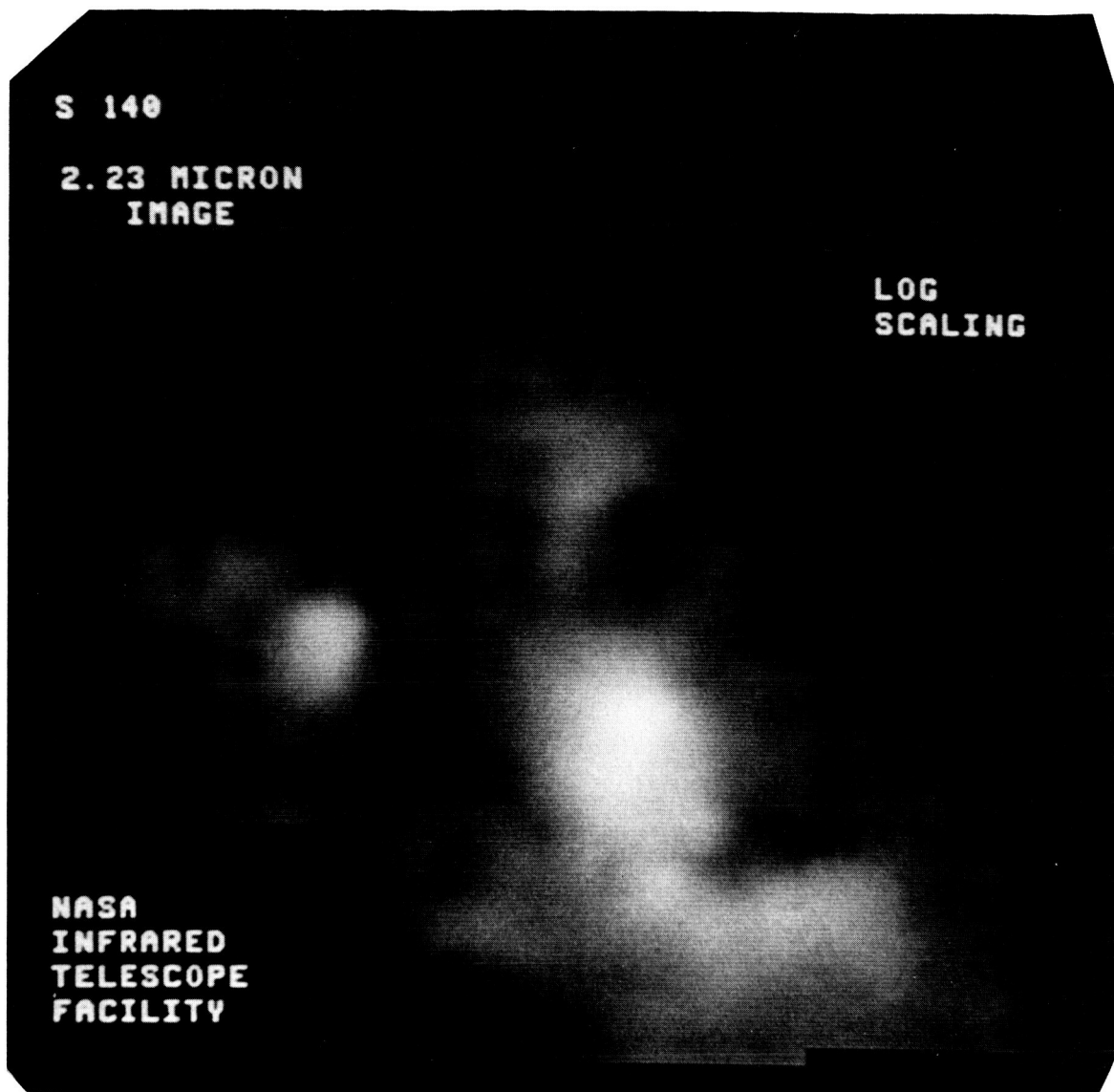
Fig. 4 A 2.23-μm image of the Sharpless 140 complex taken with the University of Rochester/SBRC 32-×-32-element InSb array (July 1985).

pixels) has been successfully incorporated into a circular-variable-filter instrument, and a variety of objects have been imaged in both the <5- and 8-12-μm regions.[12,13] On the 3-m telescope at Lick Observatory, the array system has achieved a sensitivity of +6 magnitudes/pixel in 30 min of integration at 10 μm (0.2-μm bandpass). Figure 6 illustrates an image of NGC 7027 taken with this instrument at 11.50 μm, and Figure 7 shows an image of BD+30 3639 at 11.29 μm.[14]

3. 58-×-62 Si:Sb DRO Array

Si:Sb DRO array technology has been developed by SBRC for potential application in SIRTF.[3] Preliminary data from the supplier on a 58-×-62-element array with 75-μm pixels indicate that only 6 of the 3596 pixels were inactive on the
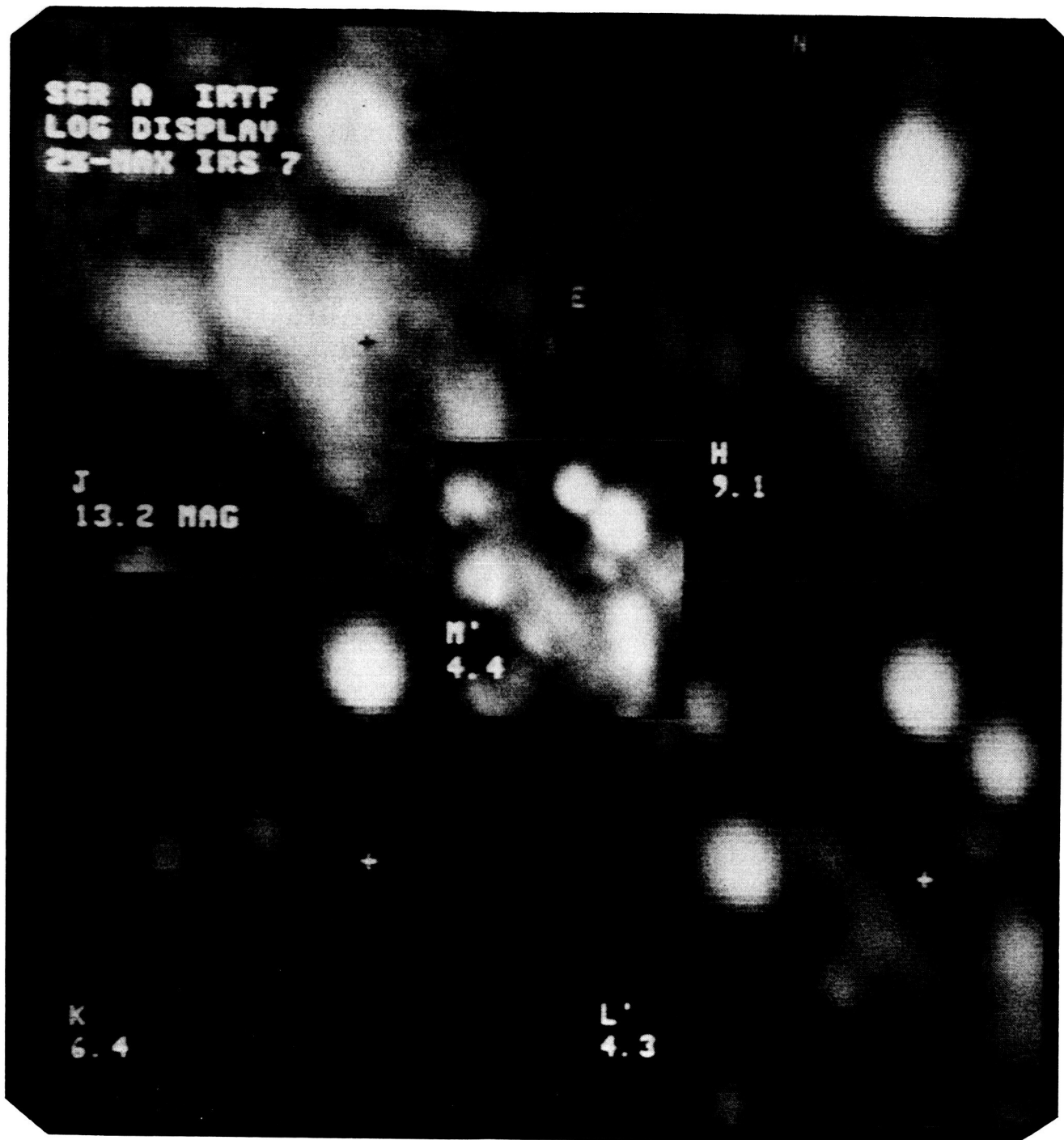
Fig. 5 Composite of images of the galactic center taken with 32-×-32-element InSb CCD array. The estimated position of the compact radio source SgrA* is indicated by the crosshairs.
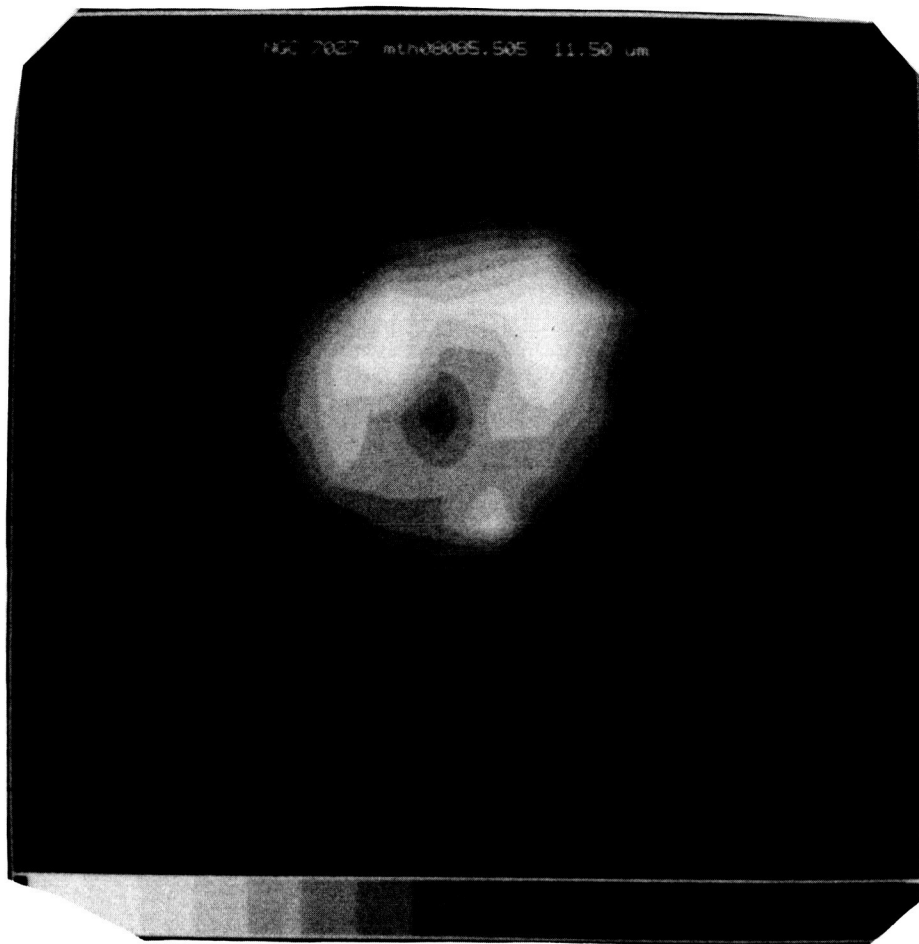
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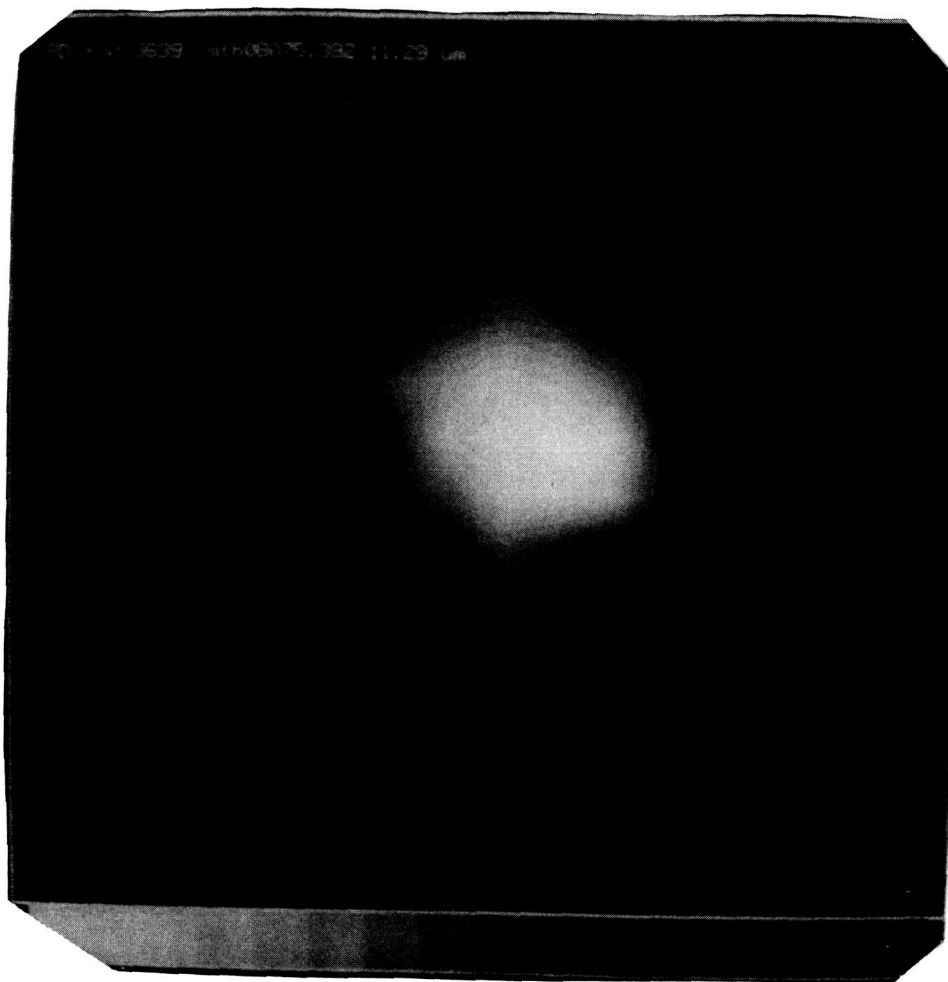Fig. 6 NGC 7027 at 11.50 μm taken with Aerojet Si:Bi 16-x-16-element AMCID array.

Fig. 7   An 11.29-μm image of BD+30 3639 obtained with 16-×-16-element Si:Bi AMCID.

first unit tested. Uncertainty in the spectral response of the Si:Sb detectors created uncertainty in the calculated responsivity, but values fell in the range 1-6 A/W. Upper bounds on read noise (<600 e$^-$) and dark current ($<3 \times 10^4$ e$^-$/s) were established in limited tests at device temperature of 7K and a bias of 1.5 V. Figure 8 shows the NEP histogram for this array, with an average of ~5 × 10^{-18} W/$\sqrt{\text{Hz}}$.
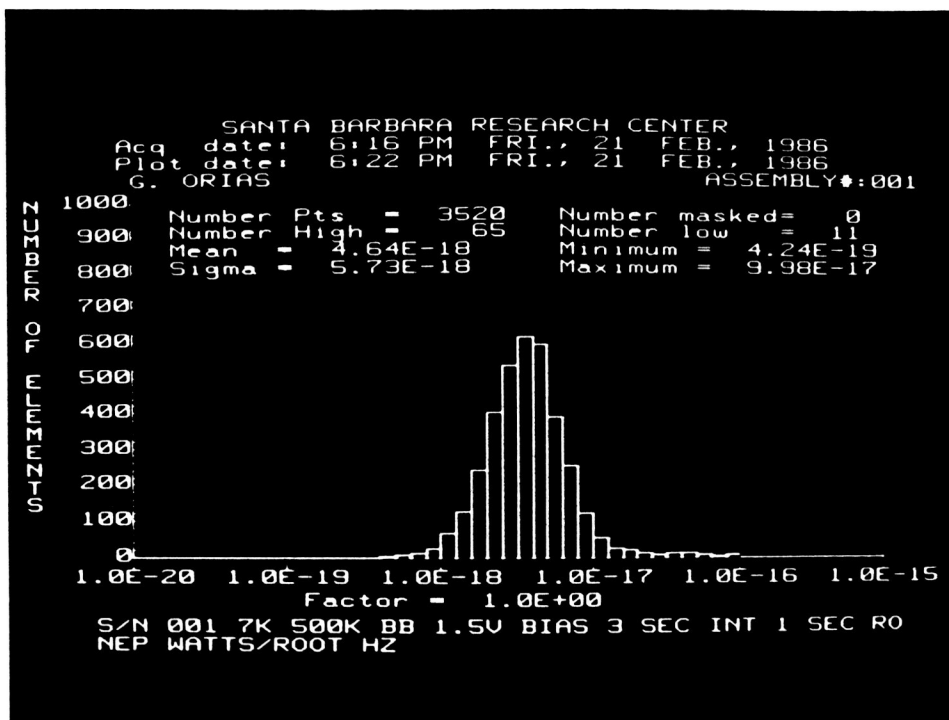
Fig. 8 Noise-equivalent power obtained with 58-×-62-element Si:Sb DRO array.

Future Directions

The past few years have seen a rapid expansion in the number of groups which have acquired and used integrated IR arrays. The rate of progress, both technically and scientifically, is expected to increase rapidly as the technology continues to proliferate. However, the sophistication of the devices and the complexity of the electronics and computer systems required to operate them have created a lag time (of about 2-3 yr) between the time an array is acquired and the time astronomical results are obtained. We expect this delay to continue to decrease as a larger user community is developed.

The sensitivity of many devices, particularly in observations of faint objects at moderate- to high-resolution, is presently limited by the multiplexed readout. The continued optimization of switched-FET multiplexers is expected, as is the continued development of advanced detector and readout concepts, such as the impurity band conduction arrays (10 × 50 format, with 125-μm pixels and
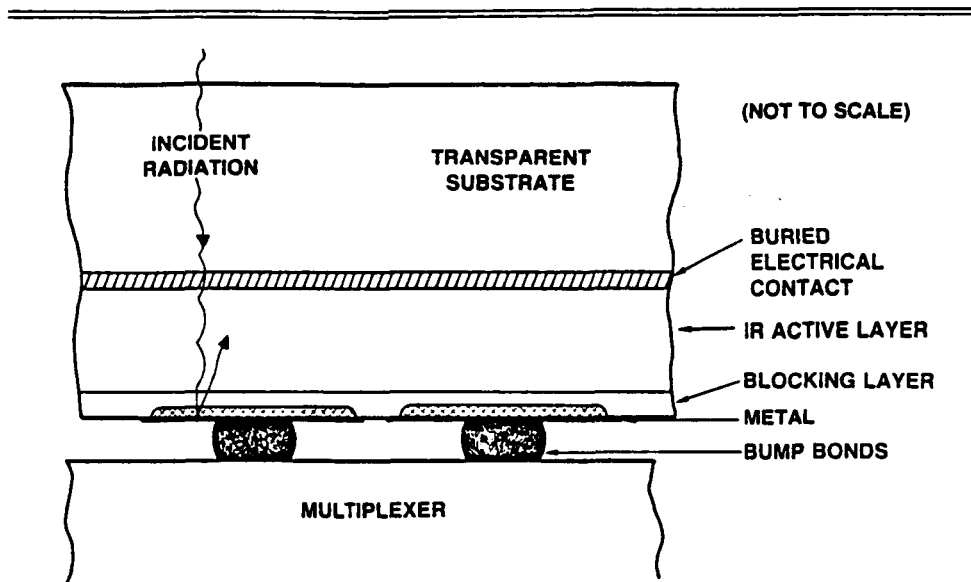
Fig. 9   Integrated array of backside-illuminated impurity band conduction detectors.

switched-FET readout) currently being researched by Rockwell (Fig. 9).   This latter device offers the potential of superior sensitivity, linearity, and radiation-hardness over conventional bulk-extrinsic photoconductors.   Another advanced concept of particular interest for space applications is the recently developed Si:As solid-state photomultiplier, which has demonstrated the ability to count single-photon events at wavelengths out to about 28 μm. Two-dimensional array versions of the device are expected to be achieved in the future.

Summary

A number of hybrid integrated-IR arrays have been developed and used in astronomical applications.   The arrays have proved to have attractive sensitivity and imaging characteristics and to be productive scientifically.   A variety of extrinsic and intrinsic detector materials are being used with low-noise, switched-FET, multiplexing readouts.   A number of advanced arrays (e.g., impurity-band-conduction Si:As arrays) are under active development. While the achievements accomplished to date on IR astronomical arrays represent an exciting beginning, much work remains to be done in the areas of characterization and optimal use; e.g., device dark current, read noise, and imaging quality, need to be much more carefully established.

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16. Abstract

An overview of integrated infrared (IR) array technology is presented. Although the array pixel formats are smaller, and the readout noise of IR arrays is larger, than the corresponding values achieved with optical charge-coupled-device silicon technology, substantial progress is being made in IR technology. Both existing IR arrays and those being developed are described. Examples of astronomical images are given which illustrate the potential of integrated IR arrays for scientific investigations.

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